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PERFORMANCE EVALUATION OF IMPROVED COOKING STOVES: A CRITICAL REVIEW AND A THEORETICAL AND EXPERIMENTAL STUDY FOR A BETTER TESTING APPROACH

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Dedicated to 3 billion people

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Abbreviation Index

ABS	Advanced Biomass Stoves
AWBT	Adapted Water Boiling Test
BCT	Burning Cycle Test
BIS	Bureau of Indian Standards
CAU	China Agricultural University
CCT	Controlled Cooking Test
CDM	Clean Development Mechanism
CNISP	Chinese National Improved Cookstove Program
CS	Chinese Standard
CSI	Clean Stove Initiative
DCs	Developing Countries
GACC	Global Alliance for Clean Cookstoves
GS	Gold Standard
EPTP	Emissions & Performance Testing Protocol
HAP	Household Air Pollution
HFR	Heat Flow Rate
HTP	Heterogeneous Testing Procedure
ICS	Improved Cooking Stoves
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KPT	Kitchen Performance Test
NPIC	National Programme on Improved Chulhas
PCIA	Partnership for Clean Indoor Air
PICs	Products of incomplete combustion

PoAs	Programme of Activities
SDGs	Sustainable Development Goals
SeTAR	Sustainable Energy Technology and Research Centre
SUMs	Stove Use Monitors
TST	Testing Simulation Tool
UCT	Uncontrolled Cooking Test
WBT	Water Boiling Test
WHO	World Health Organisation
WHT	Water Heating Test

Nomenclature

δ	Diffusion boundary layer length
[X]	Molar concentration of pollutant "*X*"
B_m	Mass transfer driving force
BCR	Burning capacity rate
$c_{p,w}$	Specific heat capacity of liquid water
$c_{p,Al}$	Specific heat capacity of Aluminium
EF_X	Emission Factor for pollutant "*X*"
E_X	Emission of pollutant "*X*" per water boiled
f_d	Equivalent dry fuel consumed
FP	Firepower
FP_o	Overall Firepower
FP_u	Useful Firepower
fuelFracC	Fraction of Carbon in the fuel
h	Convective heat transfer coefficient
h_m	Mass transfer coefficient
h_{lv}	Specific enthalpy of vaporization
LHV_{AR}	Lower Heating Value as received
LHV_X	Lower Heating Value of fuel "*X*"
$\dot{m}_{CO}$	Instantaneous mass flow rate of carbon monoxide
$\dot{m}_{eva}$	Rate of vaporisation
m_{eva}	Mass of water vaporized
$m_{w,f}$	Final mass of water at the end of a phase
$m_{w,i}$	Initial mass of water in the pot
m_{wood}	Mass of wood consumed during a test phase

$m_{kindling}$	Mass of kindling material used to light the fire in a test phase
m_X	Mass of pollutant "*X*" produced
$m_{pot+lid}$	Mass of pot and lid
n	Number of pots utilised
P_C	Cooking Power
PFD	Potential Fuel Differences
PM	Mass concentration of particulate
P_o	Power Output Rating
R_b	Burning Rate
RH	Relative Humidity of ambient air
SC	Specific Fuel Consumption
t	Duration of a test phase
t_b	Time to boil
t_{tot}	Total time of the test
T_b	Local boiling temperature
TDR	Turn Down Ratio
T_f	Final temperature of water in the pot
T_i	Initial temperature of water in the pot
T_{max}	Limit temperature of water in the pot
TSP	Total Suspended Particulate Matter
UE	Useful Energy
$\dot{V}$	Volumetric flow rate of the emissions collection hood
Δt	Time between sample points
η	Thermal Efficiency

Abstract

Improved Cooking Stoves are the most commonly promoted technological solution to address the lack of access to clean cooking facilities in Developing Countries, which involves 3 billion people and entails serious health and environmental implications; nevertheless, their success is challenged by the lack of agreement about methodologies for performance evaluation. This work identifies the main criticalities of current testing methodologies and provides indications for a better testing approach.

A critical review of all existing protocols have been realised, as the literature seemed to be missing it; current protocols bring little information about average field performances and might provide misleading guidance about stove designs, due to their incomplete consideration of the *Cooking System* (stove, fuel, pot, burn cycle). A solution has been identified in the form of a repeatable and scientifically validated procedure to be integrated with considerations about the Cooking System.

A theoretical and experimental study has been carried out to identify the key requirements for this sort of procedure; it includes a theoretical model of heat and mass transfer – implemented in Excel and allowing for simulations and sensitivity analysis – and testing of analytical solutions against empirical observations. An *Ideal Heat Transfer* procedure – performed with a lid on the pot and with a limited maximum water temperature – has been identified as the optimal procedure to be integrated with Cooking System considerations.

A *Testing Simulation Tool* has been proposed to allow for a simple and cost-effective simulation of any Cooking System in any external condition, based on a single lab experience. Thus would result in a reliable evaluation of cooking stove performances and in a reduction of the gap between lab and field results.

keywords: access to energy, biomass, improved cooking stoves, testing protocol, water boiling test

Sommario

Le *Improved Cooking Stoves* sono la soluzione tecnologica comunemente promossa per affrontare il problema del mancato accesso a fonti di energia pulite per uso domestico nei Paesi in via di sviluppo, che coinvolge 3 miliardi di persone e comporta gravi conseguenze sulla salute e sull'ambiente; la diffusione di queste tecnologie è tuttavia rallentata dalla mancanza di metodologie condivise per la valutazione delle performance. Questa tesi si pone l'obiettivo di identificare le principali criticità delle metodologie correnti e di fornire indicazioni per un approccio migliore.

È stata realizzata una revisione critica di tutti i protocolli esistenti, che sembra non essere presente in letteratura; da essa emerge come i protocolli correnti forniscano poche informazioni sulle performance attese in un contesto reale oltre a fornire indicazioni fuorvianti circa il design delle stufe, a causa di un'incompleta considerazione del *Cooking System* (stufa, combustibile, pentola, ciclo di potenza). Si è identificata come soluzione l'integrazione tra una procedura scientificamente verificata e ripetibile e opportune considerazioni sul *Cooking System*.

È seguito uno studio teorico e sperimentale al fine di identificare i requisiti necessari per realizzare una tale procedura; lo studio include un modello teorico di scambio termico e di massa – implementato in Excel e utilizzato per simulazioni e analisi di sensibilità – e un confronto tra i risultati analitici e l'evidenza sperimentale. Ne è derivata la definizione di una procedura di *Ideal Heat Transfer* – da eseguire con un coperchio sulla pentola e un limite alla temperature massima dell'acqua – come procedura ottimale per l'integrazione di cui sopra.

Si è proposto un *Testing Simulation Tool* per realizzare una semplice ed efficiente simulazione di qualsivoglia Cooking System in qualsiasi condizione esterna, sulla base di una singola esperienza di Scambio Termico Ideale. Ciò permetterebbe una valutazione ottimale delle performance di una stufa e una riduzione del divario tra risultati di laboratorio e di contesto reale.

parole chiave: accesso all’energia, biomassa, improved cooking stoves, procedura di test, water boiling test

Estratto in lingua italiana

La disponibilità di energia è un elemento fondamentale dello sviluppo umano, che si intreccia a tematiche di carattere geopolitico, economico, sociale ed ambientale. L'accesso a forme di energia sostenibili, pulite, affidabili ed economicamente accessibili è ormai riconosciuto come un diritto fondamentale di ogni individuo; tra gli Obiettivi di Sviluppo Sostenibile recentemente promossi dalle Nazioni Unite[1] figura infatti quello di un "accesso universale all'energia" che appare, però, ancora lontano dall'essere realizzato. Secondo i dati più recenti dell'Agenzia Internazionale dell'Energia (IEA) circa 1,2 miliardi di persone risultano tuttora prive di accesso all'elettricità e 2,7 miliardi (il 38% della popolazione mondiale) non hanno accesso a combustibili moderni per uso domestico; per la quasi totalità, appartengono a Paesi in via di sviluppo in Asia, America Latina e Africa Sub-Sahariana. Inoltre, se le stime della IEA prevedono progressi nel tasso di elettrificazione, scarsi miglioramenti sono attesi sul fronte dell'energia per uso domestico, con 2,5 miliardi di persone ancora dipendenti dalla cosiddetta "biomassa tradizionale" (legname, sterco animale, residui agricoli, carbone da legna) nel 2030.

La dipendenza dalla biomassa, che potrebbe non rappresentare un problema di per sé, ha gravi conseguenze in relazione al suo utilizzo per mezzo di "stufe" altamente inefficienti, responsabili della produzione di particelle che favoriscono il riscaldamento globale e di fumi nocivi per la salute di chi le utilizza – circa 4,3 milioni di morti all'anno, soprattutto donne e bambini, sono attribuibili all'inquinamento domestico secondo L'Organizzazione Mondiale della Sanità. In alcuni contesti, la dipendenza da biomassa legnosa può inoltre costituire un importate fattore di stress sulle risorse forestali, favorendo la desertificazione e influenzando di conseguenza la produttività agricola e la sicurezza alimentare. Tuttavia, un passaggio a forme di

[1] Gli Obiettivi di Sviluppo Sostenibile sono stati ufficialmente adottati a partire dal 1 Gennaio 2016 e sono validi fino al 2030.

energia più moderne, come il gas o l'elettricità, risulta spesso non attuabile nel breve termine; inoltre, l'introduzione di nuove tecnologie non si traduce automaticamente in una totale sostituzione di quelle tradizionali, ma piuttosto nell'adozione multipla di diverse soluzioni a seconda delle necessità. Pertanto, le *Improved Cooking Stoves* (ICS, stufe migliorate) sono frequentemente proposte come una soluzione "intermedia", che permetta di non abbandonare la biomassa garantendo al contempo una migliore efficienza termica e di combustione.

Il termine "*stove*" può applicarsi ad una grande varietà di dispositivi, dai tradizionali "fuochi su tre pietre" (*Figura 1.a*) a soluzioni più sofisticate; il comune principio di funzionamento consiste nella generazione di calore in una camera di combustione e nella sua trasmissione verso un'applicazione specifica (*e.g.* una pentola d'acqua da portare a ebollizione). I design (*Figura 1*) si differenziano solitamente in base al tipo di combustibile (legname, carbone di legna, o altro) al principio di combustione (diretta o gassificazione) e alla circolazione di aria (naturale o forzata per mezzo di un ventilatore); in misura diversa, a seconda del grado di complessità tecnologica, dovrebbero garantirebbe benefici per gli utenti sia in termini di risparmio netto di combustibile, sia soprattutto in termini di esposizione ad emissioni nocive. Non sempre, tuttavia, i benefici attesi si traducono in risultati effettivi sul campo; un recente studio[2] del Massachusetts Institute of Technology (MIT), ad esempio, dimostra come la mancata evidenza di benefici significativi possa portare, da parte degli utenti, ad una progressiva carenza di manutenzione della stufa e in definitiva ad un ritorno alle soluzioni tradizionali. Lo studio, basato su un'osservazione di quattro anni successiva all'introduzione di stufe migliorate in un contesto rurale in India, non ha infatti riscontrato benefici rilevanti né in termini di risparmio di combustibile né in termini di esposizione ad emissioni nocive. Sulla base di casi di studio simili in altre regioni, diversi ricercatori hanno iniziato a porsi dei dubbi circa i criteri e i metodi utilizzati per classificare una stufa come "migliorata", rilevando come la

[2] "*Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves*" Hanna et al.

maggior parte delle stufe commerciali apportino riduzioni di inquinanti non sufficienti a determinare un beneficio significativo.

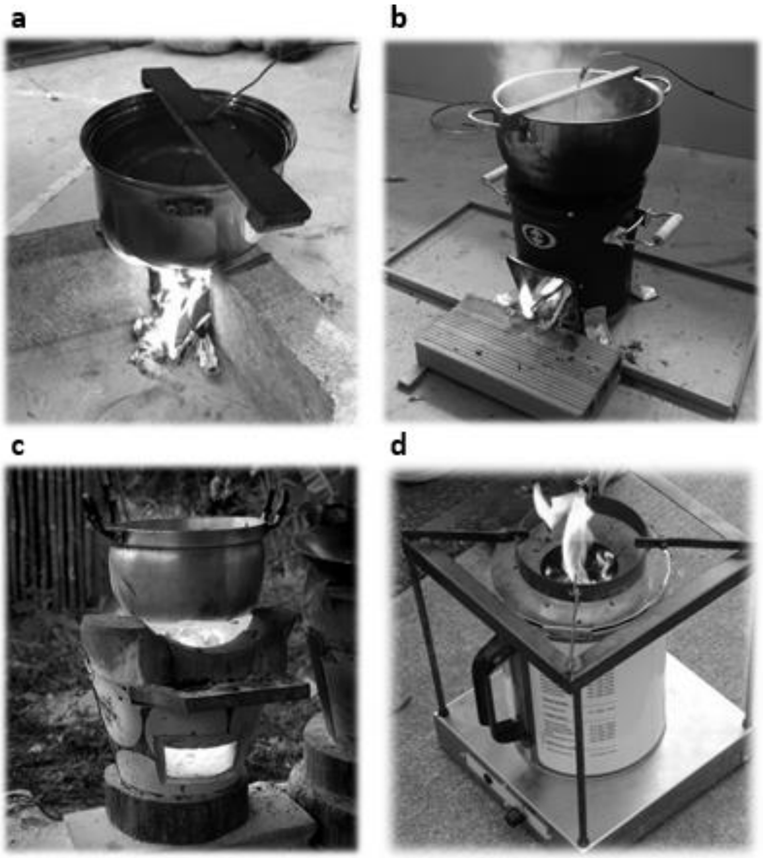

Figura 1 – Diversi design di stufe migliorate. a) fuoco su tre pietre; b) stufa a legna, modello Rocket; c) stufa a carbone di legna d) gassificatore a circolazione forzata. Le fotografie "a" e "b" sono state scattate dall'autore al Politecnico di Milano – Dipartimento di Energia; la fotografia "d" è stata scattata alla ETHOS Conference 2016.

La valutazione delle prestazioni di una stufa può avvenire per mezzo di test di laboratorio (*lab protocols*) o di rilevamenti in un contesto reale (*field protocols*). I primi, solitamente ideati come uno strumento per gli sviluppatori di ICS, sono finalizzati alla comparazione delle performance tra diversi design e rappresentano la grande maggioranza dei protocolli esistenti; l'ambiente controllato del laboratorio dovrebbe garantire l'assenza di variabilità legate alle condizioni esterne e al comportamento dell'utente. Data la loro impostazione, questi protocolli non dovrebbero però essere considerati degli indicatori rappresentativi delle performance attese in un contesto reale di utilizzo; nondimeno, è pratica comune fare affidamento su di essi – e in particolare sul Water Boiling Test[3] (WBT), il protocollo più diffuso – quali unici indicatori di prestazioni, anche in casi in cui sarebbe preferibile una valutazione sul campo, a causa dei tempi e dei costi maggiori connessi all'utilizzo di protocolli di tipo "*field*". Questi ultimi, infatti, consistono in sondaggi prolungati nel tempo finalizzati alla valutazione dei risparmi effettivi di combustibile registrati dagli utenti in seguito all'adozione di una determinata stufa, e richiedono un dispendio di risorse decisamente maggiore. Anche la Global Alliance for Clean Cookstove (GACC), istituita nel 2010 dalle Nazioni Unite con l'obbiettivo di diffondere 100 milioni di ICS entro il 2020, ha indirettamente incoraggiato la pratica dominante di utilizzare il WBT come strumento di selezione tecnologica, realizzando dei criteri di ranking delle stufe basati sul protocollo. Non c'è però condivisone unanime, all'interno della comunità scientifica internazionale, né sui criteri di valutazione individuati né sulla metodologia, con un numero crescente di studi che dimostra la totale mancanza di correlazione tra performance di laboratorio e di contesto reale. Questa situazione ha determinato il tentativo, da parte di diversi gruppi di ricerca, di definire delle proprie metodologie alternative; nessuna di esse, però è riuscita ad imporsi quale standard condiviso, andando piuttosto ad esacerbare la complessità del contesto. La dipendenza da metodologie di laboratorio non rappresentative delle condizioni reali di funzionamento può avere ripercussioni dirette sia sui progetti di disseminazione stufe, che potrebbero registrare una mancata adozione di prodotti non funzionali alle esigenze degli utenti, sia sui progetti finanziati attraverso il mercato dei carbon credits, in cui gli effettivi risparmi di emissioni inquinanti risultano sottostimati.

Emerge pertanto l'esigenza di un lavoro di **revisione critica** e omnicomprensiva di tutti i protocolli di laboratorio, finora assente in letteratura. L'analisi fornisce un

[3] Il Water Boiling Test valuta le prestazioni di una stufa nel riscaldare e portare ad ebollizione un certo volume d'acqua in una pentola; tutti i *lab protocols* considerati si basano su una procedura di riscaldamento di un certo volume d'acqua.

confronto tra le varie metodologie esistenti sulla base di una serie di criteri standardizzati, ognuno dei quali discusso in una sotto-sezione specifica:

- le indicazioni fornite circa il combustibile, il volume d'acqua, *ecc.*;
- le fasi costitutive della procedura di test;
- le formule matematiche utilizzate;
- i punti di forza e di debolezza.

Sono stati presi in considerazione tutti i protocolli di laboratorio correnti, in ordine cronologico di prima pubblicazione, ovvero Water Boiling Test (WBT), Indian Standard on Solid Biomass Chulha Specification (BIS), Chinese Standard (CS), Emissions & Performance Test Protocol (EPTP), Adapted Water Boiling Test (AWBT), Heterogeneous Testing Procedure (HTP). Infine, sono state incluse considerazioni sui protocolli attualmente in fase di sviluppo e sono stati discussi gli studi dai quali traggono origine; la partecipazione dell'autore alla ETHOS[4] Conference 2016 ha reso possibile l'inclusione di informazioni aggiornate sul grado di avanzamento del processo di sviluppo, supervisionato dalla International Organization for Standardization (ISO).

I risultati della revisione confermano come i protocolli correnti, e i *Tiers of Performance* basati sui loro risultati, non dovrebbero essere interpretati come strumenti per la selezione tecnologica, poiché sono in grado di fornire scarse informazioni circa le performance attese in un contesto reale. Infatti, come sempre più studi sembrano dimostrare, la valutazione delle performance non può essere unicamente riferita alla "stufa", ma dovrebbe piuttosto tenere conto di un "*Cooking System*" integrato, composto dalla stufa, dal combustibile, dal tipo di pentola e dal ciclo di potenza seguito. L'idea che sia possibile stimare le performance di una data stufa in qualsiasi circostanza affidandosi ad una procedura di test "fissa" è totalmente fuorviante, e il concetto dovrebbe essere maggiormente evidenziato per evitare conseguenze sui

[4] *Engineers in Technical and Humanitarian Opportunities of Service*

progetti di disseminazione stufe o sulle stime d'impatto climatico. Inoltre, l'analisi sembra suggerire che i protocolli correnti potrebbero risultare fuorvianti anche per quanto riguarda la comparazione fra diversi design in fase progettuale; infatti, poiché le stufe non sono dotate di performance "intrinseche" bensì dipendono dalle circostanze locali, non è possibile considerare la valutazione di un design come valida "in generale". Di conseguenza si propone, quale migliore approccio ai test, l'individuazione di una procedura ripetibile e convalidata scientificamente – in termini di formule e assunzioni termodinamiche – da integrare con considerazioni relative al combustibile, alla pentola e al ciclo di potenza che siano rilevanti rispetto all'utente finale. Questo dovrebbe ridurre il divario tra prestazioni di laboratorio e di contesto reale, fornendo una comparazione significativa e affidabile tra diversi design; indicazioni simili sembrano anche emergere dal processo ISO in corso. L'analisi dei protocolli esistenti non ha tuttavia permesso di individuare con chiarezza la procedura ideale sulla quale realizzare questo tipo di approccio.

Si è pertanto approfondito il campo d'indagine con uno **studio teorico e sperimentale** delle principali fonti di variabilità legate ai protocolli di test, con l'obiettivo di trarre conclusioni definitive sui requisiti necessari per una procedura ripetibile e scientificamente convalidata. Le fonti di variabilità su cui si è concentrata l'analisi sono l'evaporazione e l'incertezza nella lettura di temperatura nella regione di ebollizione; studi precedenti in letteratura hanno provato ad affrontare il problema, basandosi però unicamente sull'evidenza sperimentale di un numero estremamente limitato di osservazioni e senza fornire un'adeguata modellizzazione teorica del problema. In questo caso, seguendo il principio di falsificabilità, le conclusioni sono state dapprima derivate per via analitico-teorica, e successivamente sottoposte al controllo di un'esperienza potenzialmente falsificante; si è resa dunque necessaria la definizione di un modello teorico di scambio termico e di massa riferito ad una pentola d'acqua sottoposta ad un flusso di calore costante. E' stato realizzato dapprima un modello ristretto, riferito unicamente allo scambio di massa tra superficie liquida e aria ambiente al variare della temperatura dell'acqua; tale modello è stato definito fino ai 90°C – temperatura che si può considerare precedente all'innesco dei fenomeni di ebollizione – prendendo in considerazione due diversi approcci teorici (modelli diffusivi-avvettivi di Stefan e di Lewis) e calibrando la soluzione ottima sulla base delle osservazioni empiriche (*Figura 2*).

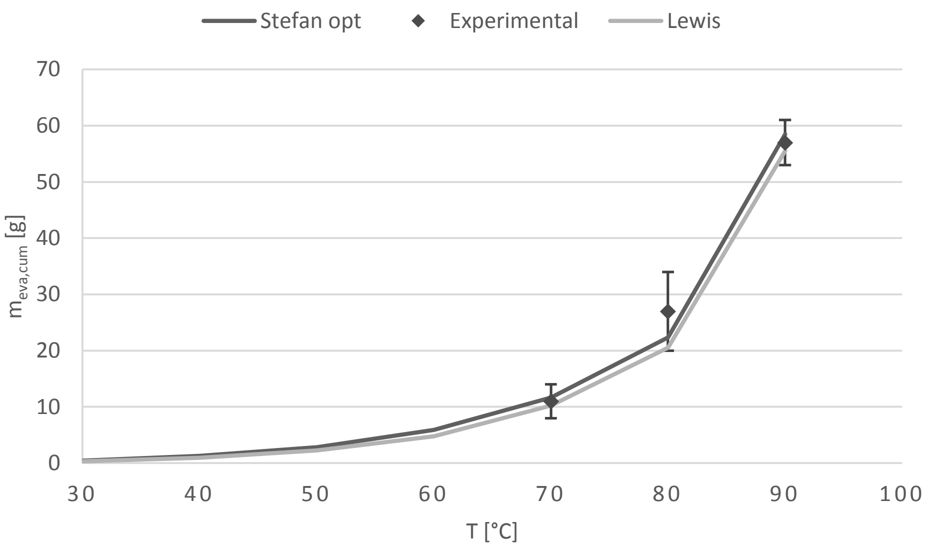

Figura 2 – Calibrazione del modello di evaporazione sui dati sperimentali.

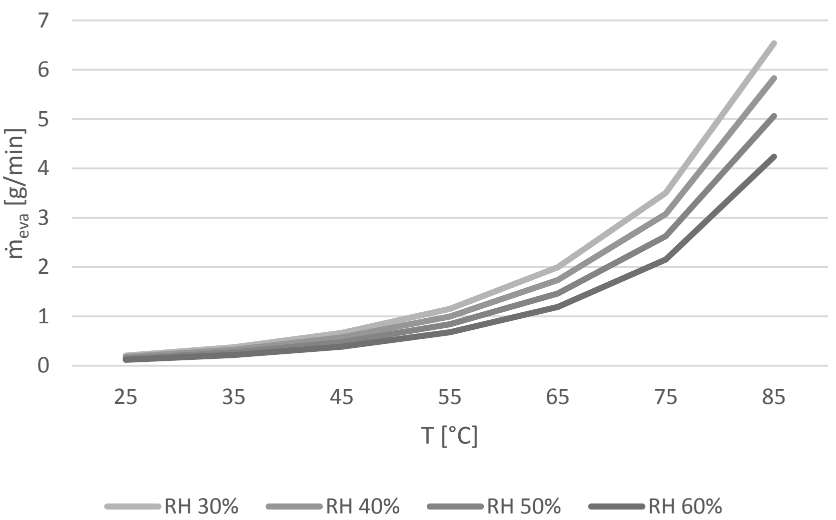

Figura 3 – Variabilità del tasso di evaporazione in funzione dell'umidità relativa.

Questo primo modello è già funzionale ad identificare quali siano le variabili effettivamente in grado di influenzare il tasso di evaporazione; si è dimostrato come, fissate le dimensioni della pentola, l'unico fattore rilevante sia l'umidità relativa dell'aria ambiente, che determina una variabilità crescente con la temperatura (*Figura 3*). Per valutare quindi come una variabilità nel tasso di evaporazione possa incidere sui parametri di performance dei test è necessario estendere l'analisi ad un modello di scambio termico e di massa generalizzato, che permetta di variare qualsiasi parametro d'interesse, dall'input termico alle dimensioni della pentola alle condizioni ambiente. Il bilancio termico complessivo del sistema (*Figura 4*) è influenzato dal tasso di evaporazione; fissato l'input termico, il tasso di evaporazione influenza direttamente il tempo del test, il quale a sua volta influenza tutti i parametri di performance.

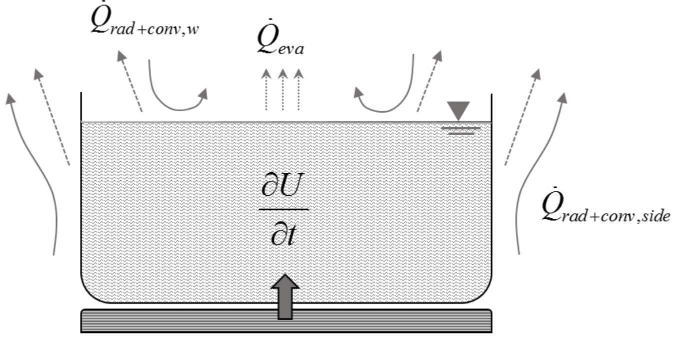

Figura 4 – Schema rappresentativo del bilancio termico del sistema considerato.

Sulla base di questo modello è stata effettuata un'analisi di sensitività – al variare dell'umidità relativa in un range realistico – sul tempo del test e sulla massa complessiva di acqua evaporata; si è valutato quindi l'impatto su alcuni parametri di performance tipici, come l'efficienza e il consumo specifico di combustibile (un esempio in *Figura 5*). L'incertezza estesa, valutata sulla base della teoria della propagazione dell'incertezza per un livello di confidenza del 95%, può essere molto rilevante già a 90°C, e presumibilmente ancora maggiore nella regione di ebollizione. La soluzione più semplice per controllare la variabilità connessa al fenomeno dell'evaporazione appare l'utilizzo di un coperchio sulla pentola; in questo caso, pochi grammi d'acqua evaporerebbero andando rapidamente a saturare il volume di controllo e arrestando il processo, indipendentemente da ogni ulteriore aumento di temperatura. Una seconda fonte d'incertezza è stata invece teorizzata nelle fluttuazioni della lettura della termocoppia nella regione di ebollizione; questo tipo d'incertezza può essere eliminato solo imponendo un limite alla temperatura massima del test che sia precedente all'insorgenza del fenomeno dell'ebollizione.

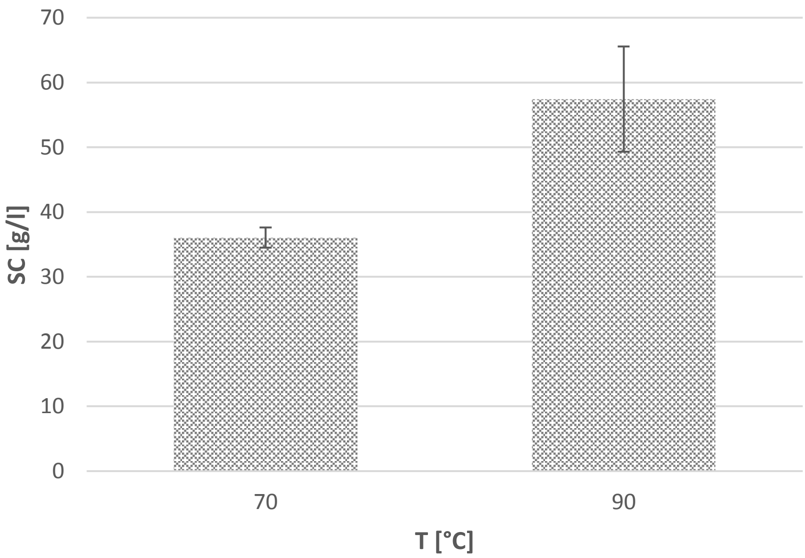

Figura 5 – Incertezza combinata a diverse temperature, relativa alla Specific fuel Consumption (SC) ed estesa per un L.C. del 95%. Le barre rappresentano la dev.std.

Tali conclusioni teoriche sono state quindi sottoposte al confronto con le osservazioni empiriche derivanti da test su una piastra elettrica; l'evidenza sperimentale ha corroborato quanto teorizzato. È stata infatti rilevata una variabilità nella quantità di massa evaporata crescente con la temperatura, e ancora più rilevante nella regione di ebollizione, come si ipotizzava pur non avendo effettuato simulazioni a causa di limiti di applicabilità del modello; utilizzando invece un coperchio, la massa d'acqua complessivamente evaporata non ha mostrato variazioni statisticamente significative ed è risultata ampiamente trascurabile in valore assoluto. È stato anche separatamente identificato l'impatto delle fluttuazioni nella lettura della termocoppia a 95°C, che è risultato statisticamente significativo ($p < 0,05$). Si può pertanto concludere che una procedura ripetibile e scientificamente convalidata debba essere eseguita utilizzando un coperchio sulla pentola e fissando un limite massimo alla temperatura dell'acqua minore o uguale a 90°C; questo tipo di procedura è stata definita di *Ideal Heat Transfer* (IHT).

La procedura IHT dovrebbe comunque essere integrata con considerazioni relative al *Cooking System* per fornire una stima affidabile delle performance di una stufa. Per realizzare questo proposito, il Water Heating Test (WHT), un protocollo in fase di sviluppo, suggerisce di testare la stufa in rapporto al ciclo di potenza tipico della popolazione destinataria del modello, e utilizzando pentole e combustibili simili. Tuttavia, una soluzione molto più semplice ed economicamente efficiente potrebbe essere rappresentata dal testare la stufa con una procedura IHT per una singola combinazione combustibile/pentola, realizzando successivamente una simulazione analitica di tutte le diverse condizioni e dimensioni di pentola necessarie. Per realizzare questa soluzione, si è proposta una versione estesa del modello precedentemente implementato, che è stata definita ***Testing Simulation Tool*** (TST). Sebbene si rimandi a ad ulteriori studi per uno sviluppo definitivo dello strumento, è stata realizzata una prima versione dello strumento al fine di dimostrarne la capacità di simulare le performance di una stufa in diverse condizioni sulla base di una singola esperienza di laboratorio. E' stata quindi dapprima definita una semplice procedura per modellizzare delle *Improved Cooking Stoves* nel modello, ed è stato condotto uno studio dimostrativo riferito alla stufa Envirofit-Econofire. Il TST è stato impostato in modo da riprodurre le prestazioni ottenute dalla stufa in 5 test di laboratorio (WBT) eseguiti dall'autore, nonché le performance derivate dal Clean Cooking Catalog della GACC, e basate su EPTP; per far ciò sono state introdotte delle modifiche per estendere l'evaporazione alla regione di ebollizione e per simulare la configurazione dell'EPTP, che prevede uno strato di schiuma isolante sulla superficie liquida. I risultati delle simulazioni hanno mostrato un'ottima consistenza con i dati sperimentali, sia nel caso del WBT che dell'EPTP; si riporta in *Tabella 1* il primo caso.

	t [min]		***η***		***SC [g/l]***	
WBT	*average*	*SD*	*average*	*SD*	*average*	*SD*
Experimental	26,94	3,76	28,45%	2,22%	105,69	7,93
TST	26,79	1,22	28,34%	0,03%	100,61	5,01
err%	0,57%		0,55%		4,81%	

Tabella 1 – Confronto tra I risultati della simulazione TST e I dati sperimentali del WBT.

Inoltre, lo strumento è stato utilizzato per simulare dei risultati equivalenti riferiti a diverse dimensioni della pentola e diverso volume d'acqua, contribuendo ad evidenziare le limitazioni intrinseche di procedure come EPTP e WBT che si basano su un'approssimazione di una "cooking task".

I risultati sembrano incoraggiare il completo sviluppo del *Testing Simulation Tool*, il quale, sulla base di pochi significativi esperimenti con procedura di *Ideal Heat Transfer*, e combinato alla conoscenza dei cicli di potenza e dei combustibili rappresentativi, potrebbe essere utilizzato per simulare le performance di una stufa non solo rispetto ad uno specifico ciclo di potenza, ma per qualsiasi ciclo desiderato e riferito a qualsiasi popolazione, risolvendo il limite maggiore di un approccio come quello del Water Heating Test. Tale simulazione, inoltre, potrebbe essere effettuata tenendo conto anche delle condizioni ambientali attese in un contesto reale di utilizzo, contribuendo ulteriormente alla riduzione del divario tra performance di laboratorio e di utilizzo reale.

Introduction

This thesis work aims at addressing a specific dimension of the challenge for a universal access to energy, namely the reliance on biomass fuelled inefficient cooking facilities. Though often not it in the spotlight, this issue involves around 3 billion people worldwide – almost all of them living in Developing Countries – and entails serious social and environmental implications. The smoke produced by inefficient biomass combustion is responsible for about 4,3 million deaths per year, stress on forest resources and emission of climate-forcing pollutants. Most important, the International Energy Agency prospects for 2040 show no significant improvement of the situation. Since an immediate adoption of modern fuels is not realistic in most cases, Improved Cooking Stoves are often promoted as an intermediate solution allowing for biomass use while ensuring higher efficiencies and cleaner combustion, thus reducing harmful effects. Nevertheless, tests and researches previously conducted within the activities of UNESCO Chair in Energy for Sustainable Development research group at Politecnico di Milano - Department of Energy, raised questions about this technological solution, and moreover about the criteria by which the claimed "improvement" is assessed. There is in fact no agreement on testing methodologies in the international community, and more and more studies seem to question the current status. The present work is therefore aimed at identifying the main criticalities related to current Improved Cooking Stoves testing methodologies and at providing indications for a better testing approach.

Chapter 1 is dedicated to an overview of the issue of access to energy for cooking in Developing Countries. Impact on health and environment is analysed in depth and the concept of Improved Cooking Stoves is presented, discussing benefits and limitations.

Chapter 2 focuses on the framework of performance evaluation of Improved Cooking Stoves, providing an immediate outlook of testing methodologies and analysing the implications of data unreliability on stove dissemination programs and carbon-financed projects.

Chapter 3 is dedicated to a critical and comprehensive review of all existing lab protocols, which the literature seems to be missing. The analysis tries to highlight strengths and weaknesses of each methodology and to identify a possible path for a better testing approach. The review also benefited from the author participation to the 2016 ETHOS Conference[1], which allowed to include a discussion of protocols under development.

Chapter 4 is finally dedicated to a theoretical study of the thermodynamic principles of testing protocols, including the implementation on Excel of a heat and mass transfer model, allowing for simulations and sensitivity analysis. Analytical solutions are subsequently tested against empirical observations derived from experiments on an electric heater and critically discussed in *section 4.3*. Furthermore, an extended version of the model is proposed as a tool to allow for simple and cost-effective simulations of any testing condition, based on a single lab experience.

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[1] "*Engineers in Technical and Humanitarian Opportunities of Service (ETHOS) is a non-profit organization whose purpose is to facilitate research and the development of appropriate technology by forming collaborative North-South partnerships between universities, research laboratories, engineers, and non-governmental organizations in foreign countries*" [1]. The conference, held annually, is attended by international stoves experts and developers, and represents one of the most important references in the world of Improved Cooking Stoves.

1 Access to energy for cooking in Developing Countries

Energy is a crucial factor for human development and life quality. As the United Nations Development Programme states: "*Energy affects all aspects of development – social, economic and environmental – including livelihoods, access to water, agricultural productivity, health, population levels, education, and gender-related issues*" [1]. For this reasons, access to energy is recognised as a fundamental right and is included among the Sustainable Development Goals (SDGs) promoted by the United Nations in 2015 and to be achieved up to 2030; in particular Goal 7 is aimed at "e*nsuring access to affordable, reliable, sustainable and modern energy for all*" [2]. Nevertheless, the objective of a universal energy access is far from being achieved, as currently 1,2 billion people still lack access to electricity and 2,7 billion people lack access to clean cooking facilities, according to the International Energy Agency (IEA) [3]. Moreover, if progresses are expected in the rate of electrification, only minor changes are foreseen in terms of access to modern fuels for cooking: still 2,5 billion people are expected to rely on unclean biomass based cooking facilities in 2030, with major improvements in Asia but with a worsening of the situation in Africa [4]. Although being less featured in promotion campaigns [5], reliance on those facilities have multiple negative effects, as stress on forest resources, impact on health and emission of climate-forcing pollutants. Possible solutions may consist in promoting a shift towards LPG or electricity, yet an immediate adoption of modern fuels is often not realistic. Accordingly, the so-called "Improved Cooking Stoves" are promoted as an intermediate solution, allowing for biomass use while supposed ensuring higher efficiencies and cleaner combustion, thus reducing harmful effects. The present chapter is dedicated to a deeper analysis of the issues related to the use of traditional biomass in developing countries, as well as to a presentation of the technological solution proposed, discussing benefits and limitations.

1.1 Traditional use of biomass

The most recent estimate, by the World Health Organisation (WHO), assesses that the current number of people relying on the so-called traditional biomass (including wood, animal dung, crop waste and charcoal) for cooking and heating purposes is around 3 billion [6]. Most live in low- and middle-income countries in developing Asia, Africa, Latin America and the Middle East, as shown in *Table 1.1.1*; in some cases (Ethiopia, the Democratic Republic of Congo, Tanzania, Uganda and Bangladesh) over 90% of the population relies on these fuels [7].

Region	***Population relying on traditional use of biomass*** *[millions]*	***Percentage of population relying on traditional use of biomass*** *[%]*
Developing countries	**2.722**	**50%**
Africa	754	68%
Sub-Saharan Africa	*1*	*0%*
North Africa	*753*	*80%*
Developing Asia	1.895	51%
China	*450*	*33%*
India	*841*	*67%*
Latin America	65	14%
Brazil	*8*	*4%*
Middle East	8	4%
WORLD	**2.722**	**38%**

Table 1.1.1 – Population relying on traditional use of biomass in 2013, adapted from IEA [8].

Biomass use may not be an issue in itself, yet problems arise from the use of traditional and low-efficient stoves – as the so-called "three-stone fire" stove – that lead to relevant smoke production and household air pollution (HAP)[1], contributing

[1] Pollution from solid fuels produced at the household level was traditionally referred to as "Indoor Air Pollution" (IAP); more recent papers and the World Health Organisation prefer the term "Household Air Pollution".

also to climate change. Furthermore, considering that cooking energy accounts for about 90% of all household energy consumption in developing countries (DCs) it can also contribute to stress on wood resources [9].

Reliance on wood biomass entails also social and economic implications, as women and children are usually responsible for firewood collection every day, preventing them for spending time in income generating activities or education, and exposing them to security risks [9]. Most important, despite massive efforts aimed at substitution and electrification, statistics for traditional biomass use are not expected to vary much by 2030 on a global level, especially as regards rural population, with the situation in Sub-Saharan Africa getting even worse, as shown by *Figure 1.1.1*.

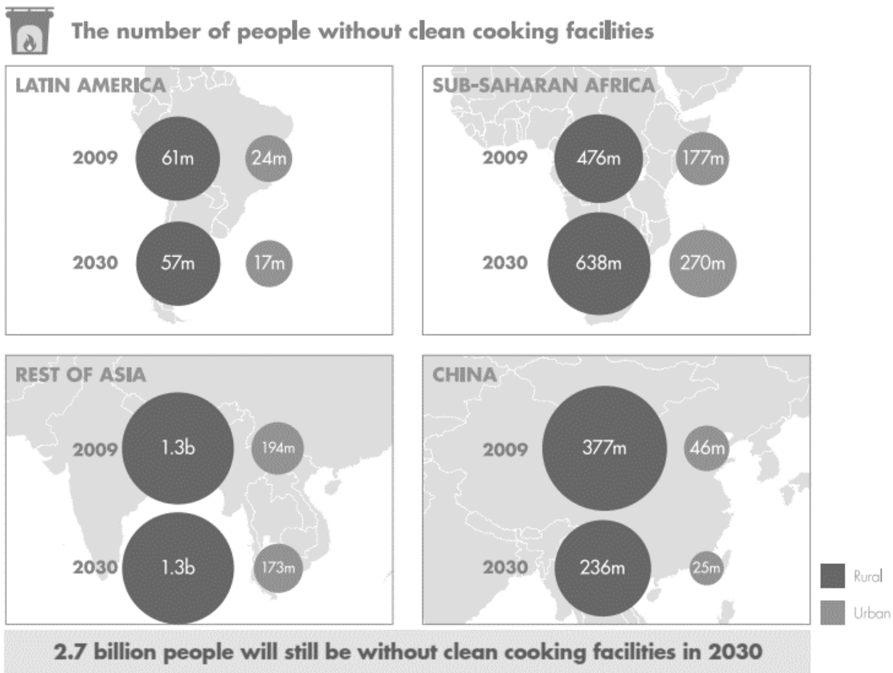

Figure 1.1.1 - Number of people without clean cooking facilities per region, adapted from Shell Foundation [10].

According to the Africa Energy Outlook[2] by the IEA [11], which extended the analysis to 2040, bioenergy demand in Sub-Saharan Africa will grow by 40% in absolute terms, leading to an increased stress on the forestry stock; 650 million people will be still relying on traditional biomass for cooking and heating, mostly in rural areas. Those numbers highlight how the challenges posed by the use of traditional biomass will be still present in 25 years. Accordingly, following sections are dedicated to a deeper analysis of potential impacts of unclean cooking facilities on health and environment.

1.1.1 Impact on health

Biomass combustion from open fires and traditional stoves produces smoke and harmful emissions, such as carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), particulate matter (PM) and organic compounds. Such smoke heavily pollutes indoor air, as cooking is performed usually inside for practical reasons [12]; in case of poor ventilation, indoor smoke can be 100 times higher than acceptable levels for fine particles [6]. Women and young children, who spend a major fraction of their time in the polluted environment, are most exposed to this form of pollution, which is responsible for about 4.3 million deaths per year [13], or one death every 8 seconds.

This is more than the deaths attributable to malaria, tuberculosis and HIV combined, as shown in *Figure 1.1.2*. Diseases associated with unclean biomass combustion are pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease and lung cancer, as shown by *Figure 1.1.3*. The heavy impact on women and young children can be highlighted considering that household pollution is responsible for more than 50% of all deaths among children less than 5 years old from acute lower

[2] Data are referred to the so-called New Policies Scenario, describing "*the probable pathway for energy markets based on the continuation of existing policies and measures, and the implementation, albeit often cautiously, of the commitments and plans announced as of mid-2014, even if they are yet to be formally adopted*" Source: IEA [11].

respiratory infections and for about 25% of all premature deaths due to stroke, half of which are women.

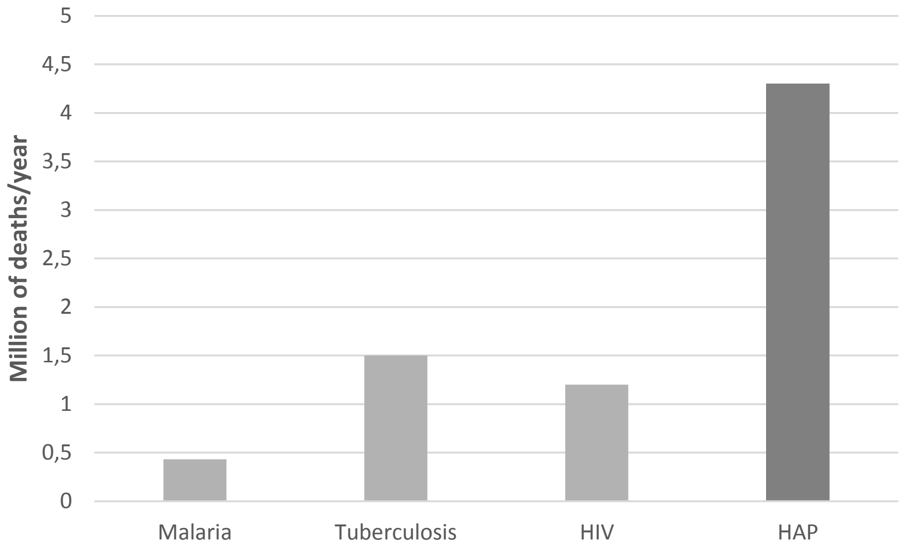

Figure 1.1.2 – Deaths per year on a global scale attributable to different causes; data from WHO [6], [14]–[16].

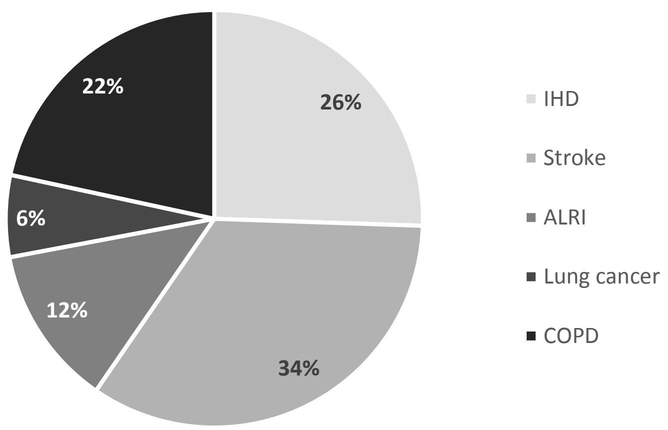

Figure 1.1.3 – Percent of total household air pollution burden per disease, adapted from WHO [13]; ALRI: acute lower respiratory disease; COPD: chronic obstructive pulmonary disease, IHD: ischaemic heart disease.

Furthermore, indoor smoke can inflame airways and lungs, affecting the immune system and altering blood pressure; it is linked to low birth weight, tuberculosis, cataract, nasopharyngeal and laryngeal cancers and it can cause eye irritations [6]. Lim et al. [17] performed a comparative risk assessment of the Global Burden of Disease[3], quantifying the disease burden caused by 20 leading risk factors and subsequently ranking them. Pollution from solid fuels produced at the household level, referred to as "Household Air Pollution" (HAP), is ranked as the fourth leading risk factor in the world, after high blood pressure, tobacco smoke and alcohol, even if only people living in developing countries are exposed. Furthermore, restricting the analysis to women only, HAP becomes the second leading risk factor on a global scale. Those results provide an impressive evidence of the link between traditional biomass use and health consequences.

It is also important to mention recent studies showing how pollution produced at the household level may move outside to the community environment and contribute to ambient air pollution in areas where homes are tightly clustered together or in urban slums [18]. A study from Chafe et al. [19] showed how PM emissions from household cooking facilities contribute to 37% of total ambient air PM in Southern Sub-Saharan Africa, 26% in South Asia (including India) and 15% in Southern Latin America. The joint effects of household and ambient air pollution are responsible for 7 million deaths per year on a global scale [13].

1.1.2 Impact on environment

The use of wood biomass for cooking can have a direct impact on the environment, as in some areas increasing wood collection for direct use or for charcoal production have led to pressure on forests and natural resources [20]. Unsustainable wood

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[3] The Global Burden of Disease project is a regional and global research program aimed at providing "*a consistent and comparative description of the burden of diseases and injuries and the risk factors that cause them*". source: WHO [105].

collection (up to 10% of woodfuel is estimated being harvested in an unsustainable way by the Intergovernmental Panel on Climate Change, IPCC [21]) can contribute to "*mud-slides, loss of watershed, and desertification, which places further pressures on regional food security and agricultural productivity*" [20]. In addition, a reduction of forest areas also entails a reduction in carbon uptake and may affect biodiversity.

A second effect of biomass combustion is the release of green house gases (GHGs) and other climate-forcing particles. Theoretically, biomass burning is considered having a zero net impact on climate, as it captures CO_2 from the atmosphere during its growth cycle. Therefore, assuming that it is harvested on a sustainable basis, the amount of CO_2 released by combustion should be equally recaptured by the regrowing biomass [22]. But even in case of sustainable harvesting, biomass burnt with inefficient cookstoves or three-stone fires releases products of incomplete combustion (PICs), as carbon monoxide (CO), methane (CH_4) and black carbon (BC) [23], [24], which also have a climate-forcing effect, and even more damaging than CO_2 [25].

Greater attention should be paid particularly to black carbon, which is not a gas but an aerosol particle; recent studies assess its climate-forcing effect being +1.1 W/m^2, or the second most damaging human emission after CO_2 [26]. In fact, although BC ground-level concentrations are not comparable to those of CO_2, it absorbs one million times more energy per unit mass [7]. It directly absorbs incoming and reflected sunlight and infrared radiation, but also has secondary effects as depositing on snow and ice, reducing albedo and consequently increasing absorption of sunlight and accelerating melt. Interactions with clouds and their characteristics are under study too [24].
Traditional biomass is assessed being responsible for about 25% of global BC emissions and 50% of the anthropogenic emissions of BC [27]; if BC emissions from other sources (transport, industry, *etc.*) are expected to decline, the same is not true

for BC deriving from biomass cooking in developing countries, resulting in an increasing share in global BC emissions [7].

1.2 Improved Cooking Stoves

To address the harmful effects deriving from the use of traditional biomass by inefficient cooking facilities, more efficient and clean technologies and fuels are typically promoted based on the concept of the "energy ladder" shown in *Figure 1.2.1*. Traditional low-quality biomass fuels are at the bottom of the ladder and a gradual shift is expected, parallel to income growth, towards cleaner fuels, the top being electricity.

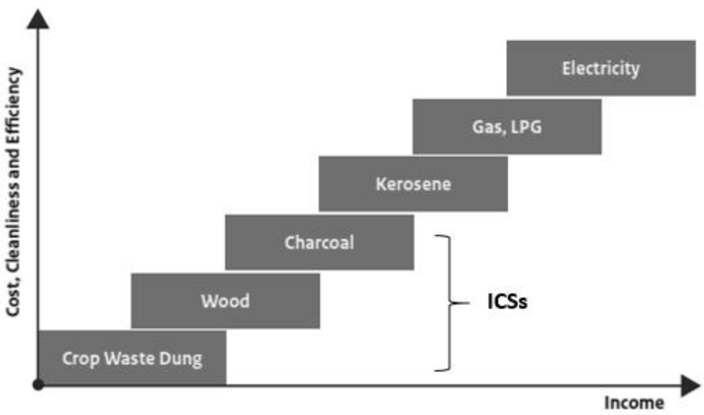

Figure 1.2.1 – The classical energy ladder, adapted from IOB [28].

Electrification is in fact often a top priority of DCs governments, yet income growth and electrification do not automatically translate into the adoption of clean cooking facilities [5]. Shifting towards different fuels or cooking technologies is not necessarily driven by economic considerations, but also depends on socio-cultural factors. More realistically, as household income increases, different fuels are used simultaneously for different tasks (which is defined "stove stacking") [29]. The classic concept of "energy ladder" is nowadays disputed, as households may adopt new fuels and technologies without completely abandoning the traditional one, which may be still used for specific tasks [7], [30]. As a consequence, many efforts are dedicated to the promotion of "intermediate" solutions, which are still based on traditional biomass yet should reduce harmful effects due to improved thermal and combustion efficiencies. These Improved Cooking Stoves (ICSs) have been the object of large dissemination programs in India [31] and China [32] and are currently promoted in many DCs by international organisations, cooperation agencies, governments and ONGs. In particular, a Global Alliance for Clean Cookstoves (GACC) was launched in 2010 in the margins of the UN summit on the Millennium Development Goals, with partnership from governments, international organisations and private companies. The goal is providing 100 million homes with "*clean and efficient stoves and fuels*" by 2020 [33].

Prospects from the IEA Africa Energy Outlook [11], referred to the Sub-Saharan Africa situation, confirm that a shift towards modern and clean fuels (LPG, electricity) by 2040 is only partly expected in urban areas, whilst traditional biomass will remain largely predominant in rural areas. Furthermore, the adoption of ICSs, based on current policies, is expected to be very limited, with the exception of East Africa, suggesting that greater attention and efforts should be dedicated to the problem. The following sub-sections are thus dedicated to the analysis of the technical concept of ICS, to its theoretical benefits and to the challenges that still need to be addressed.

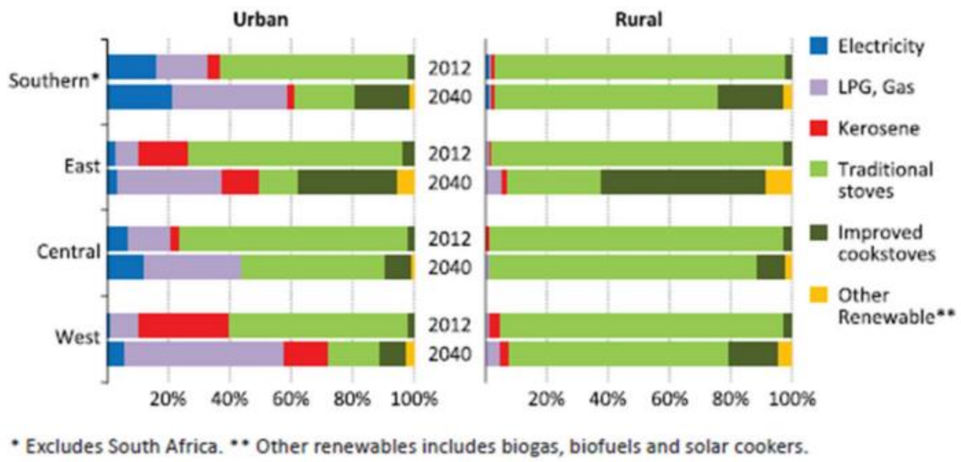

Figure 1.2.2 – Primary fuel/technology used by households for cooking in Sub-Saharan Africa in the Africa Energy Outlook New Policies scenario; source: IEA [11].

1.2.1 Technical concept

As the GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) reports, "t*he term 'stove' refers to a device that generates heat from an energy carrier and makes that heat available for the intended use in a specific application*". This definition applies to a broad range of devices, from open fires (or three-stone fires), to simple mud stoves to more sophisticated technologies. All of them are composed of a combustion chamber, where heat is generated and then transferred to a cooking pot, or a griddle, *etc.* (assuming the stove is designed for cooking purpose). The concept of Improved Cooking Stove is based on the assumption that a stove with an optimal design would allow for biomass use with improved combustion and heat transfer efficiencies, leading to improvements both in relative terms of harmful emissions (*i.e.* reduction of PICs) and in absolute terms of fuel savings and total emissions. Household's health, climate, fuel economy and sustainability would all benefit from the improved efficiency. A typical example of wood stove design is provided in *Figure 1.2.3*.

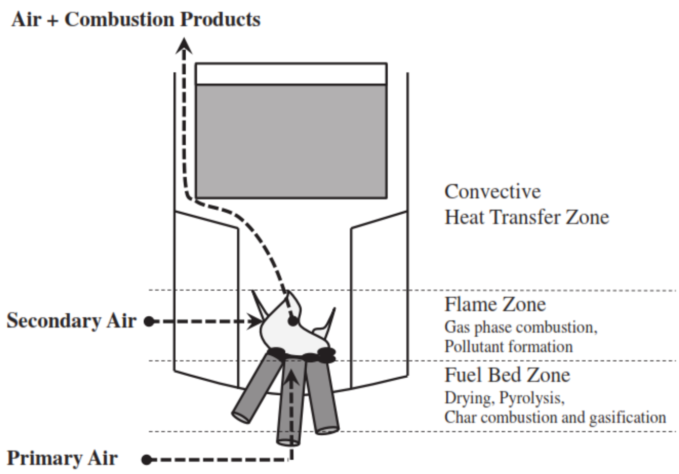

Figure 1.2.3 – Typical wood ICS design, with different processes highlighted; source MacCarty et al. [34].

ICS models encompass a wide range of designs, depending on the type of fuel (wood, charcoal, others), materials (mud, clay, ceramic, metal), the principle of combustion (direct combustion, gasification) and the presence of chimneys. Most advanced models may include also forced draft ventilation and coupling with thermoelectric generators (TEGs), and are sometimes referred to as Advanced Biomass Stoves (ABS) [35]. A few examples are provided in *Figure 1.2.4*.

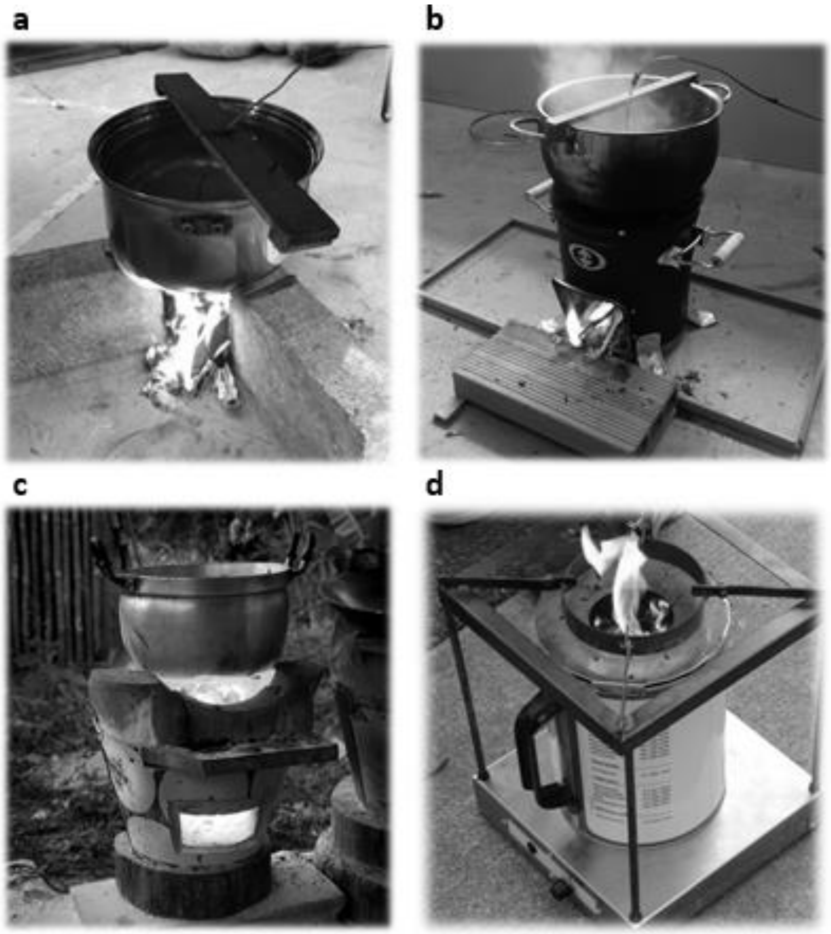

Figure 1.2.4 – Examples of different cookstove designs. a) three-stone fire; b) rocket-type wood ICS; c) charcoal stove; d) forced-draft gasifier.[1]

A detailed discussion of different design features is beyond the purpose of the present analysis; for further details reference is made to Sutar et al. [36], Colombo et al. [37]. In synthesis, the common functioning concept is to drastically reduce heat

[1] Photos "a" and "b" were taken by the author in the laboratory of the Deparment of Energy, Politecnico di Milano; photo "d" was taken by the author at the ETHOS Conference 2016.

losses in the combustion chamber towards the surroundings, as compared to an open fire, by containing the flame with circular walls. Most important, the greatest attention is paid to the air flow in order to obtain an optimal air excess and flame temperature as to avoid formation of PICs. This is a key factor to limit harmful emissions for users as well as to avoid formation of BC and other climate-forcing pollutants. A sensible reduction of BC production could be, in fact, a very effective strategy for climate mitigation, as all CO_2-related strategies are only effective in the long term, whilst BC remains in the atmosphere for a short period of time and its abatement would provide immediate effects [27].

1.2.2 Challenges

Despite theoretical benefits and efforts made to promote ICS in several contexts worldwide, dissemination programs do not always result in positive outcomes, as recently documented by a Massachusetts Institute of Technology (MIT) study [38]. The research, discussing a four-year field analysis conducted in Orissa (India), showed improvements in smoke exposure only in the first year, with no effect on the long term. Moreover, even when a reduction in exposure was registered, a specific analysis of typical HAP-related diseases showed no effect on household's health, neither self-reported nor measured; fuel savings were not observed as well [38]. The different smoke exposure over time was explained considering that for most target users a sustained stove adoption was not registered, as they were not able to adequately maintain the product and progressively abandoned the new stove to come back to traditional technologies. As the authors report, "*while households overwhelmingly claimed that the stoves used less wood, fuel use remained unchanged, and if anything, somewhat increased. The lack of obvious benefits may explain why households were not interested in using the stoves optimally*" [38]. This conclusion raises questions about criteria used to evaluate a stove as "improved" and about their actual impact. Jetter et al. [39] suggest to reflect about improvements in stove emissions in terms of ambient air pollution, as in some cases ICSs that do not directly expose the user to emissions (*e.g.* chimney stoves) are not actually "eliminating" but rather "*moving smoke a couple of meters*" away [39]. Therefore, pollution avoided in the kitchen may remain in the village or move to nearby villages, eventually coming back through the windows. Effective solutions should possibly focus more on avoiding emissions in the first place. Also Simon et al. [40] suggest that few health benefits can be registered introducing a less polluting ICS, unless considering most advanced models (*i.e.* gasifiers, LPG) and in the absence of the previously defined "stove stacking". The issue of stove stacking is particularly relevant, as Lloyd et al. [41] confirm how traditional open fires are often related to different uses than cooking, such as lighting, heating, socialising and garbage disposal; accordingly, a complete abandonment of traditional habits may not be an automatic consequence of the introduction of ICSs. It is thus crucial to take into account target user's habits and behaviour in order to provide a correct health and environmental evaluation of such technologies [38], as shown in *Figure 1.2.5*.

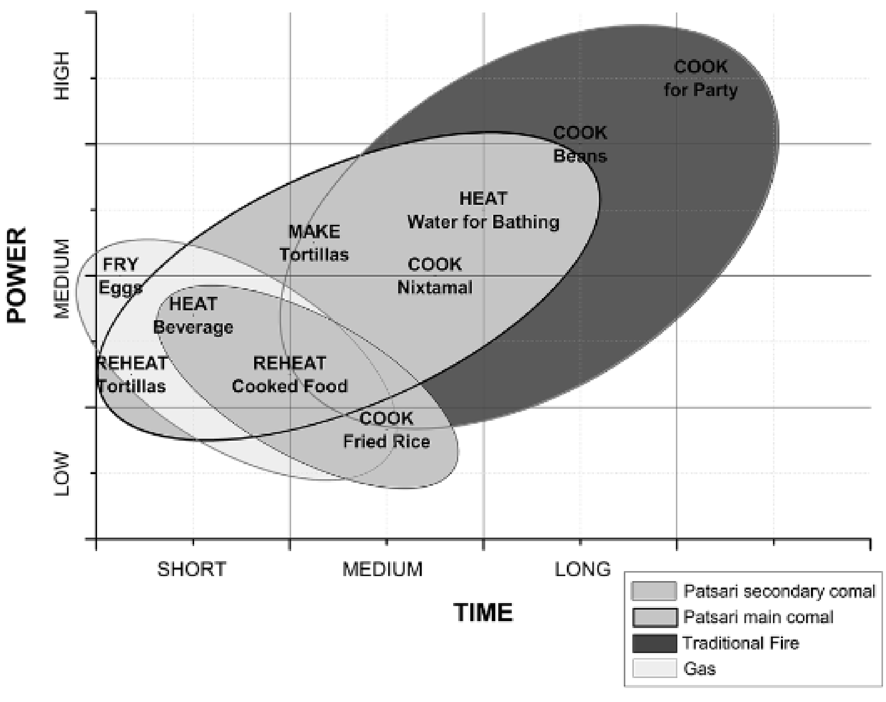

Figure 1.2.5 – Example of stove stacking as a function of the required task; possible choices are Patsari (ICS), open fire and gas (LPG). Source: Ruiz-Mercado et al. [42].

Such findings seems to suggest that greater attention should be paid on the concept of "improvement" and to its evaluation. Recently, the GACC developed benchmark performance values for stoves in order to be defined "clean" and "efficient", based on four "Tiers of performance"; nevertheless, there is no agreement on the selected performance criteria, nor on the methodologies to be followed [41]. The following Chapter is dedicated to a deeper analysis of ICSs performance evaluation methods and to their implications on the reliability of the promoted "improvements".

2 Evaluation of improved cooking stoves performances

Findings from *Chapter 1* seem to suggest that greater attention should be paid on ICSs performance evaluation methods and to their implications on the reliability of the promoted stove "improvements". The GACC developed a set of "Tiers of performance" to rank stoves technological advancement, yet there is no agreement on the selected criteria, nor on the methodologies [41]. In the absence of a standard, different research groups have formulated their own approach to cookstove testing, leading to a large number of protocols and to difficult comparison of data between labs. This possibly represents one of the key challenges to the wide-scale adoption of improved cookstoves [39], [41].

The present chapter is firstly dedicated to a simple and immediate presentation of the testing methods framework. Secondly, a deeper analysis of the implications of performance assessment, in terms of stove dissemination programs success and reliability of climate impact estimates, is performed.

2.1 Testing methodologies

The current state of the art of ICS performance testing methodologies is quite complex, with many different protocols addressing different levels of the testing process. The following sub-sections are meant to outline the key difference between a *"laboratory test"* and a "*field test*", as well as to present the evolution of testing protocols over time.

2.1.1 Laboratory and field protocols

The first key distinction to be highlighted in the context of ICS testing is the one between *lab* and *field* testing protocols.

The category of *lab testing protocols* groups all the protocols performing an evaluation of the stove performance in a controlled laboratory setting, and includes the majority of current testing methods [43] . Usually, lab protocols are meant as a tool for stove developers to evaluate changes in performance due to different designs and features; the controlled laboratory setting should allow avoiding all the uncertainties related to external conditions and users' behaviour. As a consequence, lab protocols are not supposed to be predictive of actual stove performances, since in the field these are strongly influenced by all those external factors that are instead controlled in a laboratory. Nevertheless, they are very often used as the only performance indicators, due to higher costs and time needed to perform field testing.

Field protocols consist of prolonged surveys about fuel savings among households using an ICS, as compared to their baseline situation. This kind of investigation, although not devoid of uncertainties and criticalities, can provide data about actual fuel savings of a stove in a real context of use. Field protocols are supposed to follow lab testing for an effective evaluation of stove performances among the target population, and they are usually considered as a reference for Clean Development Mechanism (CDM) and Gold Standard (GS) programs [7]. Still, they require a long period of investigation (with high costs related) and cannot provide all performance parameters needed, like pollutants emissions.

A midpoint between the lab and the field is the Controlled Cooking Test (CCT), which is still a lab protocol consisting in cooking a typical target population's meal on the stove, to assess its potential adaptability to users' cooking habits (further details are provided in *sub-section 2.1.2*). This test is supposed to provide a validation of lab stove performances when reproducing a real cooking task, but it is not sufficient to predict average field performances [44].

In recent years, researchers have been focusing on new field testing methodologies, as the Uncontrolled Cooking Test (UCT) proposed by the Sustainable Energy Technology and Research Centre (SeTAR) in 2010. This is a relatively low-cost field test, assessing stove performances when cooking any meal according to local practices and conditions, with the stove operated by target users. The authors of UCT reported a lower variation in output data than is typically reported by traditional field test methods (*viz.* prolonged surveys and local assessment), allowing for the use of fewer resources to assess the improvement of an ICS as compared to the baseline stove [45]. Another promising solution is represented by the Stove Use Monitors (SUMs), *viz.* low-cost temperature and/or emissions data logger to be installed on cookstoves in order to return reliable estimates of their pattern of utilisation, which is a source of errors for survey methods [30]. The combined use of surveys and SUMs can improve the quality of data provided by field tests and provide information about adoption rate.

At present, laboratory tests still represent the most popular and widespread performance evaluation tool, notwithstanding all their criticalities and inherent errors [46] [47], as further discussed in the following section.

2.1.2 History and evolution of testing protocols

The origins of ICS testing protocols are to be found in the 80's, and specifically in November 1980 when the first attempt to define a procedure for testing a cookstove in laboratory and field was made by the Intermediate Technology Development Group (ITDG) [48], now known as Practical Action.

A few years later, between 1982 and 1985, the Volunteers in Technical Assistance (VITA) developed the ideas from ITDG and from the Eindhoven Woodburning Stove Group [49] into three protocols addressing different testing needs. For the first time the names *Water Boiling Test* (WBT), *Controlled Cooking Test* (CCT) *and Kitchen Performance Test* (KPT) appeared in the literature [50], and in the present analysis they will be thus referred to as versions 1.0. A brief description of the three testing concepts follows:

WBT is aimed at measuring how much wood is used to boil water under fixed conditions; VITA's document affirms: "*While it does not necessarily correlate to actual stove performance when cooking food, it facilitates the comparison of stoves under controlled conditions with relatively few cultural variables*" [50]. In its first version, WBT consisted of two phases, a high power and a low power phase, during which water was brought rapidly to a boil and then simmered for 30 minutes. Emission testing was not included yet.

CCT consists in the preparation of pre-determined meals by trained local cooks, using both traditional and improved stoves, and was meant as a bridge between WBT and KPT. It is performed under laboratory controlled conditions, and used also to compare different cooking practices on the same cookstove.

KPT measures instead how much fuelwood is used per person in actual households when cooking with a traditional stove and when using an improved stove, in order to verify its benefits in terms of fuel savings. It consists in a simple but prolonged assessment of how much wood a household has at the beginning and at the end of a testing period.

A first revision and discussion of the VITA's WBT was made by Dr. Samuel Baldwin in his technical report on stoves "*Biomass stoves: Engineering design, development, and dissemination*" (1987) [51], becoming one of the most widely-cited references for stove developers since (it will be referred to as WBT 2.0). The popularity of Baldwin and Vita's publications led to the widespread adoption of water boiling tests and close variations [52].

The first years of the 80' (1982-1983) were also characterised by the launch of the first two big scale dissemination programs of ICSs in India and China, namely the NPIC (*National Programme on Improved Chulhas*) and the CNISP (*Chinese National Improved Stoves Programme*) [35], [53], [54]. The two Countries created their own methods for testing cookstoves, although they were formalised and published only some years later.

The first version of the *Indian Standard on Solid Biomass Chulha-Specification* (acronym ***BIS***) [55] is dated 1991 (a revised version dated 2013 has been cited by different authors [56], [57] but it's currently available only as a draft [58]). The first version of the *Chinese Standard* (***CS***) that can be found in the literature is instead much more recent (2008) [59], but testing methodologies and benchmarks were established since the launch of the program. Details of the two testing methods are provided in *Chapter 3 (sections 3.2* and *3.3).*

In 2003, the *Shell Household Energy and Health* project commissioned to University of California-Berkeley a revision of the VITA's protocol, which was performed by Dr. Kirk Smith and Rob Bailis in collaboration with researchers from the Aprovecho Research Center. WBT version 3.0 [60] and CCT, KPT versions 2.0 [61] were ultimated between 2003 and 2007. The most significant variations in the WBT were the introduction of a further phase, namely *Cold-Start*, and the standardisation of pot sizes and water amounts due to consultations with field organisations and analysis of common cooking practices [62]. Changes in CCT included the use of *equivalent dry fuel consumption* (see *sub-section 3.1.3.1*), while KPT was provided with extensive information on the criteria for the selection of households and on the procedure for conducting the test [36].

After the release of these updated versions, different research teams started to discuss and critic both the method of testing and some of the calculations of the WBT, and a wider debate on testing methods started after 2008. Also, first studies showing WBT results had no correlation with field performances were published (*e.g.* Berrueta et al. [52], [63]); thus, different attempts at improving testing protocols were made worldwide.
The group *Engineers in Technical and Humanitarian Opportunities of Service* (ETHOS), initiated a technical committee, led by Dr. Tami Bond of the University of Illinois along with *Partnership for Clean Indoor Air* (PCIA), and further revised the WBT to version 4.1.2 (2009), including instructions for emissions measurement and testing of non-woody solid, liquid or gaseous fuels. Still, some of the main debate topics about WBT were not addressed in this version.

Also in 2009, Colorado State University and Shell Foundation, in collaboration with cookstoves manufacturers Philips and Envirofit, developed their own protocol called *Emission & Performance Test Protocol (**EPTP**)* [64], on the basis of the updated WBT but aimed at optimising repeatability (see *section 3.4*).

In 2010 two more protocols were released by research teams from different continents. The *Adapted Water Boiling Test (**AWBT**)* [65] was developed by researchers from GERES Cambodia as a modification of WBT 3.0 and is focused on following cooking practices that are common in the target area, rather than relying on standardised parameters. It does not account for emission testing (see *section 3.5*).
The SeTAR Centre, based in Johannesburg, also developed a new testing protocol for the needs of a GIZ project (named Pro-BEC) on domestic stoves in 2010. It was called the *Heterogeneous Testing Procedure (**HTP**)* [66], and went into a different direction than WBT in terms of procedure concept, equipment and calculated parameters (see *section 3.6*).

Finally, in 2012, an ISO-IWA workshop was held in The Hague, gathering more than 90 stakeholders from 23 countries [67]. It was hosted by the Global Alliance for Clean Cookstoves and the Partnership for Clean Indoor Air, and chaired by the American National Standards Institute. The workshop provided interim guidance for rating cookstoves on four performance indicators: efficiency, total emissions, indoor emissions, and safety; for each indicator, multiple *Tiers of Performance* (0 to 4) were defined, to set a hierarchy in the ICSs technological advancement.

The most recent version of WBT 4.2.3 (2014) includes results from the ISO-IWA meeting and Tiers of Performance, as well as indications coming from other research groups.

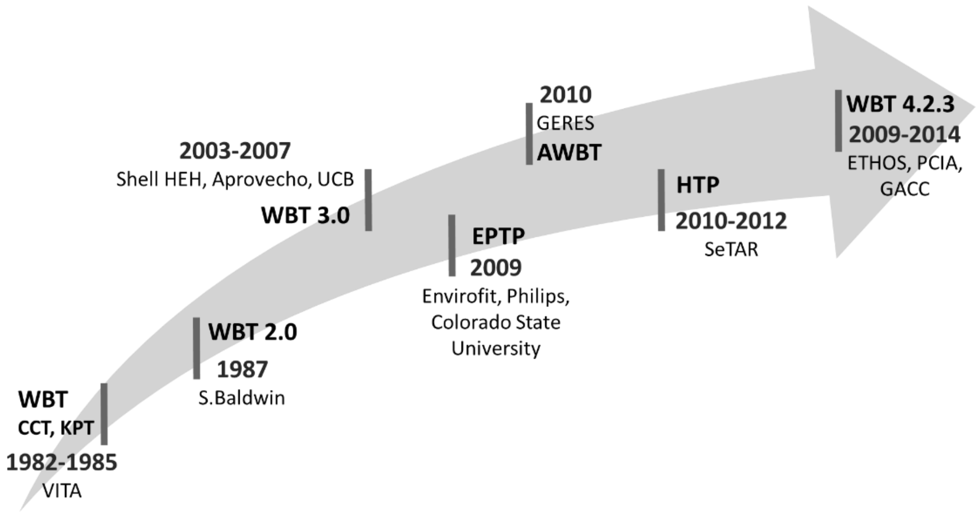

Figure 2.1.1 – Historical evolution of cookstove testing protocols.

Still, criticism about WBT is raising as more comparative studies against field performances are coming out, and as researchers raise questions about the rationale of some calculations [57]. Different authors (*e.g.* Johnson et al., Zhang et al. [61], [57]) have come to the conclusion that it is impossible to predict ICS field performances without a user-centred approach, properly accounting for local burn cycles and practices. For this reason, the ISO Technical Committee 285 is currently working with these research groups in order to develop new and effective protocols and solve the issue of the lab-field gap. Further details are provided in *section 3.7*.

2.2 The importance of reliable data

Different authors have been documenting how the lack of accepted performance evaluation standards and protocols is one of the key challenges to the wide-scale adoption of improved cookstoves [39], [41]. The complex framework of cookstove testing protocols resulted in a widespread adoption of the most time saving and cheap lab protocols, especially WBT, as a source of data for different purposes. Nevertheless, as discussed in *sub-section 2.1.1*, the WBT is not meant to provide reliable estimates of field performances; the lack of correlation between lab and field performances has been, in fact, verified by many studies [63], [68], [69]. Therefore, the dominant practice of solely relying on WBT results may negatively affect both stove dissemination programs and climate impact estimates. As this practice has been further encouraged by the definition of stoves performance rankings, by the GACC and the ISO-IWA, based on the WBT, a deeper analysis of the possible implications is critically needed.

2.2.1 Failure of stove dissemination programs

As suggested by the MIT case study (*sub-section 1.2.2*), the lack of perceived benefits from the introduction of an ICS may lead to low adoption rates; this may be a direct consequence of unreliable lab performance assessment [39]. Stoves performing well, according to current lab performance criteria, have been reported to perform poorly in the field or being rejected by target users [41], [69]. Rejection may be indeed a consequence of poor performance or of inadequacy of stove characteristics compared to the needs of the target population. In particular, a stove should be able to satisfy the required range of cooking powers, efficiently working with the fuel that is locally available, and suited to local cooking habits [41]. When lab performances are employed for stove selection prior to any analysis of the final context of use, they may provide misleading guidance and result in disappointing field performances [69]. In fact, performances evaluated in a lab with a standardised fuel may change consistently when using local fuel, both in terms of emissions reduction [68] and in terms of power, or time to boil, which is one of the most important parameters from a user's point of view, more than emissions or fuel savings. A case study in Haiti by Lask et al. [69] proved how a longer time to boil may represent a potential barrier to the adoption of an ICS, regardless of improvements in other parameters. Similarly, Wang et al. [70] reported target users considering very attractive a promoted ICS model due to its capability of boiling water in about five minutes, which was "*the single most important feature from their perspective*" [70]. The common evidence of those findings is that the greatest attention should be paid on the target user rather than on stove design solely, and to what is most relevant in relationship to its cooking experience. In fact, examples of successful programs can be found where promoted stoves were specifically designed on the basis of the required burn cycle and cultural habits, taking into account target user's cooking practices, and where the dissemination phase was followed by a long-term monitoring period [63].

2.2.2 Errors in climate impact estimates

As mentioned, traditional biomass combustion releases climate-forcing particles, especially Products of Incomplete Combustion (PICs) that could be reduced by means of a more efficient combustion. In particular, black carbon (BC) is attracting more and more interest, as recent studies estimate it being the second most damaging human emission after CO_2 [26] and as traditional biomass is assessed contributing for about 25% of global BC emissions and 50% of the anthropogenic emissions of BC [27]. ICSs are promoted as an effective solution to reduce climate-forcing emissions while still allowing for biomass use. A correct assessment of the impact of traditional cookstoves on climate change is thus in the interest of both international organisations (such as the Intergovernmental Panel on Climate Change, IPCC) and carbon finance. Recent years have been in fact characterised by an increasing number of carbon-financed stoves projects; according to Simon et al. [71], as of May 2013 there were approximately 75 CDM stoves projects and 63 Programs of Activities

(PoAs)[1]. Furthermore, voluntary market offset programs such as the Gold Standard (GS) enabled crediting of emission reductions from ICSs projects as well [7].

GS projects must be verified by means of KPTs, whilst CDM allows for three options: WBT, CCT and KPT. Although KPTs are considered a more reliable source to estimate fuel savings, as compared to lab tests, CO_2 savings are evaluated by means of default emission factors (regardless of the ICS type) that are considered to underestimate reductions by 30% [7]. Furthermore, KPTs are costly, require prolonged surveys and need participation of household's. Therefore, for CDM projects, WBT data are usually preferred, even if derived from testing with homogeneous, well-dried fuel, and no regard for actual cooking practices [47]. Lee et al. [7] interviewed market actors reporting that most project developers "*use the WBT, because it is cheaper and easier to implement, with default values provided by the stove manufacturer*". Also Masera et al. [47], performing a literature review of 36 studies about cookstove emissions, found that only eight out of thirty-six studies analysed were field-based. The lack of reliability of lab-based emissions assessments has been diffusely documented: Roden et al. [72] found that emission factors in the field are about three times those estimated in the lab; Johnson et al. [73], [74] also showed that significant errors may be generated in estimating carbon savings by means of lab-based tests. Results from this latter study are shown in *Figure 2.2.1*, highlighting how the open fire was found to be better performing than the "Patsari" ICS according to WBT, whilst the converse was registered during actual use in the field.

Furthermore, carbon markets currently consider CO_2, CH_4 and NO_2 reductions, but do not include BC, leading to further under-estimations. A recent study on *Nature*

[1] "*As emission reductions of small-scale projects such as projects disseminating efficient cookstove are often too small to justify the efforts of implementing a stand-alone CDM project, several small-scale projects can become CDM programme activities (CPA) under a Programme of Activities (PoA) in order to reduce the high transaction costs*". Source: Energypedia [106].

Climate Change [21] estimated that by disseminating 100 million state-of-the-art ICS would save from 98 to 161 Mt$CO_{2\text{-eq}}$/year, if considering BC; this would result in 1.1÷1.8 billion US$ earnings based on current carbon markets values for $CO_{2\text{-eq}}$ savings, far exceeding current investments in household energy in DCs.

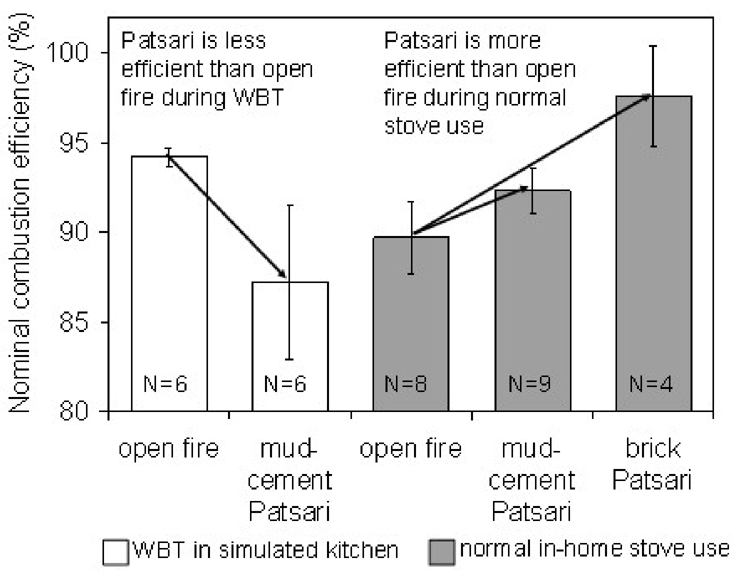

Figure 2.2.1 – Comparison of nominal combustion efficiencies of different stove types, referred to WBT and field measurements. Source: Johnson et al. [74].

To improve the diffusion and the success of carbon finance stoves projects it is therefore crucial to develop reliable estimates of ICS emissions savings, including all climate-forcing pollutants, which seems to be not achievable relying on current state-of-the-art protocols.

2.3 Key concepts

It has been highlighted how lab protocols represent the most diffused performance evaluation tool, even in cases where field tests should be preferred, due to economic and time-saving reasons. In particular, relying on WBT is the common practice, which has been further encouraged by the interim guidance provided by the ISO-IWA meeting in 2012. Nevertheless, more and more studies have been raising awareness about the limitations entailed by this approach, contributing to the development of a variety of alternative protocols, although none of them has been adopted by the international community as an accepted standard. Instead, protocols multiplication exacerbated the complexity of the framework, which represents a major challenge for the success of both stove dissemination programs and carbon-financed projects.

Further investigation is needed to clearly understand the different approaches promoted by each protocol and the reasons behind the general lack of agreement among researchers; accordingly, the following chapter will be dedicated to a comprehensive and detailed review of all existing lab protocols.

3 Testing Protocols review

As mentioned in *sub-section 2.1.2*, many different protocols for testing ICS performances have been developed since first attempts in the 80's; nevertheless, the literature seems to be still missing a precise and complete comparison among all of them.

An attempt to group and briefly discuss some of the existing protocols was made by Kshirsagar and Kalamkar [35], but their analysis remains on an informative level and it is not intended to include technical considerations; furthermore, some protocols are not mentioned in the study (*viz.* Chinese and Indian standards, AWBT). Sutar et al. [36] realised a more detailed analysis on how different protocols (WBT, Indian BIS and EPTP) address some of the most discussed topics in cookstoves testing (*viz.* insulation, maximum temperature, emissions, *etc.*) and grouped them into a comparative table for an immediate outlook. Still, protocols such as the Chinese Standard, AWBT and HTP are not taken into account in their work. Zhang et al. [57] focused on metrics definitions, terminology and technical considerations, highlighting the key differences between WBT, Indian BIS and HTP. Finally, a recent study by Arora et al. [46] reviewed the WBT focusing on thermal and emission parameters as well as on procedure requirements.

A comprehensive review, bringing together all the existing protocols and drawing a complete comparison of both conceptual and technical aspects, seems never having been realised, and is the object of the present chapter. The study structure is organised as follows:

i) firstly, it takes into account all the lab protocols which have been published to date, in their most recent available version, namely WBT, Indian BIS, Chinese Standard, EPTP, AWBT and HTP (in chronological order of first release).

ii) secondly, it discusses protocols under development, integrating burn cycles with lab testing, as a chance to address the issue of the gap between field performances and current testing methodologies outputs.

Field protocols are not considered in the analysis; in fact, the common practice consists in using laboratory tests even in cases where field tests should be preferred, due to economic and time-saving reasons, as discussed in *Chapter 2*. Moreover, field protocols are much more limited in number and simply based on prolonged surveys about fuel savings.

The work is aimed at allowing a clear comparison between all protocols, analysing them on the basis of standardised sections; specifically:

- ***Preparing for testing***, which takes into account prescriptions about the type of *Fuel*, *Pot* dimension and water content, and *Insulation*;
- ***Testing Procedure***, highlighting the differences in terms of *Ignition*, *Stove Operation* and *End of Test* phases;
- ***Performance Metrics***, accounting for *Energy* and *Emission Metrics*;
- ***Strengths & Weaknesses***, drawing conclusions about the benefits and limitations of the protocol features.

Thus, each protocol will be firstly presented and analysed in detail, and subsequently discussed in terms of relative strengths and weaknesses.

Finally, the conclusive *section 3.8* will be dedicated to an ultimate and comprehensive critical discussion of all the issues emerging from the review, with the purpose of identifying the key questions to be addressed.

3.1 Water Boiling Test 4.2.3 (2014)

WBT is the milestone of ICSs testing. Since its first release in 1985, the protocol has faced many updates and reviews, with contributions by different authors and research teams, leading to its current version 4.2.3, last revised in 2014. The WBT is currently referenced by the Global Alliance for Clean Cookstoves (GACC) and has been a reference for the work of the ISO-IWA held in 2012.

3.1.1 Preparing for testing

Fuel

The WBT does not impose standard dimensions or moisture content for the fuel, although it suggests to use a locally available fuel, uniform in size and "well dried" (which for the WBT means 10-20% moisture content). Cross-sectional dimensions should range between 1.5 x 1.5 cm^2 to 3 x 3 cm^2. Still, additional requirements are provided for testers whose goal is comparability between labs; WBT 4.2.3 includes, in fact, a section named "*Changes to Testing Conditions to Improve Repeatability*" [62] providing stricter indications about:

- *wood type*: high heat content (20-21 MJ/kg)
- *moisture content*: 6,5% or 10%
- *dimensions*: 1.5 x 1.5 cm^2 (cross-section)
- *water initial temperature*: 15°C.

Different fuels than wood are accepted with minor implications on the procedure (*Appendix 2.2* of the WBT 4.2.3), but the tester should avoid fuels the stove was not designed for. Before running a test, a bundle of 5 kg of fuel should be prepared for each phase of the test, and weighed including eventual kindling material.

Pots

A 7 litres pot is prescribed (5 l of water), except when testing a stove designed for much smaller pots, or when boiling as much as 5 litres of water is very uncommon in the target area. In such cases, a smaller pot (3.5 l volume, 2.5 l of water) should be preferred. Once selected, the same pot must be used throughout all test phases and replicates.

Insulation

The standard version of the WBT does not admit the use of lids or other forms of insulation, since they are supposed to increase the variability of results thus affecting the purpose of comparability between test replicates [62]. It is nevertheless asserted that the eventual use of lids is currently the subject of intense debate, and that specific studies would help resolving such challenge.

3.1.2 Testing procedure

As mentioned in *Paragraph 2.1.2*, the current WBT version consists of three phases, namely Cold-Start High-Power, Hot-Start High-Power and Low-Power Simmering; the *Cold-Start* phase was introduced in version 3.0 to compensate for the difference between "*high and low mass stoves*" in the first portion of a test.

Following the procedure, an entire test should be conducted at least three times for each stove, to ensure results reliability; this recommendation has raised some doubts [70], which are further discussed in *sub-section 3.1.4*.

3.1.2.1 Cold-Start High-Power

Ignition

Before lighting the fuel, background emissions readings are recorded, and emissions measurement begins. The fire is lit according to local practices, eventually using kindling material; the procedure must be accurately documented, and the test timer starts only "*after the fire has caught*" [62].

Stove operation

The stove is operated in order to rapidly bring the water to a boil, following local habits and "*without being excessively wasteful of fuel*" [62].

End of test

The cold-start phase ends as the temperature reaches the local boiling point. Emissions measurement is stopped, and all the wood is removed from the stove and extinguished; the unburned wood is weighed together with the remaining wood from the prepared bundle, while all the charcoal is collected in a separate container, and weighed as well.

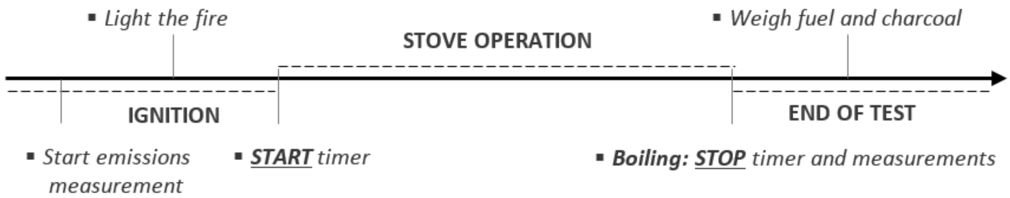

Figure 3.1.1 – Summary of WBT Cold-Start High-Power phase.

3.1.2.2 Hot-Start High-Power

Ignition

Same as *Phase1* (=Cold Start); notice that in this case the stove temperature is already much higher than the ambient temperature, as a consequence of the previous operation.

Stove operation

Same as *Phase1*.

End of test

Same as *Phase1*, except that charcoal is not weighed at this stage, on the hypothesis that it should not differ significantly from the Cold-Start step (Notice that in case of large differences in charcoal production between Cold and Hot-Start steps, the WBT procedure allows for changes in order to weigh charcoal produced during the latter; for further details reference is made to the WBT official document [62]).

Unburned wood is immediately returned to the stove to proceed with the following phase.

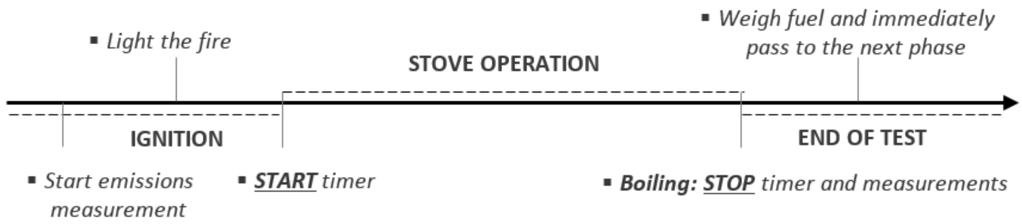

Figure 3.1.2 – Summary of WBT Hot-Start High-Power phase.

3.1.2.3 Low-Power Simmering

Ignition

Fuelwood is re-ignited immediately after the end of *Phase2* (=Hot Start), following the same ignition method as for *Phase1*. Notice that in this case emissions measurement starts only after the fire has caught; this phase is in fact intended as a continuation of the Hot-Start phase, and ignition pollutants peaks should not be measured twice.

Stove operation

The stove is operated in order to maintain the water temperature as close as possible to 3°C below the boiling point; the test is invalid if the temperature in the pot drops more than 6°C below the local boiling temperature.

End of test

After 45 minutes, the simmering phase is concluded, the fuel is extinguished and wood and charcoal are weighed following the same procedure as for *Phase1*.

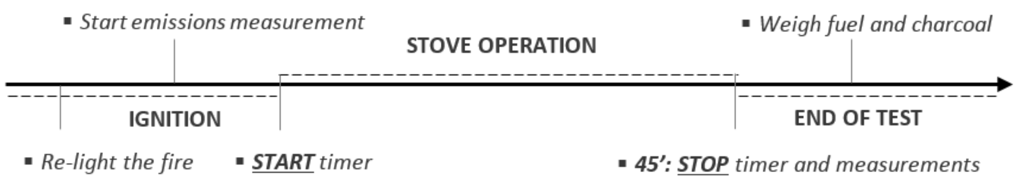

Figure 3.1.3 – Summary of WBT Low-Power Simmering phase

Notice that slight differences in the procedure occur in case of batch-feed stoves testing [62].

3.1.3 Performance metrics

WBT calculates performance metrics for each of the three phases; nevertheless, their general formulation keeps uniform throughout the test, with only slight differences in a few cases. The following analysis will discuss metrics formulation only once, eventually highlighting remarkable changes among phases.

3.1.3.1 Energy metrics

η – Thermal Efficiency

Thermal efficiency is calculated as the ratio of the heat absorbed by water and the heat produced by combustion; the former is computed as the sum of sensible and latent heat, while the latter is computed as fuel consumed times lower heating value of the fuel, both on a dry basis

$$\eta = \frac{m_{w,i} c_{p,w} (T_b - T_i) + m_{eva} h_{lv}}{f_d \cdot LHV} \qquad (3.1.1)$$

Notice that f_d is the "*equivalent dry fuel consumed*", which adjusts the amount of dry fuel that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the fuel and (2) the amount of char remaining unburned:

$$f_d = dry\ fuel - fuel\ to\ evap.\ water - fuel\ in\ char$$

For further details about this calculation, refer to WBT 4.2.3 [62].

In the simmering phase, the formulation of η is slightly different: the mass of water simmered is not the initial mass of water, as for the high-power metric, but it is the average of the initial and final masses of water in the pot:

$$m_{w,simmering} = \frac{m_{w,i} + m_{w,f}}{2}$$

SC – Specific Fuel Consumption

SC is calculated as the ratio between the equivalent dry fuel consumed and the "*effective mass of water boiled*", *viz*. the final mass of water in the pot:

$$SC = \frac{f_d}{m_{w,f}} \quad [\frac{kg_{fuel}}{kg_{water}}] \tag{3.1.2}$$

Since 1 kg_{water} = 1 l, the WBT expresses SC as kg_{fuel}/l. The protocol also includes two "adjusted" versions of this metric for the two high-power phases, in order to allow for better comparisons across stoves tested under different environmental conditions or to consider energy instead of fuel consumption; they will not be discussed in the present analysis [62].

FP – Firepower

FP is the ratio between the fuel energy consumed to boil/simmer water and the time to boil/simmer. It expresses the average power output of the stove:

$$FP = \frac{f_d \cdot LHV}{t} \quad [kW] \tag{3.1.3}$$

Where t = duration of a test phase [s].

TDR – Turndown Ratio

TDR is the ratio of high and low firepowers, representing the degree to which the firepower of the stove can be controlled by the user:

$$TDR = \frac{FP_{cold-start}}{FP_{simmering}} \tag{3.1.4}$$

3.1.3.2 Emission metrics

The WBT allows for different collection and calculation methods, but provides indications about preferable solutions: the *hood method* is recommended for collection, because cooling and drying are done simultaneously through natural dilution, and because equations are easiest to implement [62]; real-time measurement is also suggested.

Since instruments measure pollutant concentrations, the protocol provides metrics that relate concentrations to the amount of fuel burned or to the task performed; both *exhaust flow* or *carbon balance* methods would be suitable to perform such correlation, and WBT 4.2.3 states the best approach would be using both and ensuring results match.

However, WBT emission metrics are derived specifically from the *carbon balance* method, which is based on the principle that:

> "*All the carbon in the fuel is transformed to combustion products that contain carbon (CO_2, CO, unburned hydrocarbons, and particulate matter). These can be used to infer the amount of fuel burned that corresponds to the amount of pollutant measured. By taking the ratio between the pollutant concentration and the carbon concentration in the exhaust air, one avoids the need to quantify ambient air mixed into the exhaust*" [62].

EF – Emission Factors

Emission factors are calculated for each of the measured pollutants: CO, CO_2 and PM. They represent the average grams of pollutant emitted per kilogram of fuel burned. The EF for CO_2 is computed as:

$$EF_{CO_2} = \frac{[CO_{2,test}]-[CO_{2,bk}]}{[C]} \cdot \frac{44}{12} \cdot fuelFracC \cdot 1000 \quad [\frac{g_{CO_2}}{kg_{fuel}}] \tag{3.1.5}$$

Where the fraction represents the difference between exhaust and background CO_2 concentration divided by the carbon atoms concentration in stove exhaust; this ratio is then multiplied by the fuel carbon fraction and by the molar ratio to obtain $\frac{[g_{CO_2}]}{[kg_{fuel}]}$

.

Similarly the EF for CO results:

$$EF_{CO} = \frac{[CO_{test}]-[CO_{bk}]}{[C]} \cdot \frac{28}{12} \cdot fuelFracC \cdot 1000 \quad [\frac{g_{CO}}{kg_{fuel}}] \qquad (3.1.6)$$

EF for PM slightly differs from the previous two, since PM concentration is directly measured as a mass concentration, so there is no molar ratio and the scale factor is different:

$$EF_{PM} = \frac{PM_{test} - PM_{bk}}{C} \cdot fuelFracC \cdot \frac{1}{10^3} \quad [\frac{g_{PM}}{kg_{fuel}}] \qquad (3.1.7)$$

***$m_{pollutant}$* – Pollutant Mass produced**

Multiplying EFs by the mass of dry fuel consumed (see WBT 4.2.3 [62] for further details) it is possible to obtain the total mass of each pollutant emitted: m_{CO_2}, m_{CO}, m_{PM} .

***$E_{specific}$* – Emission per Water boiled**

It is the total mass of pollutant emitted divided by the final mass of water in the pot, then multiplied by the approximate density of water to obtain $\frac{[g_{pollutant}]}{[l_{water}]}$:

$$E_{pollutant} = \frac{m_{pollutant}}{m_{w,f}} \cdot 1000 \qquad (3.1.8)$$

3.1.3.3 IWA Tiers of Performance

WBT v.4.2.3 also includes the results coming from the work of the ISO-IWA 2012 (see *sub-section 2.1.2*), namely the IWA Performance Metrics and Tiers of Performance. The international workshop, in fact, identified a number of performance metrics to be used as a standard for comparing ICS; those metrics are also grouped into tiers to allow for an immediate comparison of different stove performances, as shown in *Table 3.1.1*.

IWA VITA WBT Tiers	units	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4
High Power Thermal Efficiency	%	< 0.15	≥ 0.15	≥ 0.25	≥ 0.35	≥ 0.45
Low Power Specific Consumption	MJ/min/L	> 0.05	≤ 0.05	≤ 0.039	≤ 0.028	≤ 0.017
High Power CO	g/MJd	> 16	≤ 16	≤ 11	≤ 9	≤ 8
Low Power CO	g/min/L	> 0.2	≤ 0.2	≤ 0.13	≤ 0.1	≤ 0.09
High Power PM	mg/MJd	> 979	≤ 979	≤ 386	≤ 168	≤ 41
Low Power PM	mg/min/L	> 8	≤ 8	≤ 4	≤ 2	≤ 1
Indoor Emissions CO	g/min	> 0.97	≤ 0.97	≤ 0.62	≤ 0.49	≤ 0.42
Indoor Emissions PM	mg/min	> 40	≤ 40	≤ 17	≤ 8	≤ 2
Safety	Johnsons	< 45	≥ 45	≥ 75	≥ 88	≥ 95

Table 3.1.1 – IWA Tiers of Performance, adapted from WBT v.4.2.3 [62].

Details about IWA metrics formulation are not reported here, as they are basically derived from WBT metrics, eventually modifying units of measure.

3.1.4 Strengths & Weaknesses

The main strength of the WBT is being (in its current 89 pages version 4.2.3) the most detailed protocol officially published; testing concept, procedure details, metrics rationale and formulation, and emissions equipment are thoroughly exposed, in a simple and clear manner. Protocol variations are provided to account for different fuels or different stove types, thus allowing for adaptation to different testing needs; furthermore, the document includes chapters dedicated to the evolution of the protocol, with contributions from different research teams, and a critical discussion of the unsolved debate topics. In addition, an Excel Spreadsheet is downloadable (from the GACC website [75]) and ready to use. The WBT 4.2.3 is thus regarded as the most user-friendly document for someone approaching the world of ICS testing. Still, some of WBT critical issues remain unsolved, with a number of researchers claiming the protocol would need to be reviewed in terms of precision and accuracy [76] [57] [77].

A lot of debate has been made around **metrics formulation**, primarily on thermal efficiency, which is often interpreted as the most immediate and distinctive stove performance parameter. Studies from Bailis et al. [52] highlighted how relying on

WBT thermal efficiency outputs, regardless of the relative importance of high and low power cooking tasks among the target population can lead to misleading interpretations. Furthermore, the same study showed how the output of Low-Power thermal efficiency might lead to scientific paradoxes: a comparison between three ICSs and a traditional stove resulted in two of them showing an improved thermal efficiency at Low-Power at the same time as they showed an increased fuel consumption. This is because the significant amount of vaporisation occurring during the simmering phase is rewarded as a positive contribute in the calculation of η (*Equation (3.1.1)*), although the stove mission at simmering is not evaporating water from the pot, but rather counterbalancing all thermodynamic losses.
The scientific meaningfulness of η at Low-Power has been also questioned by Zhang et al. [57], claiming that simmering and low power operation are not synonyms and that a proper way to evaluate Low-Power efficiency would be simply operating the stove at the lower power possible to heat water. As highlighted by Smith et al. [39], evaluating low-power efficiency by means of a simmering phase characterised by highly variable steam production and no measured sensible heat, also results in a variable output. The WBT 4.2.3 itself suggests to interpret this parameter with caution and to better rely on *Specific Fuel Consumption* as an indicator of stove performances at Low-Power. Thermal efficiency at Low-Power, in fact, is not included in the IWA Performance Metrics; still, a definitive clarification should be made on this topic, avoiding ambiguities and wrong interpretations of the results.

Criticism about WBT also concerns **thermodynamic subjects**. The WBT is a controlled laboratory test, thus supposed to have little uncertainty and to be effective in comparing different stove designs. Nevertheless, the choice to approximate a typical cooking task (boiling and simmering) is not functional to this purpose; in fact, as documented by L'Orange et al. [78], uncertainties related to temperature reading and vaporisation in the boiling region lead to high variability between test replicates. Other testing protocols avoid those problems by ending the test at a fixed temperature (10 or more degrees lower than boiling point) and by using pot insulation (lid or foam) – they will be discussed afterwards. The WBT rejects these kind of variations, asserting that "*testing should be conducted to determine whether a stove optimized with pot insulation results in an optimal stove for conditions without pot insulation*" [62]. Of course, a stove which is specifically designed and optimised for insulated pots would be performing differently without insulation; yet testing all stoves without a lid is not a solution either. To better understand this concept, a simple experiment on a common European electric heater – which was actually experienced by the author on a *Severin KP 1092* (1500 W_{nom}) – may be performed: the appliance, operated at its maximum power, might not be able to heat a small pot of water (2 litres) up to the boiling point, when no lid is placed on it; yet it may be perfectly able to perform the task when the pot is insulated (as commonly done by the average European user). Therefore, the electric heater would fail to perform a WBT (even on a small pot) yet it would be perfectly functioning from a user's point of view. The example highlights how stove performances are not inherent to the design, but rather depend on several external factors (*viz.* pot dimensions and insulation, as well as fuel type, moisture content and burn cycle in case of wood burning stoves). Trying to approximate a fixed "task" cannot be representative of the variety of cooking tasks and habits that may be experienced in a real context of use [68]. A proper way to evaluate stove designs should be therefore testing the stove over a range of different pot/fuel combinations and for different power levels, without trying to approximate any cooking task, and all changes allowing for an improved repeatability should be taken into account. Surprisingly, "*Changes to Testing Conditions to Improve Repeatability*" – *changes* here refer to fuel and pot characteristics – are indeed included in the WBT document, although caution is suggested as such changes "*may make the stove perform differently than it would in practice*" [62]. Therefore, changes involving *some* parameters are allowed to improve repeatability (even if leading to results that are unrepresentative of different conditions), while changes involving *other* parameters, such as pot insulation and maximum temperature (with identical purpose and effect), are not. Such ambiguities lead to confusion and to the evidence of an unsolved conflict between the declared purpose of the WBT to be a design-phase test, not intended to be representative of real-use performances, and the tendency of the authors to motivate conceptual choices as if the test was a tool to effectively select the most appropriate stove in the lab already.

The "Tiers of performance" system represent a further source of results misinterpretation: as WBT procedure is not able to capture a representative range of stove performances, the usefulness and reliability of comparing stove designs a priori should be questioned. The literature also clearly showed how an "optimal" stove design may result in very different performances when performing different burn cycles in different regions [43], [52], [68]. Rating stoves on performance Tiers based on a single approximated burn cycle (boiling and simmering), which may be unrepresentative of the target population's, is possibly one of the greatest causes of failure in technology selection.

Finally, some considerations about **statistical analysis** of data must be included, as this is often a source of errors in the interpretation of results.

WBT v.4.2.3 includes "*Statistic Lessons for Performance Testing*" in its Appendix 5, which address the topic in a simple yet comprehensive way. The appendix specifies that the minimum number of replicates for each stove tested should be three; yet, it also specifies how three replicates are not necessarily sufficient to determine a stove performance within a certain confidence interval, as this must also take into account variability. It highlights the importance of paying attention to the statistical significance of a series of comparison tests between two stoves, and simple examples are provided to show how to apply these basic principles of statistical data analysis to WBT results.

Nevertheless, a great majority of studies are performed and published using a number of replicates that is equal or inferior to three, as reported by Wang et al. [70]. This is due to a misinterpretation of the Appendix message as "only three tests are needed", regardless of variability and confidence interval. Wang et al. investigated this topic on a simplified version of WBT 3.0, proving how the minimum number of replicates to obtain a confidence interval of 95% for *Time to Boil* or EF_{PM} is likely greater than 5 [70]. The number of replicates needed is even greater when comparing two stoves performances. Thus, greater attention should be paid on data consistency; if the number of replicates needed to obtain statistically significant data is likely to be much greater than three, the Appendix should better highlight this, avoiding misinterpretations.

Water Boiling Test v.4.2.3	
Strengths	***Weaknesses***
▪ Highly detailed and user-friendly document, including Excel Spreadsheet ▪ Adaptability to any fuel and stove type	▪ Confusion on the protocol purpose and usefulness ▪ Not suitable to assess average field performances ▪ Questions on some metrics meaningfulness ▪ Questions on thermodynamic issues ▪ High variability between test replicates and uncertainty ▪ Misleading statistical considerations ▪ High number of replicates needed to obtain statistically significant data.

Table 3.1.2 – Water Boiling Test Strengths & Weaknesses.

3.2 Indian Standard on Solid Biomass Chulha-Specification (1991)

The Indian protocol was developed in 1991, as part of the "National Programme on Improved Chulhas" (NPIC) launched in 1985. It was, along with the "Chinese National Improved Stoves Programme", the first case of big scale ICS (viz. *Chulhas*) diffusion programme. The four objectives of the NPIC were:

> "*to conserve and optimize the use of fuelwood, especially in the rural and semi-urban areas; to help alleviate deforestation; to reduce the drudgery associated with cooking (especially on women) and the health hazards caused by smoke and heat exposure in the kitchen; to bring about improvements in household sanitation and general living conditions* [31]".

This protocol was therefore designed specifically for the testing of Chulhas against traditional stoves, and does not account for stoves using different fuels or multiple pots, but it does account for emission testing.

It is often referred to with the acronym BIS (Bureau of Indian Standards), and was originally developed in 1991 [55]; nevertheless, Sutar et al. [36] mention in their work a "Revised version" of BIS, dated 2013, also giving a few details about changes in the protocols. Unfortunately, this version has not been officially published, and only a draft version is available from the Bureau of Indian Standards website [58]; the present analysis will thus refer to the original BIS of 1991.

3.2.1 Preparing for testing

The protocol provides prescriptions about fuel type and pots material to be used for testing; nevertheless, fuel amount and pots dimension are not determined a priori, but in response to the *"burn capacity rate" (BCR)* of the stove tested, which shall be calculated firstly if not specified by the manufacturer. The local boiling point should be determined as well, but no method is suggested for this calculation.

Fuel

The only fuel admitted by the BIS protocol is wood: a wood type has to be selected from a suggested list, and then cut into pieces of 3x3 cm^2 cross-section, and length of half the diameter/length of the combustion chamber. The wood shall be also completely dried following a specific oven-drying procedure. As regards fuel amount, see definition below.

Burn Capacity Rate and fuel amount

Fuel amount is determined a priori as a function of the so called "Burn Capacity Rate" (*BCR*), which is estimated by means of a simple procedure: the whole cookstove is put on a balance, filled with test fuelwood and weighed; the fuel is then allowed to burn for half an hour, without any pot on the stove, and finally the cookstove is reweighed along with charcoal left. The change in mass, due to fuelwood consumption, is multiplied by the calorific value of the wood (estimated by means of a bomb calorimeter):

- $BCR = 2(m_1 - m_2) \cdot LHV_{wood} \quad [kJ/h]$ (3.2.1)

  Where,
  m_1 = initial mass of the stove with test fuel [*kg*];
  m_2 = mass of the stove after burning the test fuel for half an hour [*kg*].

This formulation allows the calculation of a BCR value that is equivalent to a mass of fuel burning for 1 h (2 times half an hour); a corresponding mass of wood is then prepared, and divided into 4 parts, to be used in a sequence.

Pots

The pots to be used for testing shall be made of aluminium, and at least two pots are necessary to perform the BIS test. Dimensions, weight (with lid on), and mass of water are instead selected by means of a table, based on the BCR and included in the protocol [55]. Notice that water mass in the pot can vary from 2 up to 18 *kg*.

Insulation

The Indian BIS prescribes the use of lids as this is considered to reflect the actual cooking practice of Indian households, thus allowing for an appropriate evaluation of the ICS performance in the local context [56].

3.2.2 Testing procedure

Two pots are used in a sequence; the fuelwood prepared should guarantee a test duration of 1 h.

Ignition

The first pot is placed on the stove (water temperature should be $T_i = 23 \pm 2°C$) and the first of the four portions of fuelwood is lit by means of kerosene. Note that the BIS protocol starts measuring all the parameters only after the fire has been allowed to catch up for 30 seconds.

Stove operation

The stove is fed every 15 minutes with each of the three remaining portions of fresh fuel. The water in the pot is allowed to warm steadily until it reaches a temperature of about 80°C, then stirring is commenced, and continued until the temperature of water reaches 5°C below the local boiling point (defined as T_{max}). The time needed to reach T_{max} is recorded, and the first pot is removed from the stove, as the second is put on immediately. The experiment is repeated by alternatively putting the two pots on the stove.

End of test

When there is no visible flame left in the combustion chamber, the test is over, and the temperature of the water in the last pot (T_f) is recorded.

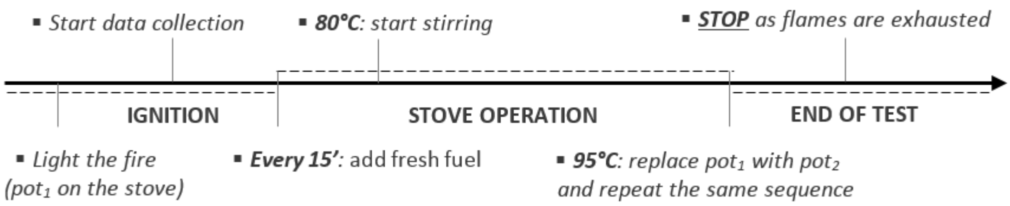

Figure 3.2.1 – Summary of BIS procedure.

3.2.3 Performance metrics

3.2.3.1 Energy metrics

η – Thermal Efficiency

It is calculated as the ratio between *Heat Utilised* and *Heat Produced*. The former does not take into account the mass of water vaporized, as in most protocols, but considers instead the heat transferred to the pot walls, and it is therefore calculated as:

$$HeatUtilised = \\ = (n-1)(m_{pot+lid}c_{p,Al} + m_w c_{p,w})(T_{\max} - T_i) + (m_{pot+lid}c_{p,Al} + m_w c_{p,w})(T_f - T_i) \quad (3.2.2)$$

Where: n = number of pots utilized;

$m_{pot+lid}$ = mass of pot and lid [*kg*];

T_i = initial water temperature [K];

T_{max} = water temp. corresponding to 5°C below local boiling point [*K*];

T_f = final water temperature in the last pot.

It is not specified whether the mass of water to be used for this calculation is the initial or final mass of water in the pot. As underlined by Zhang et al. [57], attention should be paid to *Equation (3.2.2)*, since it includes the heat gained by the pot materials, which is never considered in the WBT calculations regardless of the pot thermal mass. In case of massive pots this heat fraction may be not negligible.

As regards the *Heat Produced*, it is the sum of the heat released by wood and kerosene combustion:

$$Heat\ Produced = m_{wood} LHV_{wood} + m_{kerosene} LHV_{kerosene} \qquad (3.2.3)$$

Thermal efficiency results therefore:

$$\eta = \frac{(n-1)(m_{pot+lid}\, c_{p,Al} + m_w c_{p,w})(T_2 - T_1) + (m_{pot+lid}\, c_{p,Al} + m_w c_{p,w})(T_3 - T_1)}{m_{wood} LHV_{wood} + m_{kerosene} LHV_{kerosene}} \qquad (3.2.4)$$

BCR – Burn Capacity Rate

$$BCR = 2(m_1 - m_2) \cdot LHV_{wood} \quad [kJ / h] \qquad (3.2.1)$$

(As defined in *sub-section 3.2.1*)

P_o – Power Output Rating

The power output rating is conceived as a measure of the total useful energy produced during one hour by the fuel. It is computed as follows:

$$P_o = \dot{m}_{fuel} LHV_{fuel} \cdot \eta / 3600 \quad [kW] \qquad (3.2.5)$$

Where: $\dot{m}_{fuel}$ = rate of consumption of fuel wood [*kg*/*h*].

3.2.3.2 Emission metrics

CO/CO_2 ratio

The ratio between the concentrations of the two pollutants is used as indicator for combustion efficiency. CO and CO_2 are products of biomass combustion, with CO resulting from incomplete combustion; thus, a high CO/CO_2 ratio reflects an incomplete and not efficient combustion.

As regards their measurement, the BIS reports:

> "*any of the recognized methods may be used for gas analysis. For carbon monoxide, it is recommended that co-indicator of prescribed accuracy or the iodine pentaoxide method or catalytic method, for example the Drager method, Katz method, or infra-red analysis may be used.*

Carbon dioxide may be tested with Orsat apparatus, Haldance apparatus or by the infra-red analysis" [55].

TSP – Total Suspended Particulate Matter

The gravimetric method is used to calculate PM mass concentration; the total suspended particulate matter is computed by measuring the mass of collected particulates and the volume of air sampled in the ambient air, in the following manner:

$$Total\ suspended\ particulate = \frac{mass\ of\ collected\ particulate\ [mg]}{Volume\ of\ air\ sample\ [m^3]}$$

$$= \frac{(m_{filter,f} - m_{flter,i}) \cdot 10^6}{\dot{V}_{air} \cdot 60} \quad [\frac{mg}{m^3}] \qquad (3.2.6)$$

Where,

$m_{filter,I}$ = Initial mass of filter paper [*g*];

$m_{filter,f}$ = Final mass of filter paper [*g*];

V_{air} = Flow rate of ambient air [*l/min*].

3.2.4 Strengths & Weaknesses

The BIS protocol is based on a different concept than WBT; it does not try, in fact, to approximate a real burn cycle (boiling and simmering) but rather aims at studying an ideal heat transfer process. Rigid procedure requirements are also meant to avoid tester discretion and variability; specifically, the fixed amount of fuel is highlighted by Arora et al. [56] as an important factor reducing variability as compared to WBT.

Doubts arise from the choice to set the temperature limit to 5°C below boiling point, which is still too close to boiling to limit the mentioned uncertainties, as documented by L'Orange et al. [78]. Other protocols performing *pot swapping* and trying to reproduce an ideal heat transfer process, in fact, set the maximum temperature at much lower values (70/80°C); further studies would be needed to clearly define an effective temperature limit.

Moreover, the BIS protocol does not repeat the process for different power levels, and completely avoiding low power testing can lead to very misleading interpretations of the stove performances. In fact, as shown by Berrueta et al. [63], actual burn cycles are likely to include low power tasks and one of the most recurrent errors in assessing ICS performances is the excessive reliance on High Power parameters alone.

Another possible source of variability comes from the choice to set the *End of Test* as there is "*no visible flame*" in the stove body; this observation is subjective and variable with stove operator and design. Also, attention should be paid on fuel prescriptions (*sub-section 3.2.1*); fuel moisture content has been proved to highly influence stove performances [79]-[78], and the choice to use completely dried fuel for testing can lead to results that are very unrepresentative of typical field usage.

No indications are provided regarding the minimum acceptable number of replicates.

Indian Standard on Solid Biomass Chulha-Specification	
Strengths	***Weaknesses***
▪ Rigid procedure requirements, ensuring higher repeatability ▪ Simple and quick to realize (single phase, no fuel/charcoal weighing)	▪ Metrics and procedure are not accurately detailed, leading to possible ambiguities ▪ Testing of different fuels is not considered ▪ Temperature limit (95°C) is not sound to the purpose ▪ No indications about number of replicates ▪ Use of completely dried fuel, not representative of average fuel conditions for typical contexts of use

Table 3.2.1 – Indian BIS Strengths & Weaknesses.

3.3 Chinese Standard (2008)

China was the first country to launch a national campaign to improve the use of domestic biomass for cooking in rural areas; the "Chinese National Improved Cookstove Program" (CNISP) was planned back in 1980, and has been the widest national stove dissemination project since then [80]. This standard protocol was however developed more recently (2008), by the "*Quality and Technical Supervision Bureau of Beijing Municipality*"[59], and it is designed for the testing of "household stoves" (biomass stoves for cooking or heating, with a power up to 50kW); the following analysis will take into account "cooking stoves" only.

The stove needs to satisfy some basic requirements in order to be approved based on this protocol, namely:

- Reasonable, convenient and safe stove design;
- Attractive appearance, smooth surface;
- Cooking power greater than stove nominal value;
- $\eta \geq 35\%$;
- $P_C > 2kW$;
- Emission limits of air pollutants (*Table 3.3.1*)

Pollutant	**Upper limit**	
$[mg/m^3]$	Central area	Out of central area
Dust	10	30
SO_2	20	30
NO_x	150	150
CO	0.2	0.2

Table 3.3.1 – pollutants limits, adapted from "*General specifications for biomass household stoves*" [59].

More information about design and safety requirements are exposed in the full protocol; a remarkable aspect is that the protocol suggests the stoves to be equipped with a chimney, and to maintain a temperature of less than 60°C in normal functioning conditions. Also, the lifetime under normal operation should be at least 3 years.

3.3.1 Preparing for testing

Fuel

The protocol does not specify in detail fuel type or moisture content to be used for testing; it generically refers to "biomass fuel", divided into three possible categories: particle biomass fuel, pressed block-shaped biomass fuel, rod biomass fuel. The quantity of biomass fuel (in *kg*) is fixed – here reported in *Table 3.3.2* – in response to the stove *Cooking Power* nominal value, which must be indicated by the manufacturer in the stove model number. The model number should include, as well, a reference to the type of biomass fuel for which the stove was designed.

Pots

Cooking pots are made of aluminium; dimensions (diameter) and water content are also chosen in function of the nominal *Cooking Power*, as for the fuel. Water content varies from a minimum of 5 kg to a maximum of 9 kg.

Insulation

The Chinese standard prescribes to use a lid on the pot, even if no arguments are provided for this choice.

Cooking Power [*kW*]	**Initial water mass** [*kg*]	**Pot diameter** [*mm*]	**Biomass fuel quantity** [*kg*]
< 3.5	5	240	< 2
3.5 - 7	7	280	2 - 4
> 7	9	310	> 4

Table 3.3.2 – pot, fuel and water amount indications; adapted from "*General specifications for biomass household stoves*" [59].

3.3.2 Testing procedure

The testing procedure is performed in a continuous sequence, including both the high-power and the low-power phases.

Ignition

The ignition procedure is not precisely defined; the protocol indications are to "*light the fire*" and record the time "*when the fuel starts to burn*" [59].

Stove operation

The stove is firstly operated in order to raise the temperature of water to the local boiling point, keeping the lid on the pot; as the boiling point is reached, time and temperature are recorded and the lid is removed.
Therefore the test continues directly with the "evaporation" step, during which the stove is fed with the remaining fuel from the pre-determined bundle and the temperature is recorded every 5 minutes.

End of test

As the temperature of water drops to 95°C, due to insufficient fuel power, the test is over and the time is recorded.

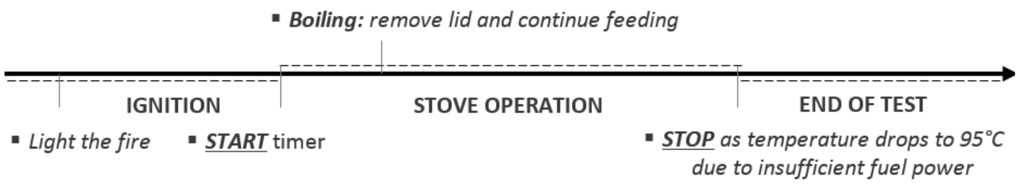

Figure 3.3.1 – Summary of Chinese Standard procedure

3.3.3 Performance metrics

3.3.3.1 Energy metrics

η – Thermal Efficiency

η is calculated as the ratio of the total heat absorbed by water (heat used to reach the boiling point plus heat used for the evaporation step), and the heat produced by the combustion of fuel plus kindling:

$$\eta = \frac{m_{w,i} c_{p,w} (T_b - T_i) + (m_{w,i} - m_{w,f}) h_{lv}}{m_{wood} LHV_{wood} + m_{kindling} LHV_{kindling}} \qquad (3.3.1)$$

P_c – Cooking Power

It is computed as the total heat absorbed by water divided by the total time of the test:

$$P_C = \frac{m_{w,i} c_{p,w} (T_b - T_i) + (m_{w,i} - m_{w,f}) h_{lv}}{t_{tot}} \quad [kW] \qquad (3.3.2)$$

Where t_{tot} is the total time of the test.

3.3.3.2 Emission metrics

No specific emission metric is calculated, but pollutants are measured in order to verify that the stove respects the prescribed pollutants limitations (see *Table 3.3.1*). As regards measurement methodologies, the protocol refers to "*The Determination of Particulates and Sampling Methods of Gaseous Pollutants Emitted from Exhaust Gas of Stationary Source GB/T 16157-1996*"; no other indication is provided.

3.3.4 Strengths & Weaknesses

The Chinese Standard was developed specifically to support the CNISP and to test Chinese cookstoves; as a consequence, it is not much adaptable to different stove designs or regions (*e.g.* a chimney is prescribed for the stove). Furthermore, testing parameters are chosen as a function of a *"nominal Cooking Power"*, which should be indicated by the manufacturer, meaning that artisanal stoves could not be tested following the same procedure.

The main qualities of the protocol are its relative simplicity and quickness, as it is made up of a single continuous phase; still, testing on a fixed cycle can be a valid strategy only if precisely reflecting the target population burn cycle [68].

As regards weaknesses, the protocol is missing some procedure details (*e.g. Ignition*) and description of reasons behind some methodological choices (*e.g. Insulation*, *Emission Metrics*), leading to possible ambiguities and to tester discretion, which is a source of variability.

Questions arise also from the choice to define a single efficiency parameter from the start to the evaporation phase, without distinction between high and low-power performances. The problems related to the thermal efficiency formulation for a simmering phase have been well documented, and the WBT 4.2.3 itself advises to view this metric with caution (see *sub-section 3.1.4*) [62]. Similar considerations can be made about the *Cooking Power* metric, based on identical data in the numerator of the equation; the meaningfulness of these two parameters should be better investigated.

A peculiar feature of the Chinese Standard is accounting for the issue of stove durability: a lifetime of at least 3 years is prescribed, even if no method is provided for the estimation of this parameter. It also sets benchmark values to be satisfied by the stove in order to be classified as an ICS.

No indications are provided about the minimum number of replicates needed.

Chinese Standard	
Strengths	***Weaknesses***
▪ Prescribes specific requirements to be satisfied by the stove in order to be classified as ICS ▪ Simple and quick to realize (single phase, no fuel/charcoal weighing)	▪ The protocol detail of procedure and theoretical aspects is poor ▪ Performance metrics are questionable ▪ The range of testable stove designs is limited by specific prescriptions ▪ Poor detail on emission measurements and pollutants limits ▪ No distinction between high-power and low-power performances ▪ No indications about number of replicates

Table 3.3.3 – Chinese Standard Strengths & Weaknesses.

3.4 Emissions & Performance Test Protocol (2009)

The EPTP was developed in 2009 by researchers from the Colorado State University, in collaboration with Envirofit and Philips, as an update of the WBT 3.0 (2007) [60]. It is proposed as a standardized and replicable test to compare cookstoves made in different places and for different cooking applications, with the aim of helping stove designers in the study of both heat transfer and particulate emissions [64]; it is not intended, however, as a substitute for field performance evaluation.

Similarly to the WBT, the EPTP is composed of three phases (Cold and Hot Start plus Simmering), but it was specifically developed to address the issue of results repeatability, and thus includes some peculiar modifications intended to reduce sources of uncertainty: pots are insulated during high-power phases, and water is heated only up to 90°C rather than to boiling point.

3.4.1 Preparing for testing

Fuel

The EPTP procedure is designed for wood fuels, but testing of gasifiers, charcoal and coal stoves is allowed as well, with slight modifications in the procedure (see "*EPTP-Appendix B"* [64] for further details); non-standards fuels such as agriculture wastes, animal dung, *etc.* are instead discouraged since "*results would vary greatly*" [64], without providing the tester with a particular motivation. The standard fuels for EPTP should be softwoods such as pine or Douglas fir, with a moisture content of 4-10% and recommended dimensions of 1.5 cm^2; if such dimensions are not possible, the tester should still strive for uniformity in cross section.

Three bundles of fuelwood should be prepared, about 5 kg each, including eventual kindling material.

Pots

Cooking pots should be made of steel or aluminium, with a reasonable size depending on the volume of water being used. The initial water volume ranges in fact from 4 to 6 L, depending on the stove firepower and the temperature of available water; it is evaluated by means of a chart included in the protocol *Appendix D* [64]. Pots should also have roughly equal height and diameter.

Insulation

The EPTP prescribes pot insulation for the two high-power phases, asserting this practice can help minimizing errors in energy metrics, as demonstrated by L'Orange et al. [78]. The suggested insulation is closed-cell foam, 1-3 cm thick and capable of handling temperatures of at least 100° C, to be floated on the water surface with a hole for the thermocouple.

3.4.2 Testing procedure

The EPTP testing procedure consists of three phases, conceptually similar to those from the original WBT: cold-start, hot-start and simmering.

3.4.2.1 Cold-Start High-Power

Ignition

Emissions measurement and data acquisition precede fire ignition, defining the test start time. Fuelwood is therefore ignited following manufacturer's recommendations; if no recommendations are provided, wood shims (*viz.* small pieces of wood) or similar should be used for natural draft stoves, while kerosene should be preferred for charcoal and coal stoves.

Stove operation

The stove is operated in order to rapidly raise water temperature, following manufacturer's guidelines (when present) or simply avoiding excessive waste of fuel.

End of test

As the water temperature reaches 90°C, data acquisition is stopped and the test is over. Wood is removed from the stove, extinguished and weighed together with the remaining wood from the prepared bundle; charcoal produced and water in the pot are weighed as well.

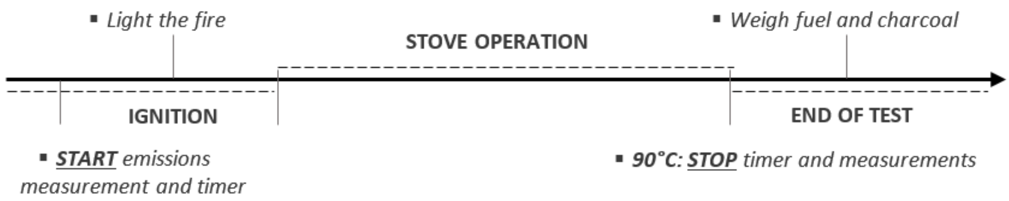

Figure 3.4.1 – Summary of EPTP Cold-Start High-Power phase.

3.4.2.2 Hot-Start High-Power

Ignition

While the stove is still hot from the previous operation, emissions measurement and data acquisition are restarted, again prior to fire ignition. Ignition procedure follows the same method as for *Phase 1* (=Cold Start).

Stove operation

Same as *Phase 1*.

End of test

Same as *Phase 1*; charcoal is not weighed at this stage, and hot water is retained for the following phase.

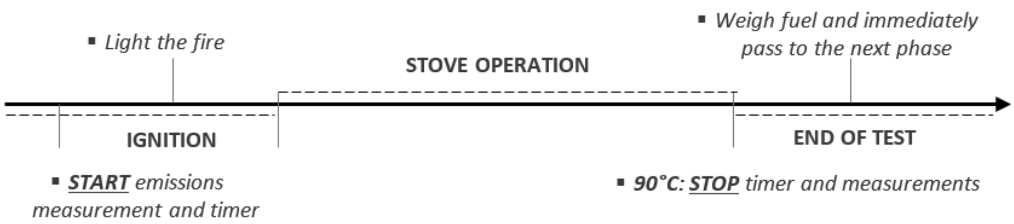

Figure 3.4.2 – Summary of Hot-Start High-Power phase.

3.4.2.3 Low-Power Simmering

Ignition

Same as *Phase 2* (=Hot-Start).

Stove operation

The stove is operated in order to maintain the water temperature at or above 90°C; the temperature can vary up and down, but must not drop under 90°C.

End of test

After 45 minutes the test is over, data acquisition is stopped and wood, charcoal and water are weighed following the same procedure as for *Phase 1*.

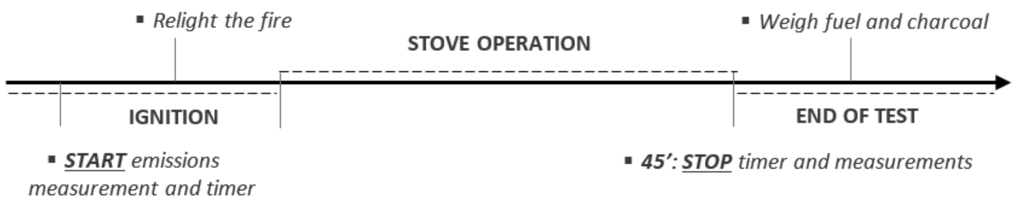

Figure 3.4.3 – Summary of EPTP Low-Power Simmering phase.

3.4.3 Performance metrics

3.4.3.1 Energy metrics

η – Thermal efficiency

The thermal efficiency formulation is the same as the WBT, *viz.* the ratio between the heat absorbed by water and the heat released by combustion of fuelwood; EPTP, however, calculates η for the two high power phases only:

$$\eta = \frac{m_w c_{p,w}(T_b - T_i) + m_{eva} h_{lv}}{f_d \cdot LHV} \tag{3.4.1}$$

It is not specified whether the mass of water to be used for sensible heat is the initial or final mass of water in the pot, or an average of the two, leading to ambiguity; equivalent dry fuel calculation is identical to WBT, accounting for fuel used to evaporate moisture content and fuel turned into char (see *Paragraph 3.1.3*).

FP – Firepower

Firepower is valuable both for high-power and low-power phases. The EPTP distinguish between *Overall Firepower* (FP_o), which is a measure of the average rate of energy released from fuel combustion transferred to the pot, surroundings, and stove over the duration of the test, and *Useful Firepower* (FP_u) accounting only for the energy transferred to the pot:

$$FP_o = \frac{LHV \cdot f_d}{t} \quad [kW] \tag{3.4.2}$$

$$FP_u = FP_o \cdot \eta_{th} \quad [kW] \tag{3.4.3}$$

R_b – Burning Rate

It is the average rate that dry fuel was consumed during the test, and it is valuable both for high and low-power phases:

$$R_b = \frac{f_d}{t} \quad [\frac{kg}{s}] \tag{3.4.4}$$

3.4.3.2 Emission metrics

The EPTP prescribes measurements of gaseous emissions via non-dispersive infrared spectrometer (NDIR) system or better for at least one test replicate; the remainder tests may be conducted with electrochemical or equivalent equipment [64]. The gravimetric method is used instead for PM collection.

Further details about collection methods are included in the EPTP, which also refers to "*US Environmental Protection Agency (EPA) guidelines*" for exhaustive information.

m_{CO} – Mass of carbon monoxide emitted

It is the total mass of CO accumulated throughout a test phase (valuable both for high and low-power) and it is calculated from an instantaneous non-dispersive infrared analyser:

$$m_{CO} = \Delta t \cdot \sum_{i=0}^{n-1} \dot{m}_{CO,i} \quad [g_{CO}] \tag{3.4.5}$$

Where: Δt = time between sample points [s],
$\dot{m}_{CO}$ = instantaneous mass flow rate of carbon monoxide [g/s].

The equation is a numerical integration of the mass flow rate function, and EPTP states that any numerical integration method can be used, although the Riemann Sum method is proposed.

Instantaneous mass flow rate is calculated as:

$$\dot{m}_{CO,i} = \dot{V} \cdot \frac{[CO]_i}{10^6} \cdot \frac{p_{e,i}}{R_{CO,i} T_{e,i}} \tag{3.4.6}$$

Where: $\dot{V}$ = volumetric flow rate of the emissions collection hood [m^3/s];
T_e = instantaneous temperature at exhaust sampling location [K],;
p_e = instantaneous pressure at exhaust sampling location [Pa];
$[CO_i]$ = carbon monoxide concentration [ppm].

m_{PM} – Mass of particulate matter emitted

The gravimetric method is used to calculate particulate matter mass:

$$m_{PM} = m_{filter,f} - m_{filter,i} - \dot{m}_{PM,bk} \cdot t \quad [g_{PM}] \tag{3.4.7}$$

Where: $m_{filter,i}$ = initial mass of particulate filter [g];
$m_{filter,f}$ = final mass of particulate filter [g];

$\dot{m}_{PM,bk}$ = average background particulate collection rate [*g/s*];
t = sampling period [*s*].

3.4.4 Strengths & Weaknesses

The declared purpose of the EPTP is the reduction of variability in testing results, allowing for a more reliable comparison of stoves tested in different areas; changes in the procedure, as compared to WBT, are all motivated as reductions of uncertainties.

L'Orange et al. [78] conducted studies comparing results from three EPTP replicates on the Envirofit International B1100 cookstove to standard WBT results on the same stove. Dry fuel use and CO emissions output parameters were compared in particular; no statistically significant difference between results from the two protocols emerged, although the EPTP was found to reduce the coefficient of variation (COV) for "*nearly every stove performance metric tested*", as showed in *Figure 3.4.4*. Results from this study proved the effectiveness of the EPTP in decreasing variability thanks to procedural changes introduced (*viz.* heating to 90°C and foam insulation). Also, those changes entail a reduction in the total time needed to complete the test, as compared to WBT. Nevertheless, some of the intrinsic WBT weaknesses are embodied in the EPTP; an improvement in testing variability would still not solve the issue of testing the stove only for a fixed cycle, fixed pot and fixed fuel type. Results provided by this kind of testing are not only untranslatable to any field context using a different burn cycle, but also insufficient to perform an effective comparison between different stove designs (as diffusely discussed in *sub-section 3.1.4*).

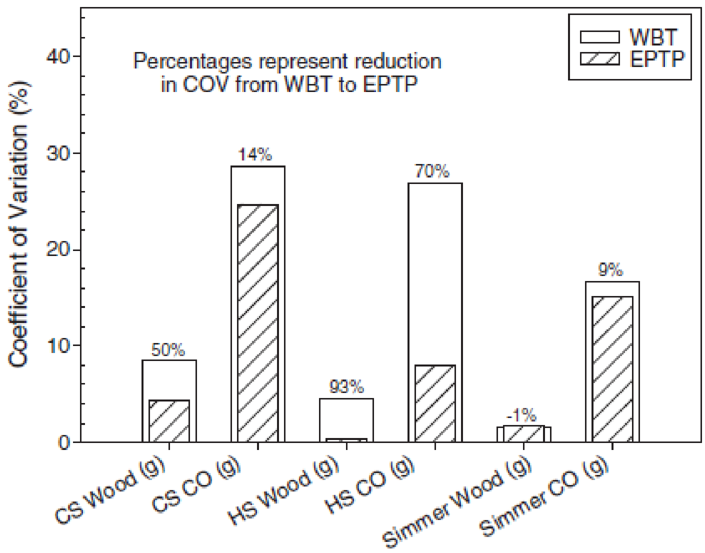

Figure 3.4.4 – COV reduction from WBT to EPTP, adapted from L'Orange et al. [78].

As regards metrics formulation, it must be highlighted that EPTP avoids WBT ambiguities related to performance evaluation at low power, as it does not define any efficiency parameter for the simmering phase, relying solely on *Burning Rate* and *Firepower*.

Instead, the EPTP approach to the issue of statistical confidence and number of replicates reflects the WBT's: three tests are indicated as the minimum standard, yet an exhaustive appendix (*Appendix G: Statistical Considerations* [64]) is included in the protocol, explaining the basic principles of confidence intervals and the influence of replicates number. This can arguably lead to misinterpretations, as diffusely discussed in *sub-section 3.1.4*; in fact, tests by L'Orange et al. comparing EPTP and WBT [78] are based on 3 replicates only for each protocol.

Emissions & Performance Test Protocol	
Strengths	***Weaknesses***
▪ Addresses problems of variability between test replicates ▪ Reduced time to complete the test as compared to WBT ▪ No simmering efficiency	▪ Intrinsic weaknesses of WBT are embodied in the protocol (inability to provide an exhaustive range of stove performances, ambiguities on number of replicates)

Table 3.4.1 – EPTP Strengths & Weaknesses

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3.5 Adapted Water Boiling Test (2010)

The Adapted Water Boiling Test was developed by GERES in 2010 [65], as an evolution of their previous "*Protocole de Test d'Ébullition de l'Eau Comparatif*" (also known as Comparative Water Boiling Test) [81], and as an alternative to WBT 3.0, released in 2007.

GERES (*Group for the Environment, Renewable Energy and Solidarity*) is a non-governmental, non-profit organization created in 1976 and active in Cambodia since 1994, specialized in the implementation of efficient energy solutions adapted to developing countries to improve the living conditions of their inhabitants [82].

According to GERES, this protocol was designed to ease its implementation in developing countries, reduce errors, and take into account local methods of cooking, as well as to be more accessible to local development agencies and organizations working on the evaluation and dissemination of cookstoves, as compared to the WBT [65].

The protocol main features directly reflect this purpose:

> "*the ICS is tested at the same time as the traditional stove (when possible), to ensure identical testing conditions; the same quantity of fuel is used in both cookstoves; there is no "hot starting" step; the fuel is not weighed during the test; local cooking conditions are used as a reference for the testing set up (type of pot, quantity of water, type of fuel, geographic and climate conditions).*" [65].

Stove emissions are instead not taken into account by the AWBT.

3.5.1 Preparing for testing

A preliminary study of local cooking practices is necessary, since pots and fuel to be used for testing need to follow target population habits. Some prescriptions and indications are still provided by the protocol.

Fuel

No prescriptions are given regarding fuel type, since any fuel used by final users is admitted for testing.

Still, the AWBT suggests the fuel to ideally have a moisture content of about 15% in case of fuelwood and 5% in case of charcoal. Fuel amount is definite, and assessed a priori in response to local habits as well.

Pots

Pot material and dimensions, as well as the volume of water, are again dependent on local practices. Nevertheless, a volume of water between 2 and 3 litres is suggested (2/3 of the cooking pot should be filled).

Insulation

The pot must be uncovered during testing, since the lid is considered "as a potential source of error" [65]. The choice is not further motivated.

3.5.2 Testing procedure

The AWBT consists of two phases that immediately follow each other [82], called *Cold-Start High-Power* and *Evaporating High*-Power; in practice, the protocol consists of a single continuous sequence, similarly to the Chinese Standard (see *sub-section 3.3.2*), and hence the two phases will not be distinguished in the present analysis.

Ignition

The ignition method follows target population habits as well; data collection is commenced only after the fuel "has been allowed to burn easily", that is until the kindling is exhausted, "usually after a few minutes" [65].

Stove operation

After the starting point, temperature is read every 3 minutes: if the temperature reading is constant for 10 seconds, the boiling point is considered to be reached, and the *Time to Boil* (t_b) is recorded.

The test continues, keeping the water boiling within a maximum range of 3°C below the boiling point.

End of test

As fuel is exhausted to the point that the temperature of the water drops 3°C below the boiling point, the test is over and the *Total Time of Test* (t_{tot}) is recorded. The remaining fuel in the cookstoves can be weighed for comparison, but this measurement is not used for the AWBT calculation. The cookstove performances are evaluated only by comparing the useful energy provided to the water and the time needed to complete the different test phases.

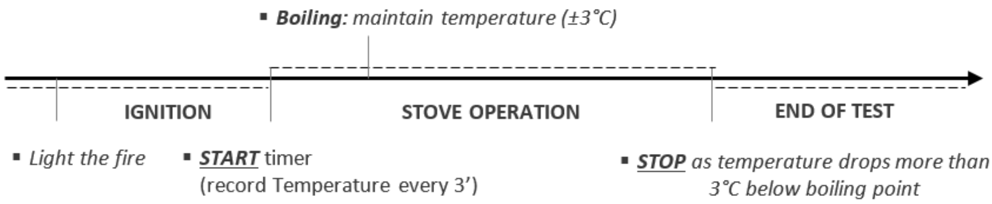

Figure 3.5.1 – Summary of AWBT procedure.

3.5.3 Performance metrics

Only four parameters of performance are considered: *time to boil* (t_b) and *total time of test* (t_{tot}), which are measured directly; *useful energy*; *potential fuel use differences*.

Time to boil, total time of test

As regards the interpretation of t_b and t_{tot}, they should not differ too much as compared to the traditional methods used for cooking in the target area; otherwise, they can represent a barrier in the adoption by the target community.

3.5.3.1 Energy metrics

UE - Useful energy

Useful Energy is the sum of sensible heat, absorbed by water to raise its initial temperature to the boiling point, and latent heat, absorbed by the mass of water evaporated:

$$UE = m_w c_{p,w}(T_b - T_i) + m_{eva} h_{lv} \quad [kJ] \tag{3.5.1}$$

It is evaluated globally, without distinguishing high and low-power performances.

PFD - Potential Fuel Differences

PFD are calculated as:

$$PFD\% = 100 \cdot \frac{UE_{ICS} - UE_{traditional}}{UE_{ICS}} \qquad (3.5.2)$$

PFD% should highlight the potential fuel differences between two cookstoves; it starts to be significant above 10%. According to GERES, multiplying this ratio by the current quantity of fuel used it is possible to give an estimation of the actual fuel difference. Such difference should be then validated in real use conditions [65].

3.5.4 Strengths & Weaknesses

The AWBT is based on the assumption that taking into account typical cooking practices of the target area and including them in the testing procedure (in terms of fuel amount, pot type etc.) can help predicting average field performances. This is a user-centred approach, which many authors actually consider a necessary step to improve current testing methodologies [83], [68]. Still, the AWBT is based on the same procedure as the WBT, keeping a fixed burn cycle instead of following the target population's one, not achieving an actual user-centred approach. Therefore, the protocol embodies WBT intrinsic weaknesses and problems of variability (see *sub-section 3.1.4*), possibly adding new ones; in fact, doubts may arise from the criterion chosen to determine the local boiling point (see *Stove Operation – sub-section 3.5.2*), which seems dependent on tester discretion, leading to further variability and errors.

A second peculiarity of the AWBT is that performance evaluation is focused on the concept of "improvement" in relationship to the baseline stove used for comparison, which is an important parameter in relationship to the success of stove dissemination programs. Nevertheless, only time and fuel savings are investigated, which are a few parameters as compared to other protocols, and emissions are not measured at all. Furthermore, the "improvement" is assessed by testing the two stoves (ICS and baseline) simultaneously, filling both with an identical amount of fuel; such practice can lead to errors in case of testing batch-feed charcoal stoves, when the optimum amount of fuel for one stove can be different from the other one, as reported by Beritault et al. [82]. Moreover, studies from Wang et al. [70] prove how the minimum number of test replicates needed to obtain a statistically significant result is much higher than three when comparing two different stoves. Thus, the simplicity of the AWBT procedure may be possibly affected by a higher number of replicates needed. The AWBT affirms that "*results are considered statistically valid if the Coefficient of Variation (CoV) for the useful energy of each cookstove is below 10%*", without providing any further explanation.

As a final remark, the AWBT presents very few restrictions in terms of stove and fuel types, in line with its purpose, and it can be used across a wide range of stove/fuel combinations.

Adapted Water Boiling Test	
Strengths	***Weaknesses***
▪ User-centred, takes into account local cooking practices ▪ Highlights the improvement in relationship to a baseline stove, which can be chosen and adapted depending on the area of intervention ▪ Simple procedure and calculations, little training required	▪ Does not reproduce local burn cycle, relying on a WBT-based procedure ▪ The use of a lid is always denied, even if eventually included in local practices; this is a paradox as far as the aim of the protocol is following local habits ▪ The method used to determine local boiling point (and t_b) is subjective and tester dependent ▪ Emissions are not taken into account ▪ Inaccurate statistical approach

Table 3.5.1 – Adapted Water Boiling Test, Strengths & Weaknesses.

3.6 Heterogeneous Testing Procedure (2010)

The Heterogeneous Testing Procedure (HTP) was developed in 2010 by the Sustainable Energy Technology and Research Centre (SeTAR), from the University of Johannesburg, as a response to the increasing need for the certification of stoves under both Clean Development Mechanism (CDM) and voluntary market projects, calling for the creation of testing protocols capable of simulating real-world use of stoves [76].

The main peculiarity of the HTP is to test the stove over a range of three different power settings (high, medium and low) and over more than one representative pot size. This approach is based on the assumption that pollutant emissions vary with power setting as well as with the changed flow patterns associated with different pot sizes [76]; furthermore, the authors assert that the calculation of performance curves over different power levels, rather than single performance parameters, can give a better representation of real-use stove performances. In addition, the HTP requires the stove to be put on a digital balance throughout the whole testing period, since a real-time measure of the stove and fuel mass change is needed.

As a final remark, notice that some important information regarding metrics and materials are missing in the available HTP document [66]; more information have been recovered from other scientific papers published by the same authors [84], [76]. Moreover, the SeTAR team is currently working on an evolved protocol, trying to integrate actual burn cycles of the target population into laboratory testing; it will be discussed in *section 3.7*.

3.6.1 Preparing for testing

Fuel

No precise indications are provided about fuel types and dimensions, but the authors affirm the HTP was developed for testing a number of solid fuels, as well as kerosene and ethanol gel stoves [84]. Fuel shall be prepared and weighed before starting the test, in an adequate amount to complete the whole test procedure; no definite quantities are suggested.

Pots

In order to increase comparability between different stoves performances, the HTP recommends the use of two standard pots: a large pot (about 6.4 litres capacity) and a small pot (about 3 litres capacity); further details about precise dimensions are available on the HTP document [66]. Pots should be 80% filled with water.

Insulation

A lid must be always used to cover the pot, and this is motivated both by the fact that it helps reducing forms of uncertainty and that it reflects actual cooking practices of many different cultures. Furthermore, the authors affirm that the lid avoids dilution of flue gases with water vapour, which would compromise emissions results [66]. Lids should be also equipped with a pipe to discharge steam outside the emission hood.

3.6.2 Testing procedure

The peculiarity of the HTP procedure is the real-time weighing of the stove and the pot during the whole test duration; an appropriate scale is thus needed (*Figure 3.6.1*). The procedure consists of a single continuous phase, during which three different power settings (high, medium and low-power) are tested by means of three subsequent water pots; this operation is called *pot swapping* method, and is similar to the Indian BIS procedure (*sub-section 3.2.2*).

Notice that the test should be performed at least three times for each fuel/pot/stove combination, that is at least 6 times if testing only one fuel for the two standard pot dimensions.

Ignition

The stove is filled with fuel and placed on the scale, with the pot off; before fuel ignition mass is recorded and emissions measurement is started. At this point, with the pot still off, the fire is lit according to local practices or manufacturer's instructions, and it is operated in order to reach the maximum power setting.

Time of ignition is noted, and every 60 seconds the real-time mass of the stove plus fuel is recorded, until fuel consumption rate stabilises.

Stove operation

As the fuel consumption rate is stable, the scale is tared and the preselected pot with water is placed on the stove (pot-1); mass and time are recorded. Every 60 seconds water temperature and total mass (pot + fuel) are recorded; the mass of the fuel burned is also read and noted down by temporarily lifting the pot from the stove. As the water temperature reaches 80°C, the power is turned down to the midpoint between the lowest and the highest possible – although detailed explanations about how to perform this passage are not provided – and fuel consumption is allowed to stabilise again. Pot-1 is replaced with an identical pot-2 filled with fresh water, and the same operations as before is performed every 60 seconds until the water temperature reaches the prescribed value again.

Finally, the same sequence of operations is repeated for a low-power setting and a third pot (pot-3).

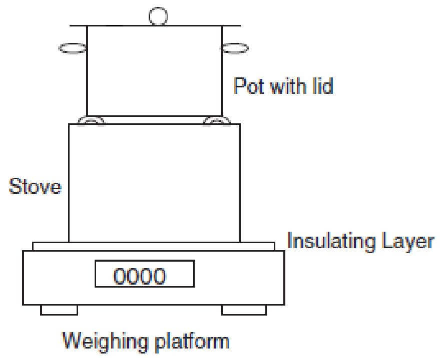

Figure 3.6.1 - HTP experimental set-up, adapted from Makonese et al. [84].

End of test

As pot-3 reaches 80°C, emissions measurement is stopped and the test is over. Remaining fuel is weighed; mass of water evaporated is measured for all of the three pots.

Notice that boiling point can be chosen instead of 80°C as the water temperature limit, according to the latest update of the protocol available from SeTAR [66]. Also, the power variation between low, medium and high is performed only in case such variation is practical.

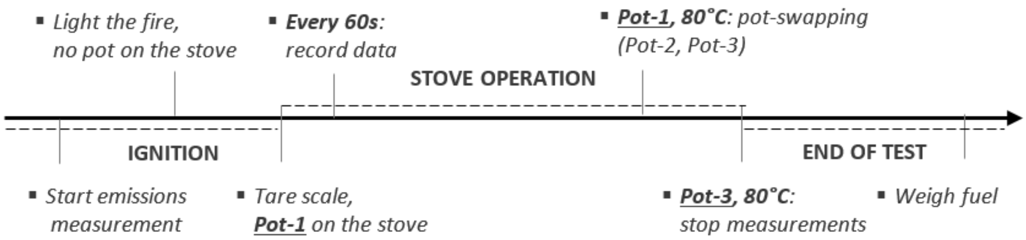

Figure 3.6.2 – Summary of HTP procedure.

3.6.3 Performance metrics

Performance metrics are missing in the available HTP document [66], and have been partially recovered from papers by Makonese and Pemberton-Pigott [76], [84]. All of HTP performance metrics are calculated separately for each power level (low, medium and high), keeping the same formulation.

3.6.3.1 Energy metrics

η – Thermal efficiency

In the 2012 paper from Makonese [84], the HTP thermal efficiency formulation was identical to WBT's. In more recent papers [57], [85], instead, it is referenced as the useful heat energy gained by a pot and its contents, divided by the energy originally available in the fuel consumed. Thus, heat gained by the pot material is included, and the energy content of the fuel is computed as net fuel consumed times LHV_{AR} (Lower Heating Value "as received", considering the energy needed to heat and evaporate moisture). We will thus refer to this latter formulation; notice that the final water temperature can be either 80°C or boiling temperature, depending on the tester's choice:

$$\eta = \frac{(m_{w,i} c_{p,w} + m_{pot+lid} c_{p,Al})(T_f - T_i) + m_{eva} h_{lv}}{f_c \cdot LHV_{AR}} \quad (3.6.1)$$

Where f_c = net fuel consumed [*kg*].

Others

In the already mentioned paper by Makonese et al. [76], *Specific fuel consumption [g/L]*, *Burn rate [g/min*] and *Firepower [W]* are calculated as well, but no explicit formulations are provided.

3.6.3.2 Emission metrics

Stove emissions are evaluated using the hood method (see *paragraph 3.1.3.2*) and by means of a continuous flue gases analyser (Testo® 350XL/454 is suggested, capable of measuring CO, NO_X, NO_2, H_2, H_2S, S, and O_2).

EF – Emission Factors

According to Makonese et al. [84], the HTP determines total emissions mass per standard task from the calculations of CO concentrations for each power level. In particular, the protocol uses a carbon balance method based on the real time fuel mass change reading. The metric formulation may reflect the WBT's, but no precise information are available.

3.6.4 Strengths & Weaknesses

The Heterogeneous Testing Procedure introduced a number of peculiarities and innovations in the world of ICS performance evaluation, testing the stove on three power levels and for different pot sizes, using a real time scale, and providing as a result a set of performance curves covering a range of cooking conditions.

The key idea that testing an ICS merely on high-power and simmering tasks cannot provide a complete assessment of the actual stove performance has been promoted by different studies [43], [68], and the HTP was one of the first attempts at addressing this issue. Unfortunately, the literature is missing case studies comparing HTP lab results with field performances, not allowing for a precise assessment of the effectiveness of the protocol. Possibly, this is because the SeTAR Centre, which developed the HTP, has subsequently moved towards a new protocol, evolved on the basis of the HTP but directly integrating actual burn cycles in lab testing, which will be presented and discussed in *section 3.7*.

The HTP also avoids all the problems and the ambiguities related to low power metrics discussed in *sub-section 3.1.4*, as it does not try to approximate any "simmering" phase, but rather reproduces the same heat transfer procedure for three power levels (high, medium and low). As affirmed by Zhang et al. [57], this should be the proper way to evaluate low-power parameters, as *low-power* and *simmering* are not synonyms.

Furthermore, even thermodynamic uncertainties due to temperature reading and vaporization at temperatures close to boiling point (see *sub-section 3.1.4*) are supposed to be reduced, by means of lid insulation and limited maximum temperature (80°C). Still, a detailed theoretical study of the specific impact of the mentioned thermodynamic phenomena on testing variability is missing, as well as an evaluation of possible changes in performance output between this procedure and a "boiling" procedure.

The main weakness of the protocol is in the lack of details of the officially published document [66], preventing its diffusion to other research centres than the SeTAR. In fact, although the procedure and the rationale being explained clearly, the document is missing important information about metrics definitions and calculations, which are a decisive part of a testing protocol. Some further information are available from papers from the same authors, as mentioned in *sub-section 3.6.3*, but they are still incomplete and moreover incoherent between each other as the protocol is continuously updated and developed.

Some other criticalities can be identified in the procedure and in the experimental set-up needed to perform the protocol. In fact, the HTP is the only protocol requiring a real-time weighing platform, adding complexity to the experimental set-up. Furthermore, the pot needs to be lifted every 60 seconds in order to read the fuel mass change; the impact of this practice on uncertainty should be better evaluated. Also, the chance to actually operate the stove at three different power levels, which can be reasonable, for example, in case of ethanol gel stoves [76], can be arguable when testing most common wood stoves, and criteria to identify power settings should be more precisely discussed.

Finally, the time needed to perform a complete testing cycle, *viz.* three times for each fuel/pot/stove combination (that is at least six times), is possibly high as compared to other protocols, regardless of statistical considerations.

Heterogeneous Testing Procedure	
Strengths	***Weaknesses***
▪ Provides a set of performance curves covering a range of cooking conditions ▪ Avoids simmering ambiguities, properly evaluating low-power parameters ▪ Tries to avoid thermodynamic uncertainties, using lid insulation and limited maximum temperature	▪ Lack of experimental validation of thermodynamic hypothesis ▪ Missing a complete, detailed and user-friendly document ▪ Complex procedure and experimental set-up ▪ Lack of experimental assessment of pot-lifting on uncertainty

Table 3.6.1 – Heterogeneous Testing Procedure, Strengths & Weaknesses.

3.7 Protocols under development

In recent years, new approaches to cookstove testing started being proposed as a response to the growing need for protocols capable of predicting average field performances [39], which was also formalised in one of the "Workshop Resolutions" of the 2012 ISO-IWA that reads:

> *"[…] research be conducted for high priority initiatives, such as coupling lab and field testing, improving indoor emissions protocols, climate change impacts, and developing a pool of resources for testing stoves*" [67].

The International Organization for Standardization (ISO) is in fact currently coordinating and leading different working groups on cookstove testing following this resolution. In particular, the ISO Technical Committee 285 on "Clean cookstoves and clean cooking solutions" is developing two new lab methodologies, trying to improve the reliability of protocols output and its translatability to field contexts [86]. They are currently defined as

a) General laboratory test sequence;

b) Contextual laboratory test sequence.

A short presentation about the progress of this work was included in the ETHOS Conference 2016 agenda – to which the author participated [87]. The "general" protocol is meant as a substitute for the WBT 4.2.3 and should therefore perform an evaluation of stove performances prior to any knowledge of the target user, but linear regression tools are under study to provide an idea of the average performance of the stove in different ambient conditions (*viz.* in the field) [88]. The "contextual" protocol, instead, is still a lab protocol but meant for testing in relationship to a specific context of use; it is conceived to translate the burn cycles that are representative of a target population into a lab test sequence.

The two protocols under development represent an attempt at formalising studies that came out in recent years, proposing alternative approaches to cookstove testing; in the present analysis, these studies will be referred to as Burn Cycle Test (**BCT**,

2010) [68] and Water Heating Test[1] (**WHT**, 2014) [83]. BCT and WHT were not directly included in the review because the former was never officially formalised and published as a protocol, rather remaining in the form of a "proposed approach"; the latter is still a work in progress and has never been officially released too. The following sections will be dedicated to a brief presentation of the two approaches.

3.7.1 The Burn Cycle Test

The BCT was proposed as a new approach to cookstove testing by Michael Johnson et al. in 2010. The main purpose of the methodology was addressing the gap between lab and field performances; the authors, in fact, motivated the urgent need for a different protocol affirming that:

> *"controlled burn cycles for specific tasks cannot encompass the variety of daily stove use activities, with up to 90% of stove tasks in some regions not involving boiling water. In addition, since efficiency varies significantly as a function of power output during the different phases of the burn cycle, a single efficiency is not a good performance indicator"* [28].

The idea of the BCT is that the critical issue is not about the cooking task being representative, but rather the burn cycle being representative of that which occurs during daily cooking activities in homes. Therefore, a meaningful protocol should test the stove over the same average daily burn cycle as the target household's. The authors, in fact, conducted experiments in the lab and in the field on different stove types (three-stone fire, brick Patsari, mud-cement Patsari) sampling emission profiles (CO, CO_2) and evaluating combustion efficiency by means of the $CO_2/(CO+CO_2)$ ratio as a proxy, as shown in *Figure 3.7.1*.

[1] The same procedure is also known as "Indonesian HTP", "Clean Stove Initiative-HTP" or "Clean Stove Initiative WBT" (GACC website); the form "Water Heating Test" (used in most recent documents [44]) has been preferred to avoid confusion with previous protocols.

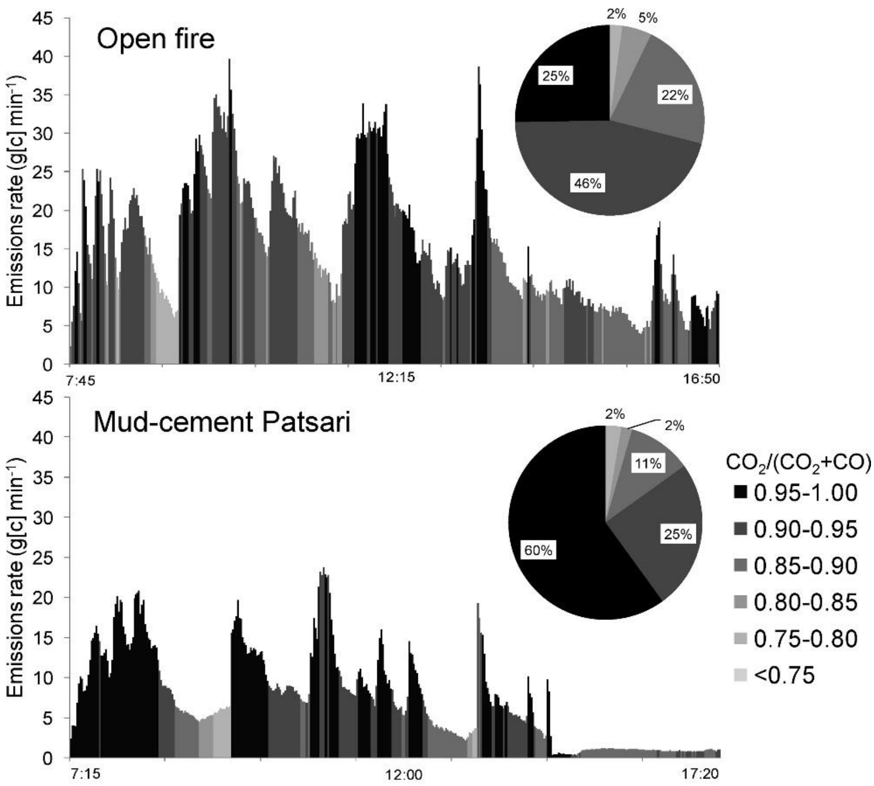

Figure 3.7.1 – Minute by minute emission rates and CO2/(CO2+CO) ratio for open fire and Mud-cement Patsari, adapted from Johnson et al. [68].

They proved how three-stone fire emission profiles produced during the WBT boiling and simmering phases overestimated combustion efficiency and emission rates as compared to normal daily stove use in homes. On the contrary, the WBT bias underestimated performances of the mud-cement Patsari stove, as shown in *Figure 3.7.2*. The bias went in opposite directions, confirming WBT adjustments are not possible between stove types.

Therefore, the Burn Cycle approach proposes to firstly derive the average daily burn cycle from 5 sample households in the field (which should allow for a statistically significant assessment) using "gas analysers" and $CO_2/(CO+CO_2)$ ratio as a proxy for combustion efficiency. Subsequently, using similar fuel type and moisture content as in the field, 1 kg of wood would be split into 5 or 6 equal parts (similarly to the BIS, *sub-section 3.2.2*) and used to feed the baseline stove (three stone fire or different) in order to reproduce the same distribution of emission rates and combustion efficiencies of the field burn cycle. Finally, any ICS would be tested over this lab burn cycle during the design phase.

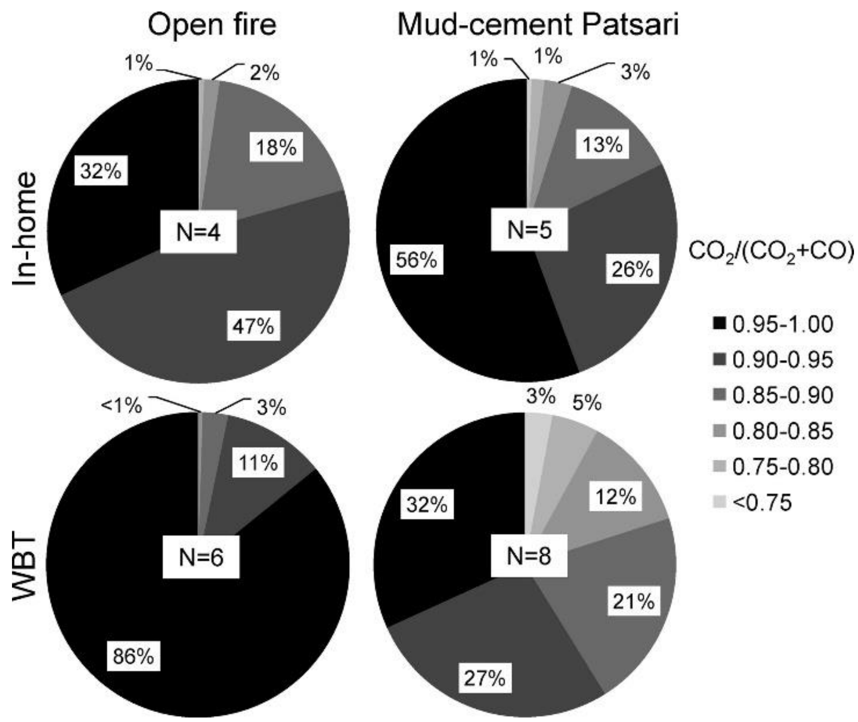

Figure 3.7.2 – Distribution of carbon emissions across combustion efficiencies during WBTs and normal stove use in homes

The Burn Cycle approach would allow for a clear linkage between the lab and the field, as stoves would be tested over the same representative burn cycle. Moreover, following the same concept of the HTP, stove performances would not be based on a single efficiency value, but rather on a distributional comparison of carbon emissions across combustion efficiencies. The authors suggest also that preliminary estimates of GHG emissions would be enabled through prediction models, as CO_2-equivalent emissions are linearly linked to combustion efficiency.

The ideas of testing the stove over a more representative burn cycle, and of using prediction models and linear regression to extend the meaningfulness of lab results, should be the main focus of the previously mentioned *ISO General lab test sequence*.

A further development of the BCT approach, called the "*Firepower Sweep Test*", was in fact presented at the 2016 ETHOS Conference [89], and should be the baseline reference for the ISO General test. The idea is no more to derive the representative burn cycle from the field but rather trying to define a generalised cycle which should encompass a more representative range of power settings than the WBT's, and subsequently extend results meaningfulness by means of prediction models. This is, however, still a work in progress; conclusions are postponed to its official publication.

3.7.2 The Water Heating Test

The Water Heating Test is a revised version of the HTP, which has not been officially formalised and published yet, but which has been already used as a performance evaluation tool in some large scale programs, the most relevant being the Indonesian Clean Stove initiative [44], started in 2012 and funded by the World Bank. C. Pemberton-Pigott, from the SeTAR Centre, was the main author of this new approach, and is currently collaborating with the ISO working group that should complete and formalise the protocol to turn it into the *ISO Contextual lab test sequence*.

The WHT purpose is "*to evaluate biomass fuel burning cooking appliances in a realistic manner such that their future performance in the hands of a given community is reasonably predicted*" [83]. The idea, similarly to the BCT, is to derive a contextual burn cycle that is representative of the average local cooking experience. In this case, the burn cycle is not derived from emission profiles in the field but rather from an evaluation by social scientist of two or more meals or cooking patterns that should be representative of all the different power levels required by a specific target population, *viz.* of the typical burn cycle. For each meal, cooking tests are conducted in the lab by local cooks using local fuels and pots. An example of the output is shown in *Figure 3.7.3*.

Cooking power	High	Medium	Low	High	Total
Minutes	19	30	None	10	59

Figure 3.7.3 – Example of a Cooking Test output for a selected local meal, adapted from Pemberton-Pigott [83].

Three replicates are needed for each selected meal; results represent the average. Subsequently, identical burn cycles as those of the selected meals are replicated by lab tests on the same stove and using the same pots but performing an ideal heat transfer procedure by means of pot-swapping, as done by the HTP. Those intermediate tests are called "Heat Flow Rate cooking tests" (HFR); if results, in terms of CO and PM emissions, match those from the previous Cooking Tests, the HFR tests are validated, and they can be combined in different proportions to reproduce the typical daily average burn cycle of that specific target user. This combined burn cycle finally becomes the relevant cycle over which ICSs will be tested; an example of the final output is shown in *Figure 3.7.4*.

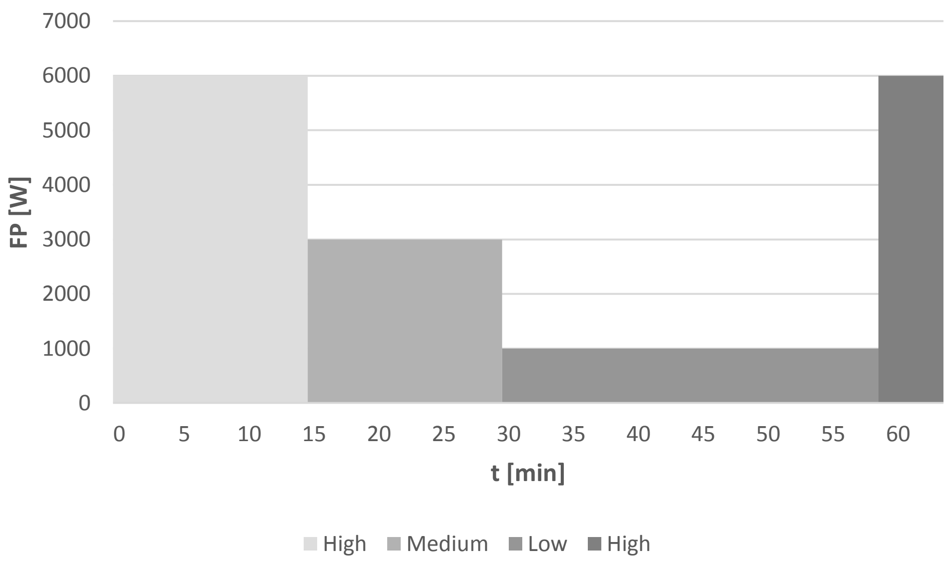

Figure 3.7.4 – Example of a burn cycle resulting from the combination of two cooking tests, adapted from Pemberton-Pigott [83]; high, medium and low represent firepower levels.

Therefore, the testing method reflects the HTP protocol and is kept identical in any case, since the authors affirm that the HTP procedure allows for a consistent reduction in variability as compared to the WBT. The burn cycle, instead, is directly derived from the local context. Once a relevant burn cycle has been derived for a target area and has been translated into a Technical Test, any manufacturer can reproduce it, and test in its lab any stove conceived for that specific area.

Although addressing the issue of the lab-field gap with a very promising approach, comments should be postponed to the publication of experimental evidences of the WHT effectiveness in providing a better assessment of stove performances as compared to WBT. Furthermore, experimental studies would be needed to clearly compare the HTP and WBT procedures in terms of scientific validity and reliability in order to validate the methodological choice of the WHT.

3.8 Discussion

The comparative analysis of all existing lab protocols realised in the previous sections was meant to provide a precise overview of each test, highlighting its purpose and procedural concept, as well as benefits and limitations. The literature is in fact missing a detailed and standardised comparison between all of them, as mentioned in the incipit to *Chapter 3*, and the primary purpose of this work was to provide a comprehensive outlook of protocols state of the art, thus allowing for a better-informed debate. Findings from this review allow drawing a number of conclusions about lab protocols usefulness and future prospects.

The first important outcome of this review work is the chance to demonstrate how none of these lab protocols is actually capable of predicting average field performances of a stove. Actually, this should not be a problem as almost all of them affirm their usefulness is limited to the design evaluation of a stove, and that they should not be intended as real performance indicators; nevertheless, as discussed in *Chapter 2*, this is contrary to what happens, and there is still a great misunderstanding about their role.

Performance rating, in fact, cannot be merely concerned with the stove, but is contingent on different factors, namely: stove design, fuel and moisture content, burn cycle and type of pots used [90] [44] [29]. All those factors together should be treated as an integrated thermal system [90] or "cooking system" [29], with the last three being strongly dependent on the local context.

The concept that relying on a fixed testing procedure it is possible to predict performances of a specific stove in any circumstance is totally misleading. To have a chance of predicting average field performances in the lab, all the factors characterising what was previously called the "cooking system" must be studied in relationship to the context of future use, and integrated into testing.

Instead, as emerging from the present analysis, most of current testing protocols are performed by fixing those factors (for the sake of repeatability and comparison of results between different laboratories), resulting in performance ratings that are only valid for that particular fixed fuel, fixed burn cycle and fixed pot, and that are untranslatable to field contexts. This is essentially the key reason why none of them can be a reliable predictor of average field performances, regardless of updates and corrections of errors in metrics or thermodynamics. As Johnson et al. [68] report: "*the critical issue [...] is not that the task or cooking activity is representative but that the burn cycle is representative of that which occurs during daily cooking activities in homes. The cooking activity itself does not matter*". Consequently, a stove that is highly rated by one of current lab test might be poorly performing under different circumstances, causing all the issues discussed in *section 2.2*.

There are only two tests partly trying to address this issue, namely AWBT and HTP: the former integrates fuel and pot types that are representative of the target area into a WBT, but still neglects actual burn cycles and relies on a prescribed and fixed one for any case. The latter tests the stove over different fuel/pot combinations and power levels, trying to provide a wider range of performance curves, but still cannot be a substitute for the reproduction of the real burn cycle of the target population, which shall be possibly composed of high, medium and low-power tasks in different proportions.

Therefore, if the purpose of the tester is indeed assessing average field performances of a stove in a specific local context, he should avoid any of the current lab testing protocols, rather looking at approaches under development considering the whole "cooking system" and reproducing it into the lab. Tiers of Performance based on WBT or similar protocols should not be viewed by stove implementers as a reliable technology selection tool.

At this point, as it has been clarified that current lab protocols should never be used as predictors of actual performances, one may guess if they can still be used to determine the effect of design alterations on performance or to identify the best stove designs, which is claimed as their main role and purpose.

Actually, assuming that stove performances are inherent to the design and thus that stove designs can be properly compared fixing all other factors composing the "cooking system", is also incorrect. For example, as proven by Bhattacharya et al. [79], CO emissions are strongly influenced by fuel moisture content; therefore, testing one stove design for a fixed moisture content may result in a certain performance, which however will not be representative of the stove performance for a higher or lower moisture content.

To avoid such problems, some protocols, as the WBT itself, suggest to use typical local fuel for testing; nevertheless, they still will put the stove design on a "Performance Tier" as if the results were inherent to that particular design and not depending on the fuel, the pot and the burn cycle, leading to misinterpretations and failures in technology selection. A large part of tests published on the GACC Clean Cooking Catalog [91] are in fact missing wood type and moisture content details, yet Tiers ratings are evaluated in any case. The key concept to be highlighted is that no design assessment can be considered as generally valid, since stoves do not have intrinsic performance characteristics, but are rather dependent on local circumstances, particularly as regards fuel consumption and emissions [68]. "*There cannot be a single universally efficient cooking stove*" [90]; a reliable design assessment should be able to capture stove performances over a broader range of conditions.

Therefore, the findings from this study can be reassumed saying that testing performed without accounting for all the factors affecting the "cooking system"

1) carries little information about actual average field performances;
2) might provide misleading guidance about stove designs.

This means that a possible solution towards better testing might be identifying a validated testing protocol, in terms of metrics and thermodynamic hypothesis, and performing it with a user-centred approach, that is with the fuel, the pot and the burn cycle that are relevant to the final users.

In fact, it is also very important to assess the validity of a testing protocol independently of the burn cycle employed, since a defective protocol would still provide unreliable results, even if performed under a locally relevant burn cycle [77]. Therefore, to have a reliable prediction of average stove performances, it is necessary both to identify a valid testing protocol and to perform it with the burn cycle, fuel and pot that are representative of the target population's.

The translatability of burn cycles into lab protocols appears to be more complicated when the protocol is already based on an approximation of real cooking tasks, and thus on a fixed burn cycle, as occurs with WBT, EPTP, AWBT and Chinese Standard. Furthermore, as diffusely discussed in *sub-section 3.1.4*, all protocols involving the heating of water up to temperatures close to boiling seem to be characterised by a larger variability due to thermodynamic phenomena (heat transfer under boiling regime, large amount of vaporisation). Consequently, the best matching procedure for an integration with different burn cycles might be an ideal heat transfer procedure with limited maximum temperature and reduced vaporisation, which is similar to the HTP's.

Still, further studies would be needed to better identify the optimal temperature to limit the impact of thermodynamic uncertainties, as the present review showed how different protocols alternatively set it at 70°C, 80°C or 90°C. Also, an independent experimental study would be needed to validate the results from L'Orange et al. [78], assessing that the combined use of insulation and limited temperature can effectively reduce variability due to thermodynamic phenomena. As shown in *section 3.7*, current attempts at coupling real burn cycles and lab testing are based on procedures performing an ideal heat transfer between the stove and the pot, with a limited maximum temperature and insulation; those experimental studies would serve therefore also as a validation of the hypothesis on which those new approaches are based.

4 Theoretical and experimental study for better testing

The previous chapter provided a comprehensive outlook of all current lab testing protocols, highlighting their main criticalities and identifying the key features that are needed for a better testing approach. In particular, considering the whole "cooking system" and testing it under a scientifically validated procedure has been identified as the most promising solution. Approaches under development trying to move towards this direction were also presented, although experimental evidences of their effectiveness both in providing more representative results and in being less variable than traditional tests are still needed. The present chapter will address the latter issue, and will be thus dedicated to a deeper analysis of the heat and mass transfer principles concerning the heating of a cooking pot filled with water, in order to precisely quantify the impact of different conceptual choices of protocols on results repeatability. The study will be supported by the implementation of an analytical heat and mass transfer model, which will be used to perform a sensitivity analysis on selected parameters. Model results consistency will be subsequently tested against experimental evidence, with the ultimate aim of clearly defining the key features to be met by any future testing protocol in order to be considered reliable and scientifically validated.

A further development of the model is proposed as a tool to simulate and virtually compare results of different lab testing protocols for the same ICS, as well as to predict performances under different conditions. Firstly, the model is extended to simulate a WBT on a commercial stove (Envirofit Econofire), and results are tested against experimental data. Secondly, the model is adapted to simulate an EPTP on the same stove, and virtual outputs are compared to those from the Clean Cooking Catalog, with promising results. Potentially, this analytical tool could be developed in order to simulate any kind of procedure, task or conditions, as well as to optimise protocols under development and to compare them with existing protocols, allowing for a better procedure design. All tests were performed at Politecnico di Milano, Department of Energy, Bovisa Campus.

4.1 Research framework

The issue of reducing variability between test replicates, as emerged also from *Chapter 3* review, is one of the main research topics in the world of ICS performance evaluation, and different attempts at addressing the problem have led to the development of alternative protocols (*e.g.* EPTP, HTP). The common idea of those attempts is that results repeatability could be effectively improved by reducing two specific thermodynamic sources of uncertainty: temperature reading in the boiling region and vaporisation. Both EPTP and HTP, in fact, fix a temperature limit for the testing procedure and try to limit vaporisation by means of closed-cell foam or a lid, respectively.

L'Orange et al. [78], among the authors of the EPTP, argued that limiting the maximum temperature is important to avoid uncertainties due to changes in the boiling point with location and water purity, as shown in *Figure 4.1.1*. Assuming a constant energy input, the trend of water temperature before the boiling region would be almost linear, and would ideally progress as represented by the dashed line. The real profile, instead, tends to flatten as the evaporation becomes more and more relevant, wasting a greater fraction of energy and requiring a longer time to increase the temperature. As shown in *Figure 4.1.2*, the result of this trend is that an uncertainty of 1°C in the boiling point can lead to a relevant uncertainty in test duration. Moreover, even assuming all replicates are performed in the same lab, with the same conditions and water purity – *viz.* the boiling point does not change – the trend shown by L'Orange et al. is still relevant. In fact, lab experience showed how the appearance of boiling turbulent phenomena in the water volume also leads to fluctuations in the thermocouple reading, determining an uncertain identification of the desired value and experimental errors.

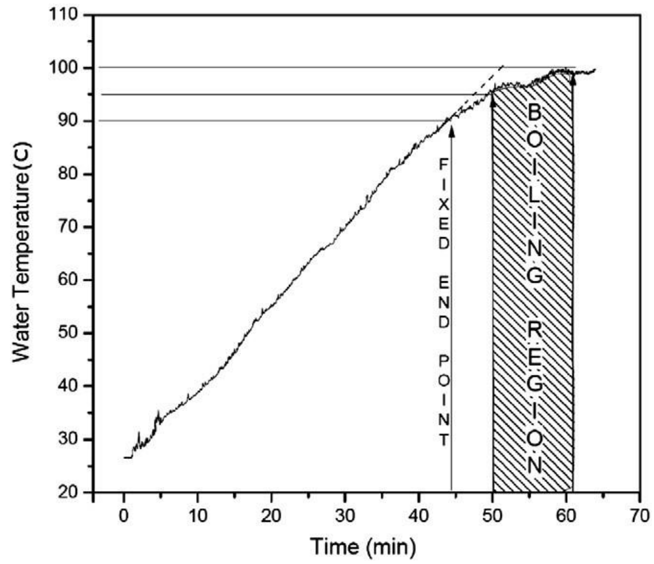

Figure 4.1.1 – Ambiguity of the boiling point for different locations and conditions; source: L'Orange et al. [78].

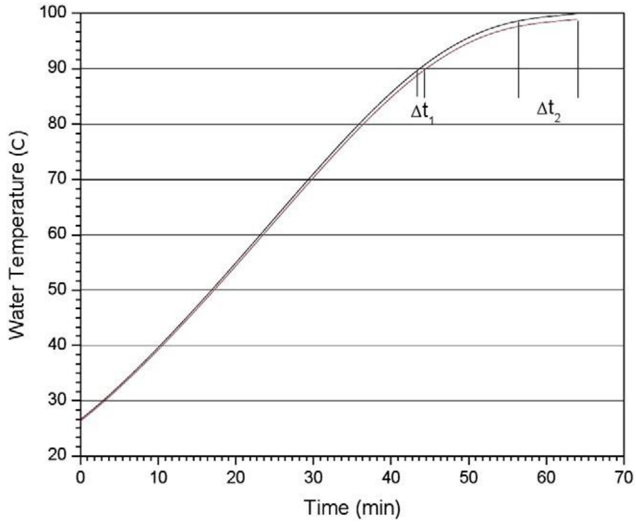

Figure 4.1.2 – Uncertainty in test duration due to slight variations of the boiling point; source: L'Orange et al. [78].

The second source of uncertainty considered by L'Orange et al. is evaporation, which in their case was limited by means of a closed-cell foam insulation layer floating on the liquid surface. They performed an experiment showing that foam insulation combined with a limited temperature of 90°C can result in an effective reduction of the coefficient of variation between test replicates for both time and mass of water vaporised. The experiment, however, cannot be considered a sufficient empirical evidence of the improved repeatability, as based only on three replicates; moreover, it does not allow to separately identify the relative impact of vaporisation and temperature on the reduced variability of the test. This is due to the lack of a theoretical analysis of the evaporation phenomenon and of the reasons why it should be affected by variability in a controlled laboratory setting. The HTP also promotes the combination of a fixed temperature (70°C) and a lid (to control vaporisation) as a proper solution for a repeatable and reliable procedure, without providing a theoretical discussion of the problem.

Therefore, following a scientific approach, the next sections will be firstly dedicated to an accurate theoretical analysis of the problem and to the implementation of an analytical model describing the evaporation phenomenon and its role in a generalised heat and mass transfer model, referred to a cooking pot subject to a constant power input. The model will be used to perform simulations of different conditions and a sensitivity analysis, drawing theoretical conclusions about thermodynamic sources of variability and their impact on typical performances parameters (η, SC). Secondly, following the principle of falsifiability [92], simulated results will be tested against experimental data to check their consistency.

4.2 Model of heat and mass transfer

The theoretical analysis is firstly dedicated to the study of water evaporation in ambient air, with the aim of describing the rate of vaporisation as a function of water temperature and ambient conditions. Several approaches are presented and subsequently optimised by means of a comparison with empirical observations. Secondly, the study is extended to a generalised heat and mass transfer model, allowing for any sensitivity analysis or simulation of different conditions.

4.2.1 Restricted model of water evaporation

The evaporation process is due to mass diffusion of water molecules into the air above the liquid surface. Mass transfer is driven by concentration gradients and occurs even at ambient temperature, but it is also dependent on the temperature of the evaporating liquid surface; the kinetic energy of water molecules, in fact, increases with temperature and so their chances to diffuse away from the surface. Furthermore, in the case of water diffusing into ambient air, interactions between the two mediums (advection, free convection) should be considered.

Different theoretical approaches are thus possible, depending on the accepted degree of approximation. A simple sketch of the physical problem is provided in *Figure 4.2.1*.

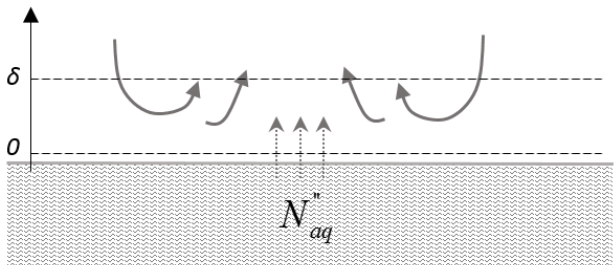

Figure 4.2.1 – Sketch of the mass concentration boundary layer as a stagnant film. The subscript "aq" indicates water.

The general formulation for the absolute molar flux per unit area of a species A into a binary mixture of A and B is:

$$N_A'' = -CD_{AB}\nabla x_A + x_A(N_A'' + N_B'') \quad [\frac{kmol}{s \cdot m^2}] \qquad (4.2.1)$$

Where: C = total concentration of the mixture [$kmol/m^3$];

D_{AB} = mass diffusivity of species A into B [m^2/s];

x_A = molar fraction of species A.

In the case considered, A would represent water and B the ambient air. This formulation includes both a diffusive component (the first term, derived from Fick's Law) and an advective component associated with bulk motion [93].

4.2.1.1 The diffusive-only approach

The simplest description of the evaporation process is obtained considering only diffusive mass transfer and neglecting the second term. The assumption is valid only when the velocity of bulk motion is relatively low, or more generally when the diffusing species is dilute ($x_A << 1$) [94]. *Equation (4.2.1)* becomes:

$$N_A'' = -CD_{AB}\nabla x_A \quad [\frac{kmol}{s \cdot m^2}] \qquad (4.2.2)$$

And the molar evaporation rate is:

$$\dot{n}_{vap} = -D_{aq,air} A \frac{(C_{aq,\infty} - C_{aq,0})}{\delta} \quad [kmol/s] \qquad (4.2.3)$$

Where: A = evaporating surface [m^2];

$C_{aq,\infty}$ = water concentration in the ambient air [$kmol/m^3$];

$C_{aq,0}$ = water concentration above the evaporating surface [$kmol/m^3$];

δ = length of the diffusion boundary layer [m].

Considering that $C_{aq,0}$ can be assumed equal to the concentration of the saturated vapour ($C_{aq,sat}$), since equilibrium exists between the vapour and the liquid phases at the liquid interface[1], and that $\frac{C_{aq,\infty}}{C_{aq,sat}} = \frac{p_{aq}}{p_{aq,sat}} \equiv \phi_{\infty}$ [2] (relative humidity of ambient air), the equation can be reformulated as:

$$\dot{n}_{vap} = D_{aq,air} A C_{aq,0} \frac{(1-\phi_{\infty})}{L} \quad [kmol/s] \qquad (4.2.4)$$

Or, on a mass basis:

$$\dot{m}_{vap} = D_{aq,air} A \rho_g \frac{(1-\phi_{\infty})}{L} \quad [kg/s] \qquad (4.2.5)$$

Where ρ_g = saturated vapour density [kg/m^3].

Unfortunately, the assumptions required for this model become less and less realistic as the temperature increases; above 50-60°C results starts to differ significantly from a more accurate approach considering also advective mass transfer [95].

4.2.1.2 The Stefan tube approach

To increase the accuracy of the model, both diffusion and bulk motion must be included. In the case considered, water cannot accumulate in the control volume and diffuses upwards. Air, instead, diffuses downwards but cannot be absorbed into the liquid; therefore, a steady-state condition can be maintained only if the molar flux of air is equal to zero everywhere in the control volume ($N''_B = 0$), which is possible if the downward diffusion of air is exactly counterbalanced by an upward advection. Accordingly, the second term of *Equation (4.2.1)* must be included in the model to obtain an accurate prediction of the evaporation rate.

[1] From Raoult's law [93], $p_A(0) = x_A(0)\, p_{A,sat}$, with $x_A(0)=1$.

[2] As $C_A \overset{(I.G.)}{=} \frac{p_A}{RT}$, assuming ideal gas law [93].

Considering that $N''_B = 0$, the equation becomes:

$$N''_A = -CD_{AB}\nabla x_A + x_A N''_A \quad [\frac{kmol}{s \cdot m^2}] \qquad (4.2.6)$$

And the molar evaporation rate is:

$$\boxed{\dot{n}_{vap} = \frac{D_{aq,air} AC}{\delta} \ln\left(\frac{1 - x_{aq,\delta}}{1 - x_{aq,0}}\right) \quad [kmol/s]} \qquad (4.2.7)$$

Where: $x_{aq,0}$ = molar fraction of water at the interface;

$x_{aq,\delta}$ = molar fraction of water outside the boundary layer;

C = total concentration of the mixture [$kmol/m^3$].

This approach is often referred to as the "evaporation column" or "Stefan tube", because it is traditionally represented, as in *Figure 4.2.2*, as a long vertical tube whose walls isolate the control volume from a gas flow on the top. In this configuration, the control volume can be easily identified with a one-dimensional diffusion boundary layer without external interactions, and the external flow guarantees ambient vapour concentration outside the tube. The length of the boundary layer is therefore identical to the height of the tube above the liquid surface.

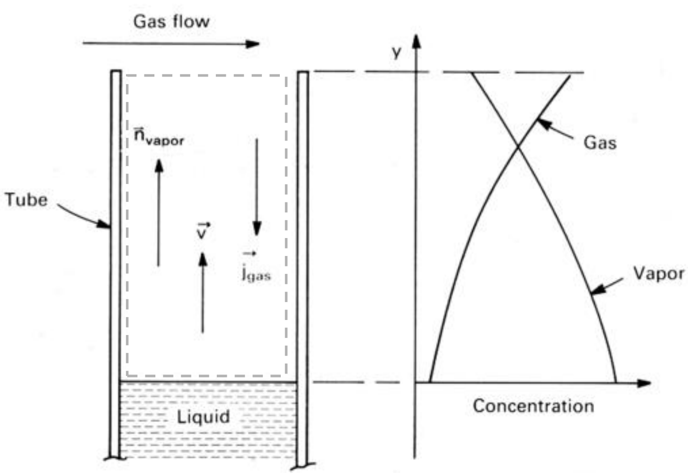

Figure 4.2.2 – The Stefan tube model; source: Lienhard et al. [94].

The same boundary conditions discussed for *Equation (4.2.3)* are valid in this case; the evaporation rate is therefore still dependent on the ambient relative humidity, since:

$$\frac{p_{aq}}{p_{aq,sat}} = \frac{C_{aq,\infty}}{C_{aq,sat}} = \frac{x_{aq,\delta}}{x_{aq,0}} \equiv \phi_{\infty} \qquad (4.2.8)$$

However, as regards the problem of an evaporating pot of water, the walls are not able to effectively isolate the control volume from free convection effects that remove vapour molecules just above the liquid surface, nor from other flows, since their height is relatively small in relationship to the pot diameter. The boundary layer, therefore, shall be realistically much smaller than the height of the walls and shall be represented as a thin stagnant film across which mass diffusion and vertical advective transport occurs, as in *Figure 4.2.1*. The exact value of this length (δ) is unknown, but it seems reasonable to assume that it shall be in the range of a few millimetres. Also, this value is expected to change during the evaporation process, as convective motion increases with temperature, thus reducing the thickness of the "stagnant film" boundary layer.

Though more accurate, this configuration is still dependent on the thickness of δ, whose hypothesised order of magnitude should be somehow verified. To do so, the Stefan model will be compared to a different approach based on the Lewis analogy between heat and mass transfer, which is not dependent on the value of δ.

4.2.1.3 The Lewis analogy approach

The Lewis analogy between heat and mass transfer allows to describe the absolute molar flux of a species *A* diffusing into a binary mixture of *A* and *B* in the same form of a convective heat flux [93]:

$$N''_{aq} = h^*_m (C_{aq,0} - C_{aq,\infty}) \quad [kmol/m^2 s] \qquad (4.2.9)$$

The mass transfer coefficient h_m^* [m/s], can be derived from the convective heat transfer coefficient h:

$$\frac{h}{h_m^*} = \frac{k_{air}}{D_{aq-air}} Le^{-1/3} \tag{4.2.10}$$

Where: k_{air} = air conductivity [$W/m{\cdot}K$], evaluated at T_{film};

T_{film} = $\frac{T_{surface}+T_\infty}{2}$ [K];

$T\infty$ = temperature of the surroundings [K];

Le = α / D ;

α = thermal diffusivity [m^2/s], evaluated at T_{film}.

In the case analysed, the convective heat transfer coefficient is relative to free convection phenomena above the hot liquid surface, and can be derived from experimental correlations for hot plates facing upward (laminar flow) [96]:

$$\overline{Nu_L} = 0,54 \cdot Ra_L^{1/4}, \qquad (10^4 < Ra_L < 10^7, \Pr \geq 0,7) \tag{4.2.11}$$

Where: L_c = characteristic length, defined as A_s/P [m];

Ra_L = Rayleigh number, defined as follows

$$Ra_L = \frac{g\beta(T_{surface} - T_\infty)L^3}{\nu\alpha} \tag{4.2.12}$$

β = $1/T_{film}$ [K^{-1}];

ν = fluid kinematic viscosity [m^2/s], evaluated at T_{film};

And

$$h = \frac{\overline{Nu_L} \cdot k_{air}}{L_c} \quad [W/m^2K] \tag{4.2.13}$$

Notice that such correlation is rigorously valid for a hot "plate" facing upward; the liquid surface can be treated as a rigid plate as long as the liquid motion is negligible, *viz.* before boiling activity starts to generate waves on the surface.

Furthermore, the simple formulation for the absolute molar flux shown in *Equation (4.2.9)* is valid only for low-rate mass transfer, which means that the velocity field is mostly unaffected by the mass flow. As seen for the diffusive-only approach, this conditions is less realistic as the temperature increases, and a more sophisticated approach is needed.

Considering both diffusion and advection, as for the Stefan tube approach, the absolute molar flux can be expressed again in the form:

$$N_A^{"} = -CD_{AB}\nabla x_A + x_A N_A^{"} \quad [\frac{kmol}{s \cdot m^2}] \qquad (4.2.14)$$

In this case, the first term (representing diffusive-only mass transfer), shall be equal to the absolute molar flux derived from the Lewis analogy in the same conditions (low-rates mass transfer); therefore:

$$N_{aq}^{"} = h_m(C_{aq,0} - C_{aq,\infty}) + x_{aq}N_{aq}^{"} = h_m C(x_{aq,0} - x_{aq,\delta}) + x_{aq}N_{aq}^{"} \qquad (4.2.15)$$

Where h_m represent the mass transfer coefficient under the new assumptions, which is different from h_m^*. Hence:

$$N_{aq}^{"} = h_m C\left(\frac{x_{aq,0} - x_{aq,\delta}}{1 - x_{aq,0}}\right)$$

(4.2.16)

The term in brackets is called the *mass transfer driving force* [94], B_m:

$$B_m = \left(\frac{x_{aq,0} - x_{aq,\delta}}{1 - x_{aq,0}}\right) \qquad (4.2.17)$$

The absolute molar flux is thus:

$$N_{aq}^{"} = h_m C \cdot B_m \quad [kmol/m^2 s] \qquad (4.2.18)$$

For $B_m \leq 0{,}2$ the problem can be treated as a low-rates mass transfer problem [94], using *Equation (4.2.9)*. Otherwise, this latter formulation should be preferred. Moreover, since in this case the transferred species affects the velocity field, the mass transfer coefficient is different from the value originally obtained from the analogy (h_m^*) and must be calculated. Firstly, the mass transfer coefficient for low-rates must be redefined as:

$$h_m^* = \lim_{N_A^* \to 0} h_m \tag{4.2.19}$$

Subsequently, the corrected value is obtained from the equivalence between the Stefan approach and the latter formulation of the Lewis approach, which are based on analogous assumptions. In fact:

$$B_m + 1 = \left(\frac{1 - x_{aq,\delta}}{1 - x_{aq,0}} \right) \tag{4.2.20}$$

$$N_{aq}^{"} = \frac{D_{aq,air}\, C}{\delta} \ln \left(\frac{1 - x_{aq,\delta}}{1 - x_{aq,0}} \right) = \frac{D_{aq,air}\, C}{\delta} \ln \left(B_m + 1 \right) \tag{4.2.21}$$

Equating *(4.2.21)* with *(4.2.18)*, and solving for h_m:

$$h_m = \frac{D_{aq,air}}{\delta} \cdot \frac{\ln(B_m + 1)}{B_m} \tag{4.2.22}$$

And

$$h_m^* = \lim_{N_A^* \to 0} h_m = \lim_{B_m \to 0} h_m = \frac{D_{aq-air}}{\delta} \tag{4.2.23}$$

Hence,

$$\boxed{h_m = h_m^* \cdot \frac{\ln(B_m + 1)}{B_m}} \tag{4.2.24}$$

This means that the value of h_m shall be corrected as a function of the group [*ln(B+1)/B*] that is called the *blowing factor* and accounts for the effect of mass transfer on the velocity field. For example, for B_m = 0,2 (the limit condition identified for low-rates mass transfer) the blowing factor is 0,91, or else an error of only 9% would be introduced assuming low-rates. Therefore, considering the blowing factor correction also for low-rates is not an error, on the contrary is a more accurate approach, although results should not differ very much.
Notice also that *Equation (4.2.23)* provides a relationship for the boundary layer thickness δ as a function of the mass diffusivity and the mass transfer coefficient, both increasing with surface temperature.

The evaporation rate on a mass basis for the Lewis approach can be therefore expressed as:

$$\dot{m}_{eva} = \rho A h_m B_m \quad [kg/s] \tag{4.2.25}$$

4.2.1.4 Optimisation

The Stefan model and the Lewis model can be compared under similar ambient conditions, for the range of water temperatures that can be assumed not to compromise the assumptions of the two models (20-90°C). In the lower temperature range (up to 65°C) low-rates mass transfer can be assumed ($B_m < 0,2$); the two approaches should therefore provide very similar results if the hypothesised value of δ is correct.
The comparison in terms of evaporation rate is performed assuming that for every temperature interval of 10°C the average evaporation rate corresponds to the evaporation rate calculated for the average temperature of the interval. For example, the average evaporation rate between 30 and 40 °C is calculated assuming properties at 35°C. As this first comparison is merely on a theoretical basis, ambient temperature, relative humidity and pot diameter could be set at will; however, realistic

indoor lab conditions (18°C , RH 30%), and a small pot (20 cm diameter) are chosen. Results are shown in *Figure 4.2.3*, using a first attempt value of δ of 5 mm.

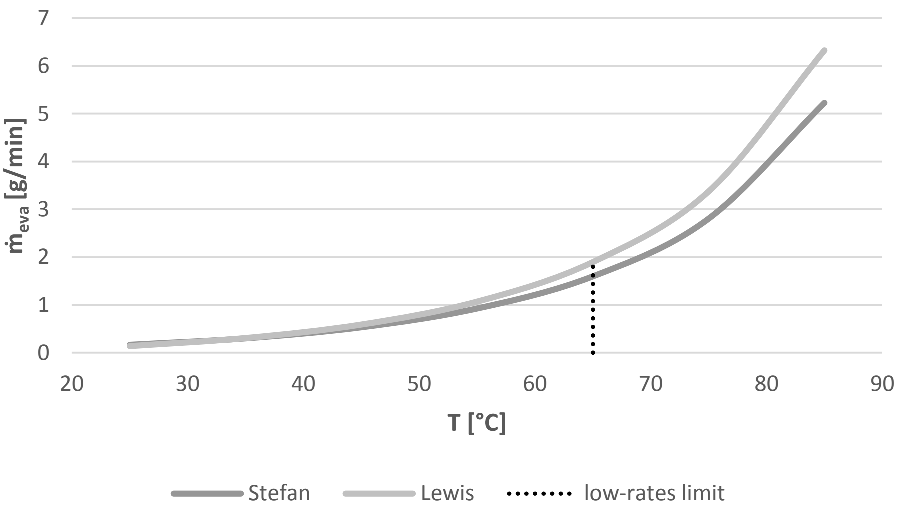

Figure 4.2.3 – Evaporation rates comparison for Stefan and Lewis models, at different temperatures.

In the low-rates region, the evaporation rates for the two models are almost identical, slightly diverging as the limit is approached. For higher temperatures, where advective phenomena become more important, the divergence increases. This proves that the estimated order of magnitude for δ is definitely correct, and that the first attempt value of 5 mm is well matching the Lewis model in the low-rates region. Then, as expected, the increased effects of free convection possibly cause a thinning of the boundary layer, and the assumed value of 5 mm results in an overestimation. The real-time value of δ can be actually calculated comparing the two models by means of *Equation (4.2.23)*, obtaining the values shown in *Figure 4.2.4* as a function of temperature. As expected, an average value of 5 mm is perfect for the low-rates range, but is slightly overestimated for the higher temperature range. A "real-time Stefan model", with boundary layer thickness varying with temperature, can be now compared to the Lewis model. Results are shown in *Figure 4.2.5*.

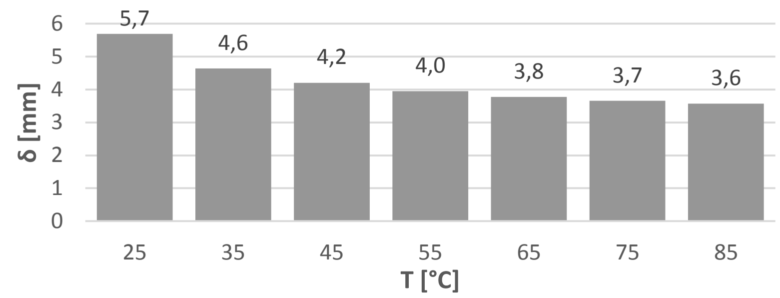

Figure 4.2.4 – Mass transfer boundary layer thickness at various temperatures.

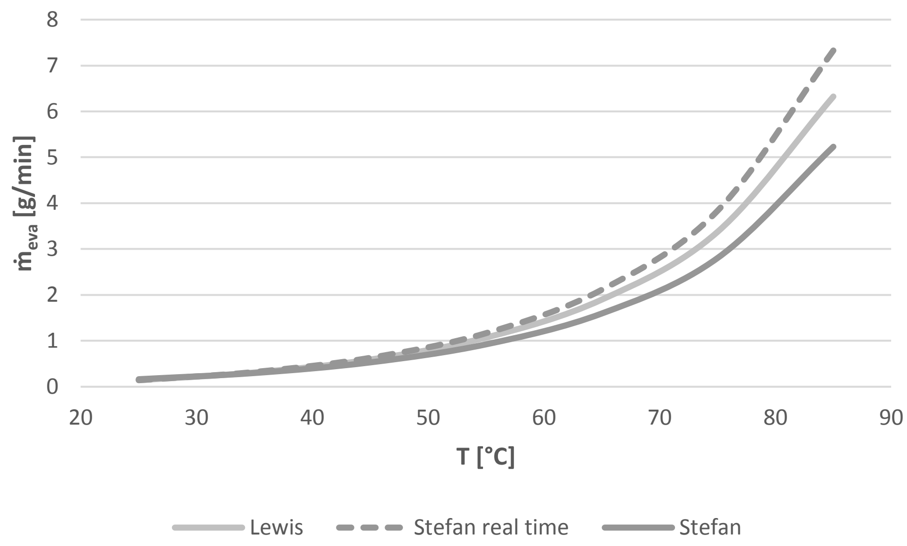

Figure 4.2.5 – Evaporation rates comparison for Lewis, Stefan and real-time Stefan models, at different temperatures

The real-time Stefan model is now slightly overestimating the rate of vaporisation, as compared to the Lewis model. Both models present a certain degree of approximation. In particular, the Lewis model is based on empirical correlations for free convection that cannot guarantee exact solutions and that are rigorously valid only for a rigid plate. The Stefan model, instead, is dependent on the parameter δ, which can be either derived from *Equation (4.2.23)* (introducing again the same empirical correlations) or arbitrarily optimised. To identify the most reliable model, theoretical results are compared with empirical observations[3]. Experiments were performed under the same conditions assumed for the theoretical analysis, namely 18°C ambient temperature, small pot (stainless steel, 20 cm diameter) filled with 2 litres of water. The pot with water was heated by means of an electric heater and the initial and final masses of water were measured by means of a digital scale, providing the mass of water vaporised at different temperatures (70, 80, 90 °C); for each temperature 5 replicates were performed and results were averaged. The time was instead recorded for every 10°C temperature interval. Therefore, the comparison is performed between the actual amount of water vaporised at different temperatures and the amount of water vaporised according to the two models reproducing the same time intervals. In the absence of a precision hygrometer, the relative humidity of the lab was analytically derived matching empirical observations with theoretical models in the low-rates range (up to 65°C) where both are supposed to be rigorously valid. Results for the whole range of temperatures are presented in *Figure 4.2.6*. Both models are within the range of experimental data standard deviation up to 80°C; however, the Stefan model appears to be slightly more precise at 80°C, when the Lewis model risks exceeding the lower limit of the experimental range. In the highest temperature range (90°C), however, the real-time Stefan model results in a clear overestimation of the water mass vaporised. It seems reasonable to suppose that the decrease of the boundary layer thickness, assessed as a function of the mass transfer coefficient without accounting for the blowing factor, might have been overestimated. Therefore, even if the Lewis model proved being quite satisfying, an improved solution could be a compromise between the two models, *viz.* a modified Stefan model with a lowered parameter δ, in order to better match the empirical observations. Results are shown in *Figure 4.2.7*, for an optimised average boundary layer thickness of 4 mm.

[3] For a complete description of the experimental set-up, reference is made to *sub-section 4.3.2*

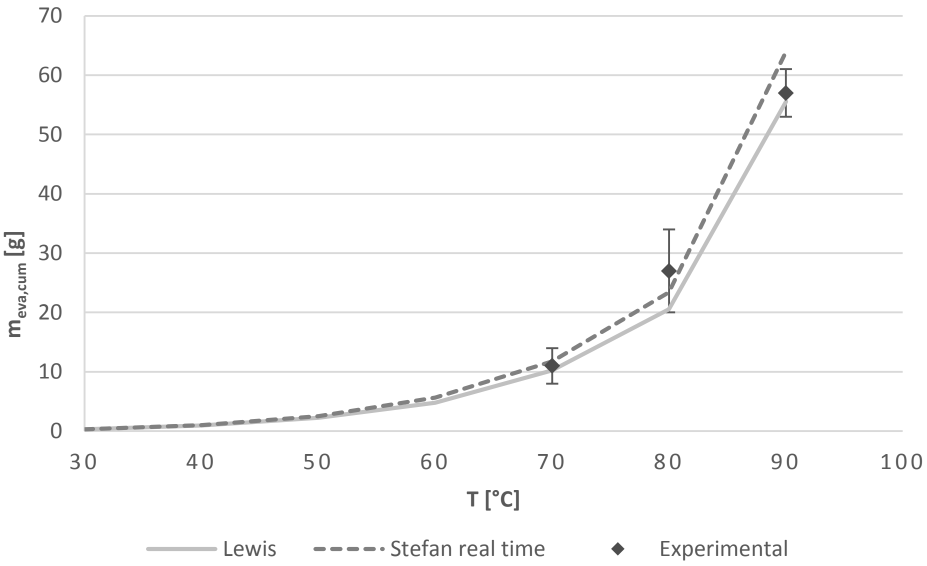

Figure 4.2.6 – Cumulative mass of water vaporised at different temperatures for Lewis and real-time Stefan models and for experimental data; bars represent standard deviation.

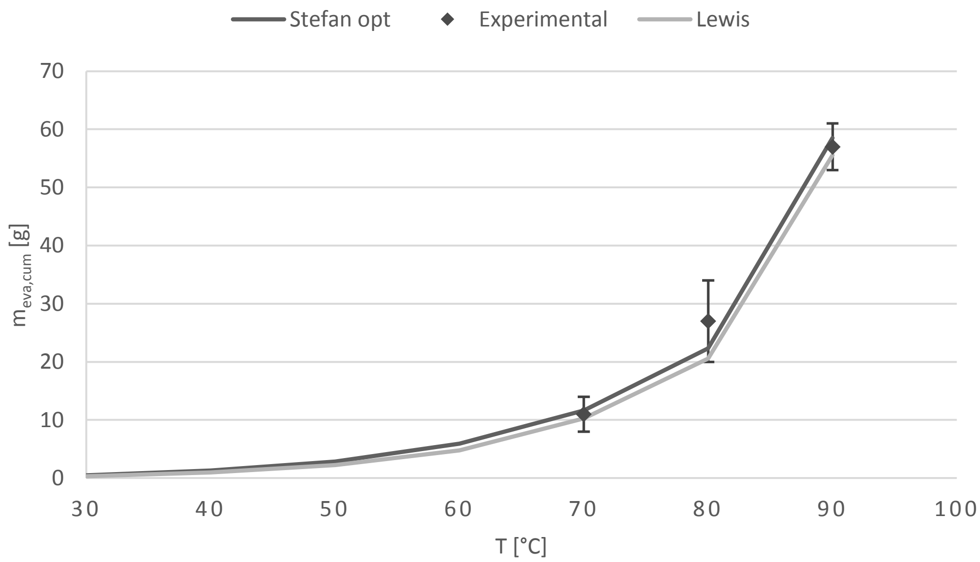

Figure 4.2.7 - Cumulative mass of water vaporised at different temperatures for Lewis and modified Stefan models and for experimental data; bars represent standard deviation.

The modified Stefan model works properly for every temperature in the considered range, and results in an overall better approximation of the experimental curve than the Lewis model. Also, the analogy with the Lewis model in the low-rates region is still largely satisfied. This optimised Stefan model, represented by *Equation (4.2.7)* with δ = 4 mm, will be therefore the reference model for the next steps.

Before passing to the analysis of the generalised heat and mass transfer model, it is important to highlight the variables – besides the temperature of water – that can affect the rate of evaporation in a controlled laboratory setting, since the evaporation phenomenon is often referred to as "variable" but sources of variability are rarely identified. Such variables are the surface area of the liquid container, A (proportional to the pot diameter), and the relative humidity of ambient air, affecting x_δ. Ambient temperature does not directly influence any of the parameters in the Stefan tube equation. Its impact could be evaluated under the Lewis model, which is indirectly influenced by ambient temperature for the determination of T_{film}, yet sensitivity analysis for typical indoor temperature ranges (18÷26°C) showed irrelevant variations in the rate of evaporation ($err_{\%}$ < 1%). Therefore, assuming that a set of replicates is performed with the same pot over several days, indoor relative humidity is the only parameter that cannot be assumed as constant and that does affect the evaporation rate. In fact, even in a controlled indoor ambient, air humidity is likely to vary in a range of 30÷60% [97] depending on outdoor conditions and season. Variations shall be therefore assumed from day to day and moreover from lab to lab, affecting the rate of vaporisation, as shown in *Figure 4.2.8*. The impact of this variability on the overall testing output, nevertheless, must be assessed in relationship to the relative importance of the heat removed by evaporation as compared to the total useful heat entering the pot. At low temperatures, the relative impact is expected to be largely negligible, but rapidly increasing as the higher temperature region is approached. The following sub-section will allow to implement the vaporisation model into a generalised heat and mass transfer model of the cooking pot, which will be the reference for the sensitivity analysis in *section 4.3*.

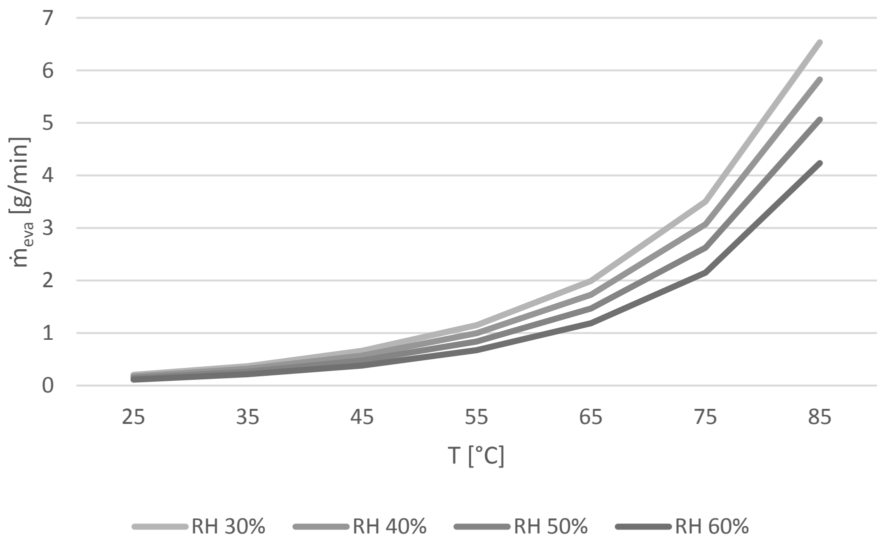

Figure 4.2.8 – Rate of evaporation as a function of water temperature for different values of indoor relative humidity.

4.2.2 Generalised heat transfer model

The theoretical analysis is extended to a comprehensive model of heat and mass transfer of a cooking pot filled with water, heated by means of a constant heat source. The energy coming from the heat source is mostly converted into internal energy of water and pot materials, increasing their temperature, but other fractions of the energy input are lost through evaporation, convection and radiative heat transfer, as shown in *Figure 4.2.9*. As the temperature of water and pot materials increase, heat released to the surroundings becomes more and more relevant. As done for the evaporation model, temperature intervals of 10°C are considered; fluid properties are evaluated at the average temperature of any interval and assumed to be constant for that ΔT. If the thermal input is known, a power balance can be formulated for any interval and solved for the time needed to realize that ΔT.

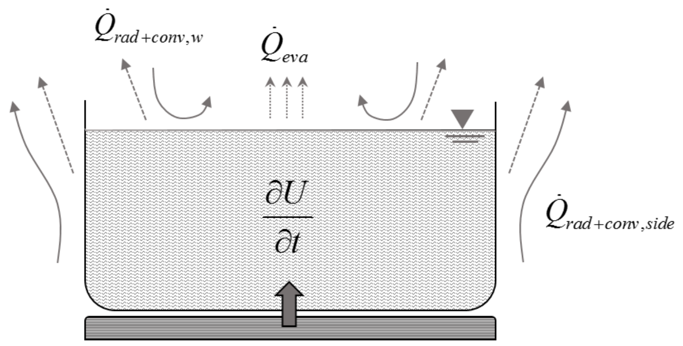

Figure 4.2.9 – Sketch of the heat transfer model for a cooking pot filled with water and subject to a constant heat source.

4.2.2.1 Heat transfer from water

A major fraction of the thermal input is absorbed by water and converted into internal energy or sensible heat; this fraction is largely predominant for the lower temperature range. The energy that is not converted into sensible heat is instead lost through evaporation, free convection and radiative heat transfer from the water surface. Temperature gradients in the water volume are neglected, since, as proved by Berick [98] for a similar case, they are largely negligible for the whole range of temperatures and volumes considered. The water temperature, therefore, will be assumed to be uniform from the bottom to the surface.

Free convection phenomena occur due to the temperature gradient between the water surface and the surroundings, and can be modelled as convection from a hot plate facing upwards. As already discussed in *paragraph 4.2.1.3*, the liquid surface can be reasonably threated as a rigid surface, yet the assumption becomes less realistic as the higher temperature region is approached and waves appear on it. The convective heat flux from the water surface to the surroundings is thus:

$$\dot{Q}_{conv,w} = hA(T_w - T_\infty) \quad [W] \tag{4.2.26}$$

Where: h = convective heat transfer coefficient [W/m^2K].

Correlations for *h*, identified in *paragraph 4.2.1.3*, are again reported:

$$\overline{Nu_L} = 0,54 \cdot Ra_L^{1/4}, \qquad (10^4 < Ra_L < 10^7, \Pr \geq 0,7) \qquad (4.2.27)$$

$$h = \frac{\overline{Nu_L} \cdot k_{air}}{L_c} \quad [W/m^2K] \qquad (4.2.28)$$

As regards radiative losses from the liquid surface, a rigorous theoretical approach should take into account both radiative heat transfer to the pot walls and to the surroundings. However, being the height of the pot walls above the liquid surface very small as compared to the pot diameter, it is reasonable to simply consider heat transfer to the surroundings. The wasted thermal power is therefore:

$$\dot{Q}_{rad,w} = \varepsilon_w \sigma A (T_w^4 - T_\infty^4) \quad [W] \qquad (4.2.29)$$

Where: σ = Stefan-Boltzmann constant, 5,67*10^{-8} [W/m^2K^4];

ε_w = water emissivity.

Berick [98] calculated the emissivity of water for a similar case by means of an infrared thermometer and his value (0.94) is used as a reference for the present analysis.

Finally, the thermal power lost through evaporation can be easily calculated as:

$$\dot{Q}_{eva} = \dot{m}_{eva} \Delta h_{eva} \quad [W] \qquad (4.2.30)$$

Where: Δh_{eva} = entalphy of vaporisation of water [*kJ/kg*].

The enthalpy of vaporisation, as the other fluid properties considered, is derived as a function of temperature for any temperature interval; the same is done for the rate of vaporisation, by means of the model built in *sub-section 4.2.1*.

4.2.2.2 Heat transfer from pot materials

The thermal input is also partly transferred to pot materials, which increase their temperature and dissipate heat towards the surroundings. The baseline setting of the model considers stainless steel pots, with the same dimensions and weight of those used in the lab, namely 20 cm diameter and 10,8 cm height, weighing about 0,35 kg. However, different pot sizes and materials can be easily implemented. Heat is dissipated via free convection and radiation from the pot walls.

In this case, correlations for free convection are those referred to a laminar flow on a rigid vertical plate, developed by Churchill et al. [99]:

$$\overline{Nu_L} = 0,64 + \frac{0,67 Ra_L^{1/4}}{[1 + (0,492/\Pr)^{9/16}]^{4/9}} \qquad (4.2.31)$$

The characteristic length, as defined in *paragraph 4.2.1.3*, coincides here with the height of the pot walls. The thermal power loss is thus:

$$\dot{Q}_{conv,pot} = h_{side} A_{side} (T_{pot} - T_{\infty}) \simeq h_{side} A_{side} (T_w - T_{\infty}) \quad [W] \quad (4.2.32)$$

Where: h_{side} = convective heat transfer coefficient form the pot sides [W/m^2K];

A_{side} = pot side area [m^2];

T_{pot} = temperature of pot materials [K].

The assumption is that temperature gradients in the pot materials are negligible, being the case of a very conductive medium with weak cooling flows; the temperature of the pot can be thus considered as uniform and equal to the temperature of the water volume.

Radiative heat transfer is again described in the form:

$$\dot{Q}_{rad,pot} = \varepsilon_{mat} \sigma A_{side} (T_w^4 - T_{\infty}^4) \quad [W] \qquad (4.2.33)$$

Where: ε_{mat} = emissivity of pot materials; it can be derived from tables for different materials. In the case of stainless steel, the value 0.25 has been derived again from Berick [98].

4.2.2.3 Thermal power balance

Once all the energy flows have been modelled, the power balance of the system can be written in the form:

$$\dot{Q}_{input} - \sum_i \dot{Q}_{loss,i} = \frac{\partial U}{\partial t} + \dot{m}_{eva} \Delta h_{eva} \tag{4.2.34}$$

Where: Q_{input} = power input from the heat source that goes into the pot [*W*];

$Q_{loss,i}$ = heat losses as defined in the previous paragraph [*W*];

U = internal energy of water and pot materials [*J*].

The balance can be solved integrating for each temperature interval of 10°C and assuming fluid properties, calculated at the average temperature of the interval, as constant for that ΔT. For example, for the first temperature interval (20 to 30°C), properties are evaluated at the average temperature of 25°C. Heat losses are a function of temperature, and are therefore constant on average for the considered ΔT; the rate of vaporisation, as well, is constant on average for the same reason. The balance thus becomes:

$$\overline{\dot{Q}_{input}} - \sum_i \overline{\dot{Q}_{loss,i}} = \frac{(m_w c_{p,w} + m_{pot} c_{p,pot}) \Delta T}{\Delta t} + \overline{\dot{m}_{eva}} \Delta h_{eva} \tag{4.2.35}$$

The equation can be solved for Δt, representing the time interval needed to cover a 10°C temperature interval with fluid properties and thermal powers evaluated at a definite average temperature. Even if the ΔT is always 10°C, the fraction of heat that is wasted to the surroundings increases with the average temperature, thus requiring a larger Δt to perform the task. Solving the power balance for the entire temperature range considered, the total time needed can be calculated, as well as the total mass of water vaporised and any other performance metric. The model can be adapted to simulate different pot dimensions and materials and different water volumes, as well as different power inputs.

4.3 Sensitivity analysis

Assuming experiments being conducted in an indoor laboratory setting, with fixed pot dimensions and materials, the only factor having a direct and sensible impact on the rate of vaporisation is the relative humidity of ambient air, as discussed in *paragraph 4.2.1.4*. It is now possible to simulate the impact of slight variations of relative humidity not only on the rate of vaporisation, but also on the thermal power balance and thus on the total time needed to complete a test, which in turn affects typical performance parameters, like thermal efficiency or specific fuel consumption. The water temperature range considered is again from 20 to 90°C, for the reasons discussed in *paragraph 4.2.1.4*. Results from the simulation can be therefore tested against experimental data obtained in similar conditions to check their consistency.

4.3.1 Model simulation

In order to compare the model output to experimental data, the simulation parameters shall be set as similar to those used for the experiments. In particular, a key parameter to be set is the power input, which in this case shall simulate an electric heater of 2 $kW_{el,nom}$, operated at 5/6 of its maximum power, *viz.* about 1,66 $kW_{el,nom}$ assuming linear power regulation. The fraction of power effectively entering the pot is nevertheless much lower, since a large fraction is wasted as heat towards the surrounding materials and another fraction is directly wasted into the ambient air through the portion of hot plate that is not in contact with the pot. Typical maximum heating efficiencies of electric heaters are about 40% (energy delivered to the pot as compared to energy produced [49]); the fraction of power effectively transferred to the pot is thus set at 640 W, which is similar to what experimentally measured. Notice that electric heaters are regulated via electro-mechanic control systems to keep the plate temperature as constant, and therefore the instantaneous power output is variable; however, on average, the power transferred to the pot can be assumed as constant with good approximation. Other parameters to be set are pot dimensions and ambient temperature, both reflecting average conditions of the lab, while the relative humidity is set as the sensitivity parameter and is varied in the range 30÷60% [97]. Outputs are discussed below.

4.3.1.1 Rate of vaporisation, time and total mass vaporised

As already seen in *Figure 4.2.8*, variations of indoor relative humidity directly affect the rate of vaporisation. The generalised heat transfer model allows now to quantify also the indirect impact of RH on the total time needed to complete the test and thus on the total mass of water vaporised.

The impact on the total time of test is shown in *Figure 4.3.1* for different values of RH in the considered range. In the lower temperature range trends are very similar, whilst they start to diverge after 70°C, determining a substantial difference in the total time of test in the upper temperature region. This figure is important to highlight that variabilities in the rate of vaporisation are already responsible for variations in the total time of test prior to any uncertainty due to thermocouple reading or boiling point change.

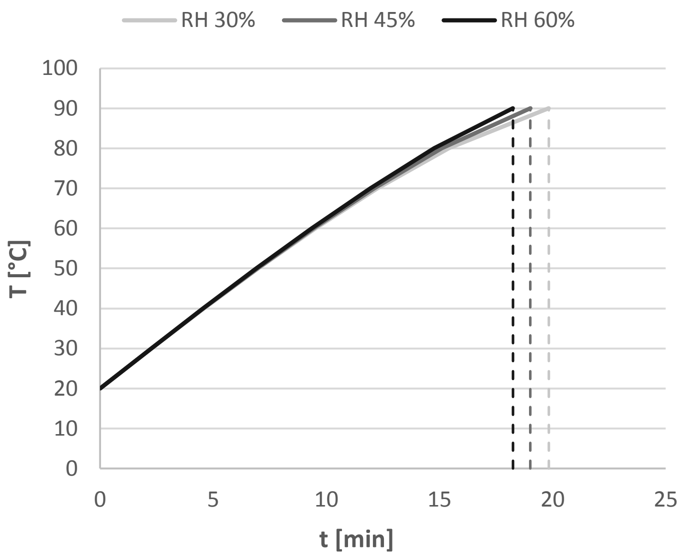

Figure 4.3.1 – Temperature trends over time for different values of ambient RH.

The time needed to reach a fixed temperature is derived from the thermal power balance. The impact of RH fluctuations on test duration is only clearly visible in the upper temperature region because the relative importance of the heat fraction lost through evaporation in the balance is very low up to 70°C, but steadily increases with temperature, as shown in *Figure 4.3.2* for the case of RH 30%.

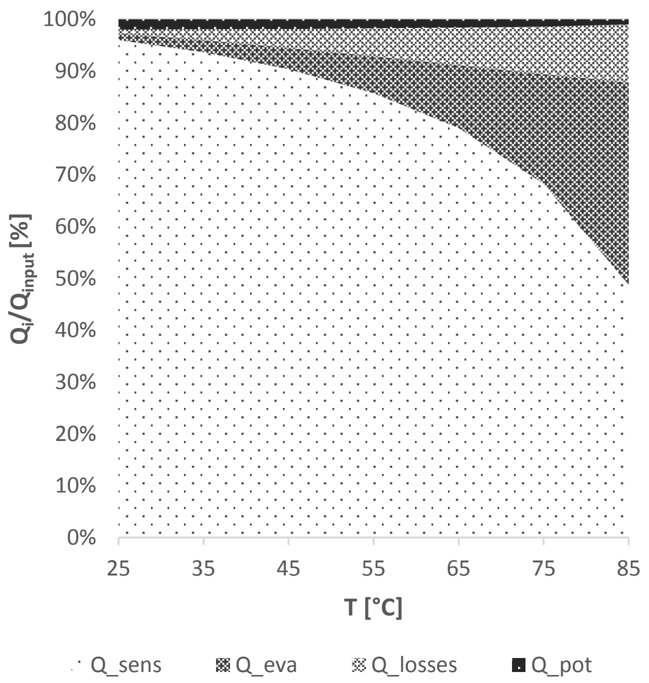

Figure 4.3.2 – Distribution of thermal power fractions as a function of temperature, for RH 30%.

The temperatures of 70 and 90°C can be thus selected as representatives of low and high-rates evaporation regimes respectively, to better quantify the sensitivity of selected parameters on RH fluctuations. Test ending time, rate of vaporisation and total mass of water vaporised are presented in the following figures.

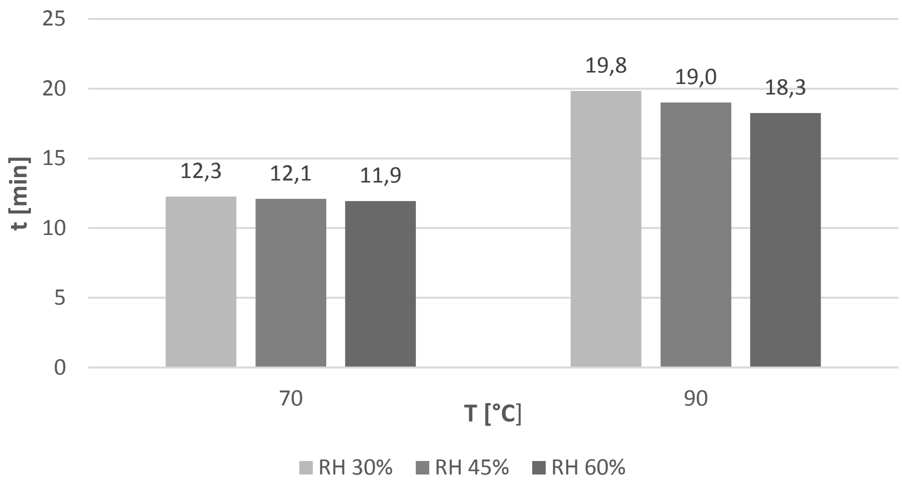

Figure 4.3.3 – Variations in the total time needed to reach 70 and 90°C for different values of RH.

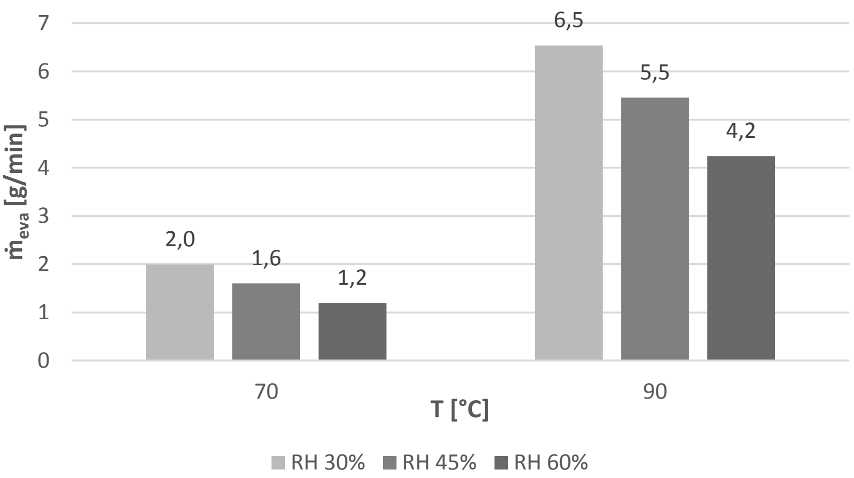

Figure 4.3.4 – Variations in the rate of vaporisation at 70 and 90°C for different values of RH.

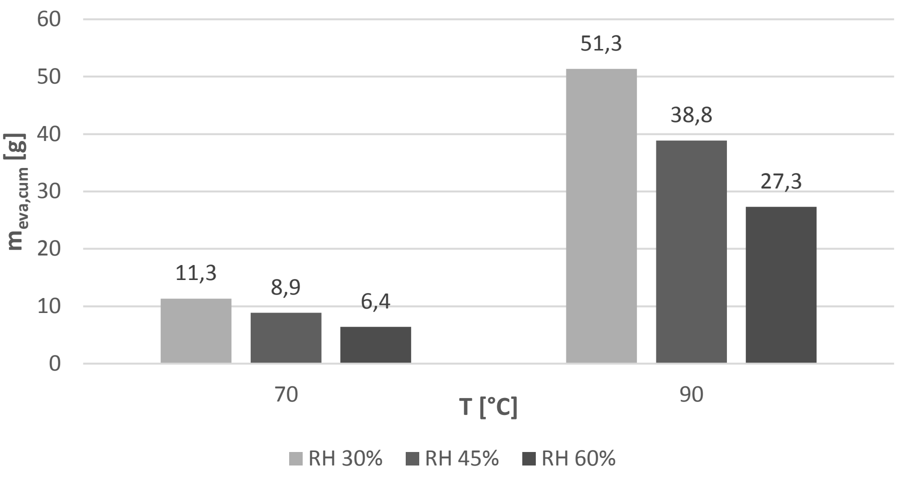

Figure 4.3.5 – Variations in the total mass of water vaporised at 70 and 90°C for different values of RH.

Figure 4.3.3 confirms that variations of RH between the two extreme values of the RH range lead to significant variations in the test ending time at 90°C (up to 1'30"), while they are negligible at 70°C for the reasons discussed above. However, the sensitivity of the rate of vaporisation to the same fluctuations of RH is already significant at 70°C (*Figure 4.3.4*), leading to relevant variations in the total mass of water vaporised (*Figure 4.3.5*).

4.3.1.2 Simulation of different test replicates

It would be interesting to simulate different test replicates as if they were performed in different days with slightly different relative humidity (5% increase each day), averaging results for the total mass of water vaporised and calculating the standard deviation of the sample. To cover the whole RH range (30 to 60%) seven replicates are simulated; results are shown in *Figure 4.3.6*. Coefficient of variation is instead highlighted in *Figure 4.3.7*.

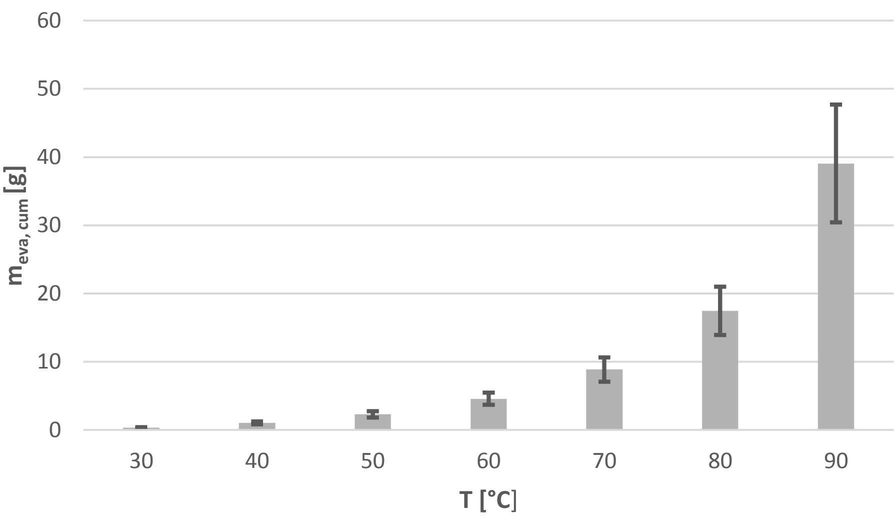

Figure 4.3.6 – Average values of cumulative mass of water vaporised at different temperatures for a simulation of 7 test replicates, each varying 5% RH from the previous. Bars represent standard deviations.

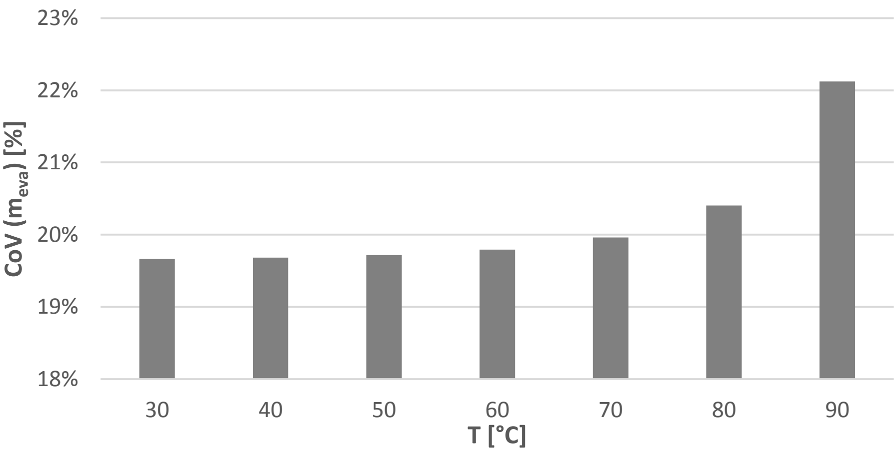

Figure 4.3.7 – Coefficient of variation for the cumulative mass of water vaporised at different temperatures for a simulation of 7 replicates, each varying 5% RH from the previous.

These figures clearly show how the sensitivity of vaporisation to realistic variations of RH can lead to variability in the assessment of the output for a set of replicates, and how such variability becomes rapidly more important (in terms of CoV) as the temperature approaches the upper region. Even larger CoVs should be expected if the model were to be extended to the boiling region.

Assuming now that only three replicates were performed, as done in most experimental studies, in the days with 30, 45 and 60% RH, results variability would be even greater:

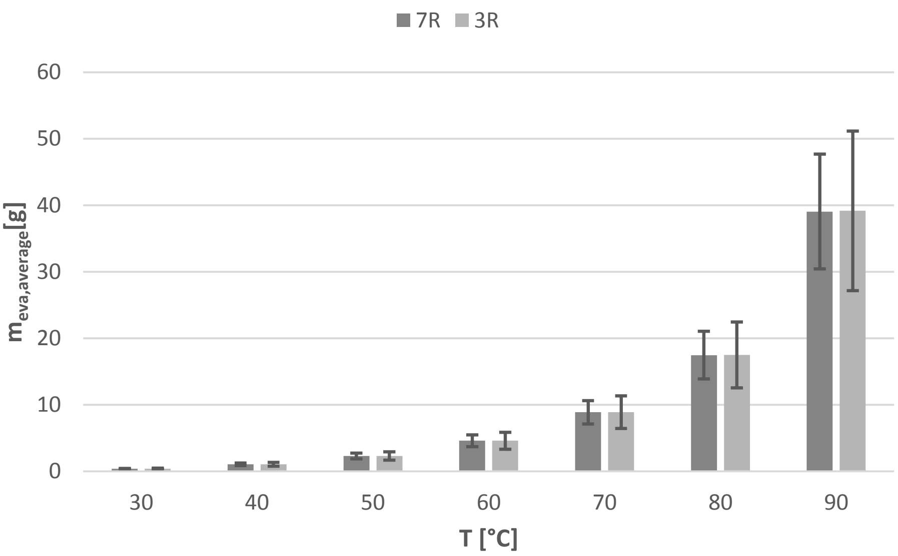

Figure 4.3.8 – Comparison of total mass of water vaporised at different temperatures between a 7 replicates simulation and a 3 replicates simulation. Bars represent standard deviations.

However, even if the evaporation phenomenon has been proved to be variable due to natural and uncontrollable fluctuations of ambient relative humidity, it would be interesting to quantify how this variability affects the overall variability of typical performance parameters.

4.3.1.3 Impact on performance parameters

The 3-replicates simulation is used as a reference, to keep uniformity with the common practice of lab protocols (see *sub-section 3.1.4*). In particular, thermal efficiency and specific fuel consumption are selected as representative parameters, keeping their most common formulation that is the WBT's (*sub-section 3.1.3*):

$$\eta = \frac{m_{w,i} c_{p,w} (T_b - T_i) + m_{eva} h_{lv}}{f_d \cdot LHV} \tag{4.3.1}$$

$$SC = \frac{f_d}{m_{w,f}} \quad [\frac{kg_{fuel}}{kg_{water}}] \tag{4.3.2}$$

In this case the simulation was set as to reproduce an electric heater, but *SC* can be virtually calculated assuming that the same power input was produced by wood combustion, with *LHV* = 16 MJ/kg:

$$\dot{Q}_{heater} = \frac{5}{6}\dot{Q}_{el,nom} = \frac{f_d LHV}{t} \quad [W] \tag{4.3.3}$$

$$f_d = \frac{\dot{Q}_{heater} \cdot t}{LHV} \quad [kg_{wood,dry}] \tag{4.3.4}$$

To provide a more accurate estimate of the variability associated with *SC* and η, the theory of uncertainty propagation is applied, based on standard deviations (type A uncertainty, as defined by the ISO GUM 1995 [100]). Combined uncertainty is calculated by means of the classical theory of combined uncertainty [101], for the 3-replicates case:

$$u_y = \sqrt{\sum_{i=1}^{p}\left(\frac{\partial f}{\partial x_i}u_{x_i}\right)^2 + 2\sum_{i=1}^{p-1}\sum_{j=i+1}^{p}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u_{x_i}u_{x_j}} \tag{4.3.5}$$

In this case, *SC* is a function of *t* and $m_{w,f}$, while η is a function of *t* and m_{eva}. Degrees of freedom are evaluated by means of the Welch-Satterwite equation [101]:

$$\nu_{eff} = \frac{u_y^4}{\sum_{i=1}^{p}\frac{\left(\frac{\partial f}{\partial x_i}u_{x_i}\right)^4}{\nu_i}} \tag{4.3.6}$$

Where ν_i are the degrees of freedom of x_i; a confidence interval of 95% is considered. Results are shown in the following figures.

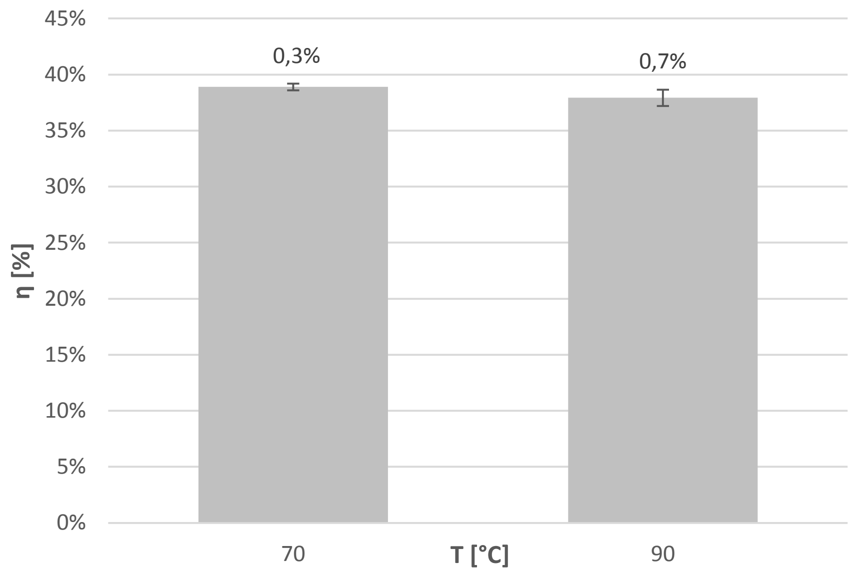

Figure 4.3.9 – Average values of thermal efficiencies for a simulation of 3 replicates, at 70 and 90°C. Bars represent combined uncertainty for a 95% CI

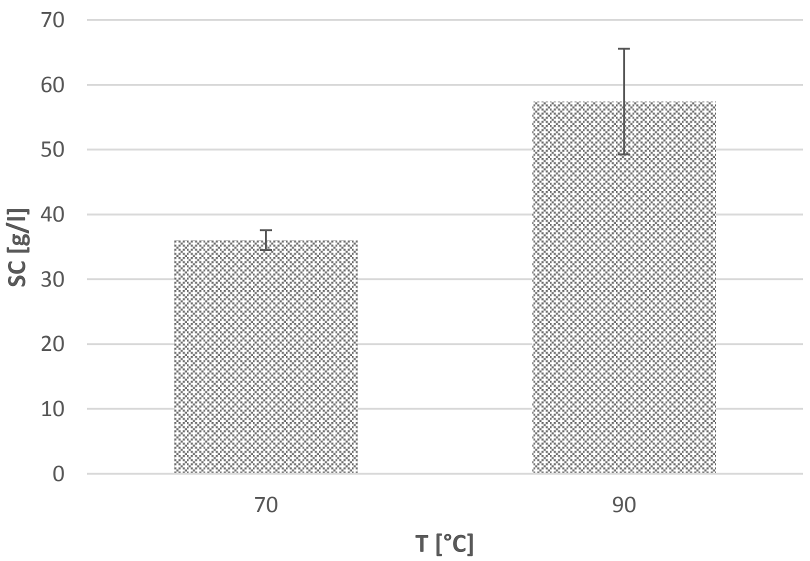

Figure 4.3.10 – Average values of specific fuel consumption for a simulation of 3 replicates, at 70 and 90°C. Bars represent combined uncertainty for a 95% CI

Figure 4.3.8 shows that, even if the variability associated with vaporisation has been proved to be significant, its overall impact on the uncertainty associated with thermal efficiency is quite negligible at 70°C and slightly more relevant at 90°C. This is because an eventual increase in the rate of evaporation causes both an increase of the numerator of *Equation (4.3.1)*, through m_{eva}, and of the denominator, through t, and the two effects counterbalance each other. More precisely, even if an increase of m_{eva} has been proved to be much more relevant than the corresponding increase of t, the numerator is composed by two terms and only partially affected by the increase of vaporisation. In the lower temperature region, the two effects results both in a very little increase of numerator and denominator; at higher temperatures, the increase of the numerator is relatively more significant than the increase of the denominator, resulting in a slightly larger overall uncertainty.

Figure 4.3.9, instead, shows how the impact of vaporisation variability is much more relevant for SC, which is directly dependent on t and on m_{eva} – *Equation (4.3.2)*. Again, at 70°C fluctuations of both parameters are quite little, even if more significant for m_{eva}, and the overall uncertainty is low. At 90°C, fluctuations of m_{eva} are instead largely predominant and cannot be completely counterbalanced by the corresponding increase of t, resulting in a large overall uncertainty.

It can be concluded that the evaporation phenomenon entails an intrinsic variability due to natural and uncontrollable variations of RH, typically occurring from day to day even in an indoor lab. Furthermore, larger RH variations shall be taken into account when comparing results from different labs located in different geographical areas or when considering outdoor or field testing. Moreover, the impact of such variability on typical performance parameters has been evaluated and proven to be significant in the higher temperature region, especially as regards specific fuel consumption. Larger variations shall be expected for procedures reaching even higher temperatures in the boiling region, as for the WBT. Notice that, though efficiency and specific consumption were chosen as representative parameters, all performances parameters are a function of the total time of test, and are thus directly or indirectly affected by the discussed uncertainties. Therefore, procedures allowing the tester to control the evaporation phenomenon are suggested as more reliable and repeatable. Closed-cell foam insulation, proposed by the EPTP, could be a possible solution, but the testing procedure should be performed keeping the foam over the liquid surface for all power levels; the EPTP, instead, is performed removing insulation for the low-power phase. However, a simpler and as reliable solution would be placing a lid on the pot for all power levels, as proposed by the HTP. If a lid is placed on the pot, in fact, evaporation is not immediately stopped, but the atmosphere between the liquid surface and the lid becomes rapidly saturated with water molecules, as shown in *Figure 4.3.11*. Once the atmosphere is saturated, the evaporation rate defined by *Equation (4.2.7)* turns to zero, and no more evaporation can occur, regardless of the temperature reached by the water. Therefore, for any temperature limit, an identical and very small quantity of water is expected to evaporate, without any variability due to external conditions and with a largely negligible relative importance. Experimental data in the following sections will be used to check these findings derived from model simulations.

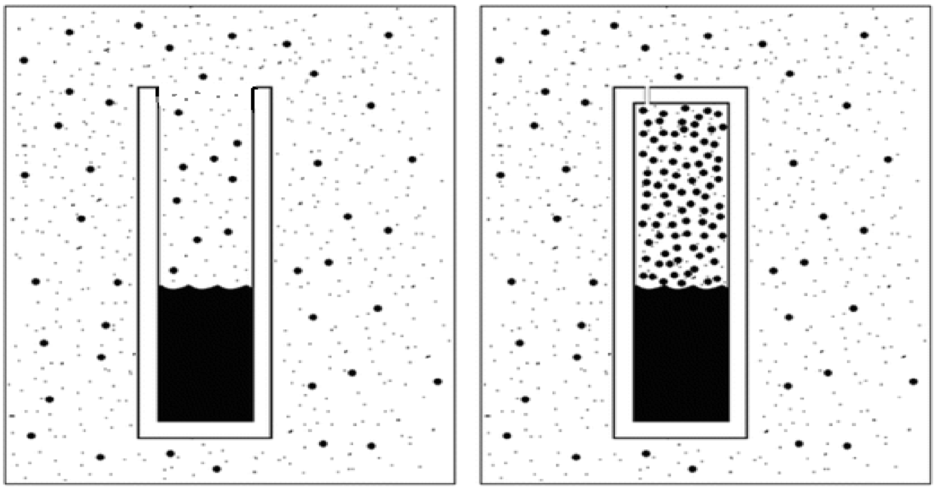

Figure 4.3.11 – Container filled with water in a humid air environment before and after placing a lid on its top; source: Sidebotham [95].

4.3.2 Experimental evidence

Experimental testing is performed in order to test simulations results against empirical evidence. Notice that the experiment is extended to the boiling region (95°C), where the model is no more rigorously valid and simulations were thus not performed, but where the same conclusions drawn for a temperature of 90°C (in terms of vaporisation variability) were expected to keep valid and even more evident. Moreover, the extension of the experiment to the boiling region is important to draw independent conclusions about the second source of variability highlighted in *sub-section 4.1*, represented by fluctuations in the thermocouple reading.

4.3.2.1 Experimental set-up and approach

Testing was performed in a controlled indoor space, with average ambient temperature of 18°C and no ventilation. Small stainless steel pots (20 cm diameter, 10,8 cm height) were filled with 2 L of water and heated by means of an electric heater (2 $kW_{el,nom}$, regulated at 5/6 of its maximum power). The initial and final masses of water were measured by means of a digital scale (precision ± 1 g), providing the total mass of water vaporised at different temperatures (70, 80, 90, 95°C). Temperature was instead measured by means of a digital data logger (Delta OHM HD 9016, precision ± 0,1°C)[1], equipped with a K-type thermocouple calibrated up to 200°C. For each temperature, 5 replicates were performed with a lid on the pot and other 5 replicates with the lid off, for a total number of 40 tests. The choice to perform 5 replicates for each case is motivated by the use of a much more controlled and predictable power input, as compared to cookstove testing, that should ensure a lower variability between test replicates. This seems to be confirmed by empirical evidence: if the CoV for a set of 3 replicates were calculated and a fourth test were added, the CoV would slightly change; if then a fifth replicate were added, the CoV would keep constant.

[1] For further details about the temperature data logger, see *Appendix*.

The time was recorded for every 10°C temperature interval (5°C for the last interval) by means of a digital chronometer. The heating plate was allowed to warm for a few minutes before each test so that it could reach stationary conditions. Replicates were performed in different days to ensure data independency.

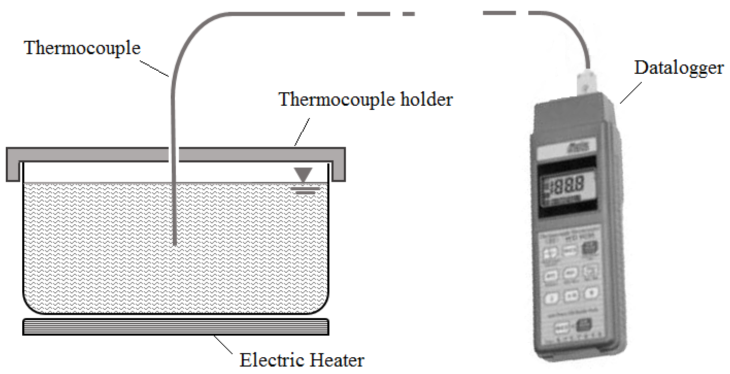

Figure 4.3.12 – Simple sketch of the experimental set-up.

In this case, an accurate variability analysis cannot be based simply on data standard deviations, since instrument uncertainty, especially as regards the digital scale, might be not negligible as compared to statistical uncertainty. Therefore, type A and type B uncertainties (as defined by the ISO GUM 1995 [100]) are evaluated in each case, and type B uncertainty is preferred in case standard deviation is not greater than the value assessed for type B uncertainty by at least 5 times:

$$\begin{aligned} &if \;\; SD \geq 5u_B \rightarrow type\,A \\ &if \;\; SD < 5u_B \rightarrow type\,B \end{aligned} \tag{4.3.7}$$

Type B uncertainty for the digital scale is:

$$u_B = \frac{r}{2\sqrt{3}} = 0,29 \quad [g] \tag{4.3.8}$$

Where *r* is the instrument resolution, that is 1 g for the digital scale. After type A or type B uncertainty has been chosen, data are presented with an extended uncertainty for a confidence interval of 95%. Coverage factors are derived as a function of the degrees of freedom for type A extended uncertainty, referred to a t-student distribution with n-1 degrees of freedom; they are instead equal to 1,65 for type B uncertainty, associated with a rectangular distribution.

4.3.2.2 Total mass vaporised with lid ON and OFF

The first output needed to check the consistency of model results is the total mass of water vaporised at different temperatures with the lid off, which should be characterised by an increasing variability as the upper temperature region is approached. On the contrary, the same value for the lid-on case should be almost constant for any temperature range. *Figure 4.3.13* shows results for the lid-off case, confirming what expected from the model output, the only exception being the larger variability occurring at 80°C as compared to that occurring at 90°C.

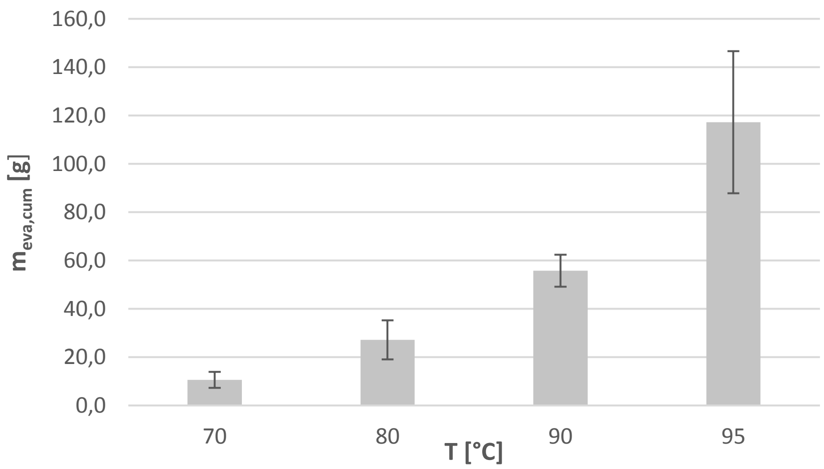

Figure 4.3.13 – Cumulative mass of water vaporised at different temperatures, lid-off case. Bars represent extended uncertainty.

It seems difficult to attribute a specific cause to this anomaly, if not experimental errors or an insufficient number of replicates. However, results at 95°C clearly corroborate the conclusion that vaporisation variability highly increases in the upper temperature region and even more after the appearance of boiling phenomena.

Figure 4.3.14, instead, shows how the total mass of water vaporised when a lid is placed on the pot keeps almost constant for any temperature level. At 70°C it is already smaller than the corresponding value for the lid-off case, showing that saturation in the control volume possibly occurs at even lower temperatures; it is besides smaller by one order of magnitude as compared to the corresponding values in the upper temperature region, as expected from theoretical discussion.

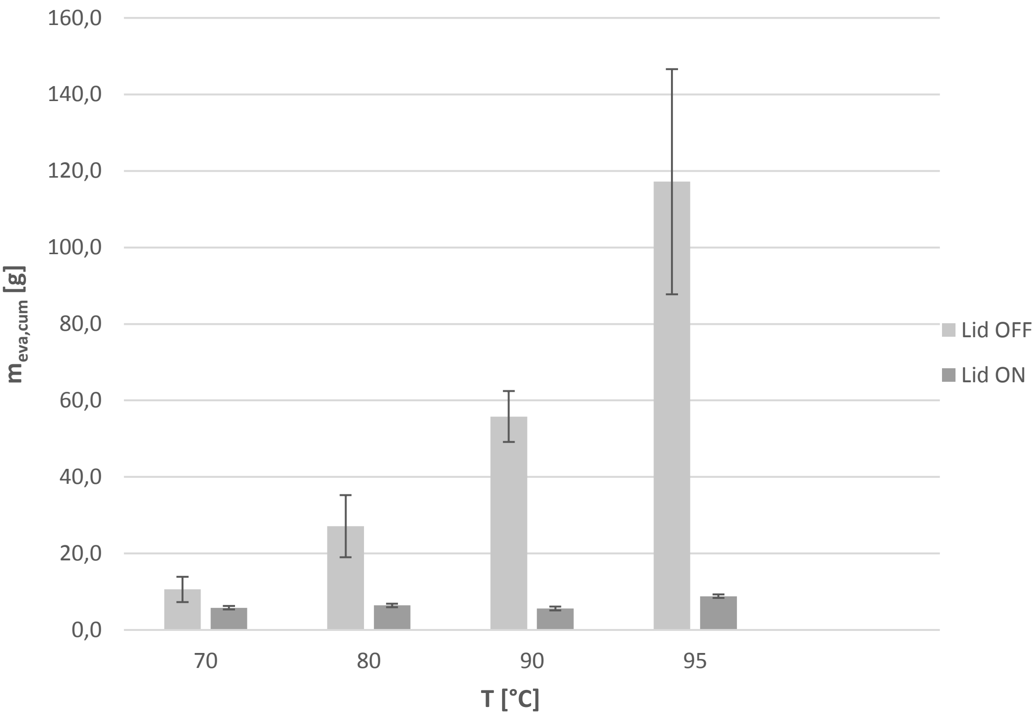

Figure 4.3.14 – Comparison of cumulative mass of water vaporised at different temperatures between the lid-on and lid-off cases. Bars represent extended uncertainty.

However, in order to confirm with a significant level of confidence that the total mass of water vaporised with the lid on keeps constant for any temperature level and that it is different from the corresponding value at 70°C, a detailed statistical analysis shall be performed. In this case, statistical inference on a comparison between two samples with a restricted number of observations is needed, and a t-test is chosen.

Conditions required to perform a t-test are:

- Normal data distribution
- Independent observations

As regards the first condition, the t-test is still approximately valid, even in case it were not respected. A two-tail t-test for two samples assuming unequal variances is required in this case. Defining (1 - α) as the desired level of statistical confidence, hypothesis testing is evaluated as a function of the p-value:

- If p-value $>$ α, there is a weak empirical evidence against the null hypothesis, which cannot be rejected;
- If p-value $\leq$ α, there is strong evidence against the null hypothesis, which is rejected. Observed data are "statistically significant".

The first statistical inference is between the mass of water vaporised at 70°C with the lid on and off, to prove that they are significantly different. The null hypothesis is that the two means are equal; results are shown in *Table 4.3.1*:

	m_{eva} *(70°C)*	*p-value*	*Significant difference (CI 95%)*	*Significant difference (CI 99%)*
Lid off	10,6	0,014272	yes	no
Lid on	5,8			

Table 4.3.1 – Hypothesis testing comparing the sample means of total mass of water vaporised at 70°C for the lid-on and lid-off cases.

Therefore, there is a statistically significant difference between the means of total mass of water vaporised at 70°C for the lid-on and lid-off cases when a confidence level of 95% is accepted. If 99% confidence is required, instead, the empirical evidence is not strong enough. A 95% CI is nevertheless considered acceptable, thus it can be concluded that the two means are significantly different already at 70°C and that saturation occurs at lower temperatures.

The second, and most important, statistical inference is between the mass of water vaporised with a lid on the pot at 70°C and the mass of water vaporised at any other temperature keeping the lid on the pot, to prove that the value keeps constant as saturation conditions subsist. As before, the null hypothesis is that the two means are equal; results are shown in *Table 4.3.1*.

	m_{eva}	*p-value*	*Significant difference (CI 95%)*	*Significant difference (CI 99%)*
70	5,8	-	-	-
80	6,4	0,547184	no	no
90	5,6	0,817918	no	no
95	8,8	0,032779	yes	no

Table 4.3.2 – Hypothesis testing comparing the sample means of total mass of water vaporised with a lid on the pot at 70°C and at any other temperature.

Results from statistical inference confirm what expected for any temperature level, except for 95°C where a significant difference between the means is identified for a 95% level of confidence. This apparent anomaly can be possibly explained considering that the evaporation rate at 95°C reaches very high values and that even in the small fraction of time needed to remove the lid and weigh the pot on the digital scale a few more grams of water can evaporate, causing a small experimental error.

4.3.2.3 Test ending time with lid ON and OFF

The second parameter that must be considered is the test ending time, which is expected to be more variable as temperature and evaporation rate increase for the lid-off case. On the contrary, when a lid is place on the pot, ending time variability should be almost constant for any temperature level before the boiling region; as boiling phenomena appear, instead, a larger uncertainty in the identification of the test ending time is expected also for the lid-on case due to thermocouple reading fluctuations, as discussed in *section 4.1*.

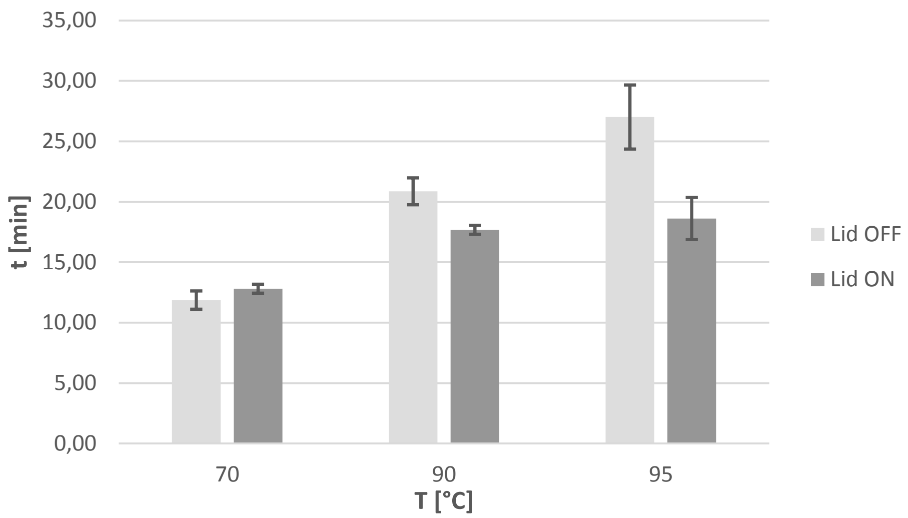

Figure 4.3.15 – Comparison of averaged values for the test ending time at different temperatures for the lid-off and lid-on cases. Bars represent standard deviation.

As shown in *Figure 4.3.15*, when the test is performed without a lid on the pot variability in the test ending time is always increasing, as expected due to the increasing impact of vaporisation variability. When a lid is place on the pot, instead, variability in the test ending time keeps low and constant at different temperatures as vaporisation is limited and controlled, but it suddenly increases at 95°C when boiling phenomena occur. This allow to clearly identify a separate source of uncertainty in the boiling region, related to a difficult reading of the thermocouple signal, which is no more stable and linear. In fact, even if the thermocouple is calibrated for temperatures up to 200°C, the exponentially augmented molecular agitation in the fluid volume and the instantaneous formation and collapse of vapour bubbles entail fluctuations in the instrument reading, leading to likely experimental errors in the identification of the limit temperature. Notice that the evidently larger variability in test ending at 95°C for the lid-on case, as compared to variability at lower temperatures, cannot be indirectly caused by variability in the total mass of water vaporised. In fact, even if at 95°C the average mass vaporised was found to be different from the corresponding value at lower temperatures, its absolute value is still largely negligible (smaller than mass vaporised at 70°C without a lid). Moreover, if the small difference were due to an experimental error in the weighing process, as discussed in the previous paragraph, that could not have any impact on the test ending time, which is recorded before weighing and removing the lid.

4.3.3 Discussion

The sensibility analysis proved that intrinsic variability in the evaporation phenomenon due to uncontrollable and natural fluctuations of ambient RH could lead to relevant variability in typical performance parameters, which is furthermore strongly increasing with temperature. The use of a lid on the pot was proposed as a possible solution to limit evaporation to a negligible and constant value for any temperature level, as it would turn to zero the modelled rate of evaporation after a short transient. Nevertheless, a second source of uncertainty was theorised in the form of thermocouple reading fluctuations in the boiling region. Therefore, experimental testing was performed to check the consistency of those theoretical conclusions.

Experimental evidence proved the increasing variability of vaporisation with temperature; moreover, it showed an even larger growth of variability in the boiling region, which was theoretically predicted even if not simulated due to model constraints. The only exception to the linear growth of variability with temperature was represented by a large variability at 80°C, which was identified as a statistical or experimental error. When testing with a lid on the pot, no statistically significant differences were observed in the total amount of water vaporised at different temperatures, which was also negligible in absolute terms. Furthermore, a comparison of test ending time variability for the lid-on and lid-off cases allowed to separately identify the impact of a second source of variability, represented by thermocouple fluctuations at 95°C.

Conclusions can be summarised as:

1. Vaporisation leads to variability in testing results, which is more relevant as water temperature increases;
2. Placing a lid on the pot can be an effective solution to limit this source of variability;
3. Testing performed in the boiling region introduces a second separate source of variability, related to fluctuations in the thermocouple reading.

The ultimate aim of the analysis was identifying the key requirements to be satisfied by a testing procedure in order to be considered as reliable and scientifically validated. It can be therefore concluded that testing should be performed with pot insulation (a lid is suggested for the sake of simplicity) and setting a limited maximum temperature before the boiling region. Any temperature up to 90°C might be chosen if a lid is placed on the pot. This kind of procedure will be hereafter referred to as *Ideal Heat Transfer* (IHT) procedure.

The HTP/WHT procedures satisfies these requirements and their hypothesis can be therefore regarded as reliable and scientifically validated. The EPTP only satisfies the requirements for the high-power phases, but not as regards the low-power phase. All other current testing protocols do not satisfy the proposed requirements.
Notice that even if an IHT has been proved to effectively reduce thermodynamic sources of uncertainty, ICS testing with such procedure could be still characterised by eventual variabilities deriving from biomass inhomogeneity, unsteady firepower and tester behaviour.

4.4 Testing Simulation Tool

A reliable and scientifically validated procedure has been identified in the previous section. Nevertheless, results obtained with such procedure for a certain fuel/pot combination may not reflect performances under different conditions. For instance, similarly to the example of the electric heater discussed in *sub-section 3.1.4*, stoves characterised by a limited firepower may be well performing when using small pots with lids, but may be unable to bring a 5 L pot to a boil. To avoid such problems the HTP, which is based on an IHT procedure, suggests testing a stove over a broader range of fuel/pot/power combinations in order to provide performance curves under different circumstances. In its "upgraded" and under development version, that is the WHT, it strictly requires to test the stove over the typical burn cycle of the target population and using similar fuel and pots. However, a much more effective solution could be represented by testing a stove in the lab with a reliable IHT procedure for a single fuel/pot combination and then performing an analytical simulation of all the different conditions and pot dimensions needed, by means of an extended version of the model built in *section 4.2*. This *Testing Simulation Tool* (TST) could also provide a better assessment of stove performances under real use conditions; in fact, it would be even possible to simulate performances under similar conditions to those experienced by the target user in a field context. For example, IHT lab performances could be translated into equivalent performances for an unlidded 7 L pot of any material, under field representative temperature and RH conditions, thus providing a much more useful and significant testing output. Notice that the same simulation could be performed on the basis of WBT or any other protocol performances, yet it would be affected by a much larger bias, as will be further discussed in *sub-section 4.4.1*.

However, to achieve those potential results the model needs to be further developed in order to be able to simulate evaporation in the boiling region, where current theoretical assumptions are no longer realistic. Furthermore, changes should be introduced in order to simulate cooking pots with lids. The present section is not aimed at building a completely developed tool, which is left to further studies, but rather at providing a demonstration of the potential effectiveness of the model as a testing simulation tool. Therefore, a simulation of a WBT and an EPTP is attempted and compared to laboratory and Clean Cooking Catalog (GACC [91]) results, respectively, with promising results. Finally, EPTP results referred to a large cooking pot are translated into equivalent results for a small pot, to show the potential ability to simulate a broader range of conditions starting from a single lab experience.

4.4.1 Simulation of different protocols

The WBT and the EPTP are chosen as a first demonstration of the potential development of the model into a TST; the choice is dictated by the need for pre-existing data as a criterion for validating simulation output. WBT databanks are in fact largely available from testing performed at the Department of Energy lab for different stove types; in addition, for one of the stoves (Envirofit Econofire), EPTP results are also available from the Clean Cooking Catalog, allowing for a double protocol simulation and for results comparison. Therefore, a few assumptions are discussed to simulate cooking stoves rather than electric heaters; subsequently, changes are introduced to extend the model to the boiling region (WBT) and to simulate an insulating foam above the liquid surface (EPTP).

4.4.1.1 How to simulate a cooking stove

The electric heater was modelled as a constant heat source, and the fraction of heat effectively reaching the pot bottom ($\dot{Q}_{input}$) was derived based on its nominal power and its heating efficiency. When simulating cookstoves, a similar logic is followed. Even if a stove firepower is typically unsteady due to the intrinsic variability of wood combustion, it can be assumed as constant on average; the same assumption was in fact made for the electric heater, whose power output is not steady but cyclically regulated via electro-mechanic systems, as discussed in *sub-section 4.3.1*. The fraction of heat released by combustion that reaches the pot bottom is instead slightly more difficult to calculate, since stove efficiency derived from datasheets is referred only to the "useful" heat reaching the pot (the fraction increasing water internal energy or lost through evaporation); furthermore, ICSs datasheets are often referred to a very restricted and unreliable number of replicates. Consequently, experimental testing is suggested as a more accurate methodology to derive the needed parameters, *viz.* firepower and $\dot{Q}_{input}$. The stove shall be tested for any required power level with an IHT procedure, ensuring the most accurate results possible; in fact, as discussed in *section 4.3*, any testing output could be directly or indirectly influenced by thermodynamic sources of uncertainty, which negatively impact on the calculation of the total time of the test.

Firepower can be directly calculated for each power level, while the average $\dot{Q}_{input}$ can be estimated by experimentally calculating the useful heat and adding heat losses as defined in *sub-section 4.2.2*. Once the two parameters are known, the model can be used to perform any kind of simulation on the stove. The steps required to implement an ICS are reassumed in *Figure 4.4.1*:

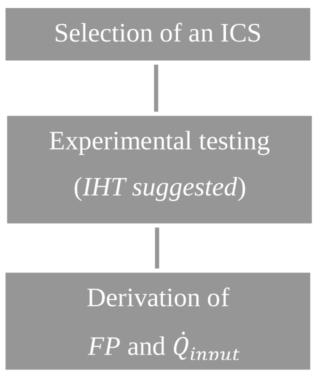

Figure 4.4.1 – Conceptual passages needed to perform a simulation with the TST

Notice that if more than one power level (*e.g.* high, medium and low) has to be simulated, the previous steps shall be repeated for each power level; the same is valid for different fuel simulations. In this case, a simulation of an Envirofit Econofire is required. However, since the modelling of an IHT with lidded pots is left to further developments, and since experimental testing with WBT was already performed as part of a parallel research, the present demonstration study will be based on WBT experimental data rather than on an IHT procedure. Only high power performances are evaluated, since the simmering phase is not considered a correct assessment of low power performances (see *sub-section 3.1.4*). Five testing replicates were performed at Politecnico di Milano, Deparment of Energy; details follow:

- *Pots*: small stainless steel pots (20 cm diameter, 10,8 cm height);
- *Wood*: fir wood, average moisture content 7%, LHV $\simeq$ 15840 $[kJ/kg]$;
- *Equipment*: PEMS[2] (Portable Emission Measurement System), including thermocouple (± 0,1°C); digital scale (± 1g) and digital chronometer.

Average values for *FP* and $\dot{Q}_{input}$ were thus derived; results are shown in *Table 4.4.1* considering extended uncertainties for a confidence interval of 95%:

FP $[W]$	$\dot{Q}_{input}$ $[W]$
2400 ± 148 (CI 95%)	740 ± 114 (CI 95%)

Table 4.4.1 – Average firepower and power input to the bottom of the pot for Envirofit Econofire, derived from experimental testing.

As expected, WBT results are affected by a large uncertainty; nevertheless, exact average values will be used as input parameters for the TST.

4.4.1.2 WBT simulation

The model built in *section 4.2* was not able to simulate evaporation in the boiling region, as the assumptions made about mass boundary layer as a stagnant film and water surface as a rigid plate were no longer realistic. Empirical evidence shows that after 90°C isolated bubbles start to form and collapse in nucleation sites where the liquid is locally superheated, even if the water volume has not yet reached the

[2] PEMS details are provided in the *Appendix*.

saturation temperature, as shown in *Figure 4.4.2*. As the temperatures increases, isolated bubbles start to separate from the surface, forming columns and a fully developed nucleate boiling in the range 95-99°C. The realism of the assumptions made for the evaporation rate is therefore particularly weak in this latter region, as the liquid surface is interested by waves and turbulent boiling phenomena.

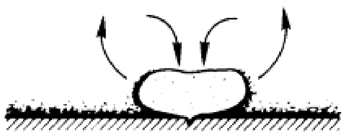

Figure 4.4.2 – Bubble growth in subcooled liquid: steam condenses on the top, while evaporation continues on the bottom, determining bubble collapse. Dark regions represent locally superheated liquid. Adapted from Lienhard et al. [94].

A detailed study describing the onset of different boiling phenomena and their impact on mass transfer would be needed for a precise modelling of the rate of vaporisation in this region. As a first approximation, the optimised Stefan model could be extended at least to the 90-95°C range where only isolated bubbles appear and mostly collapse before reaching the surface. As done in *sub-section 4.2.1*, the consistency of this assumption can be tested against empirical data from the electric heater experiment, which was performed up to 95°C, as shown in *Figure 4.4.3*. As expected, the model can still effectively predict with good approximation the rate of vaporisation for the 90-95°C range, although theoretical assumptions should be taken with caution. A further extension up to the boiling point would not be possible, as p_v would tend to $p_{sat@100°C}$ and $x_{aq,0}$ would tend to unity, resulting in an infinite value of the evaporation rate as expressed by *Equation (4.2.7)*. However, empirical evidence shows that such a drastic increase in the evaporation rate is not observed and suggests that the rate of evaporation keeps almost constant from the first onset of isolated bubbles to the boiling point. For this reason, in the present demonstration analysis, the rate of evaporation for the boiling region is calculated with the Stefan model with properties evaluated at the average temperature of the 90-95°C interval and kept constant up to the boiling point.

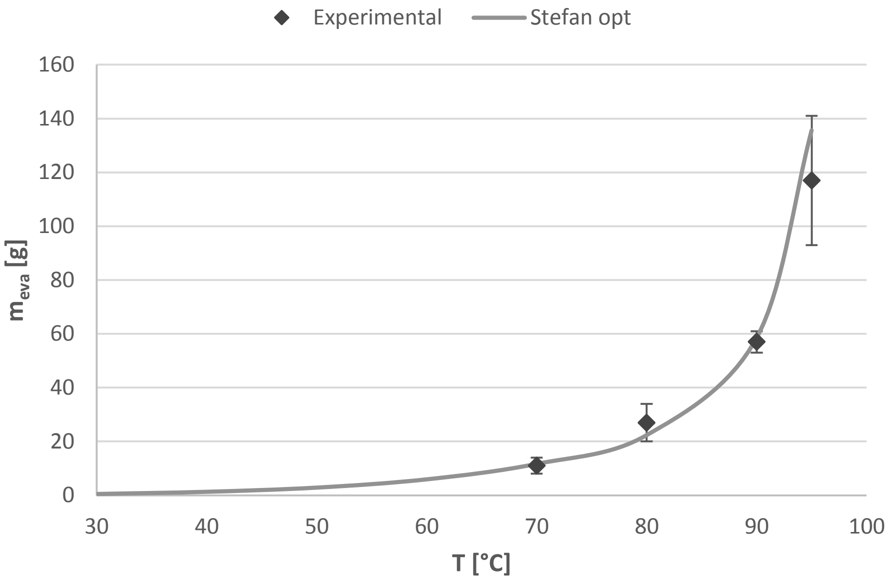

Figure 4.4.3 – Cumulative mass of water vaporised at different temperatures, comparison between the optimised Stefan model and experimental data (electric heater). Bars represent standard deviations.

At this point, setting the evaporation rate, $\dot{Q}_{input}$, pot dimensions and ambient temperature, and assuming a variability range for RH (30÷60%), five WBT replicates are simulated with the TST and compared to experimental data. The comparison is performed on high-power parameters, and performances of cold and hot start phases are averaged, as done in the WBT procedure. Before comparing performance parameters, the total mass of water vaporised is analysed to check the effectiveness of the extended model in predicting evaporation for the whole temperature range:

	m_{eva} [g]	
	average	*SD*
Experimental	112,6	13,8
TST	117,9	21,7
err%	4,49%	

Table 4.4.2 – Averaged total mass of water vaporised for experimental and simulated WBT.

Considering standard deviations, the two values fall in the same range and are indistinguishable; the standard error calculated for the two exact values is also largely acceptable, proving that the extended model is well functioning. As the simulated value presents a larger variability, it can be inferred that the actual RH variations between test replicates were slightly lower than what assumed.

As regards performance parameters, results are shown in *Table 4.4.3*:

	t [min]		***η***		***SC [g/l]***	
WBT	*average*	*SD*	*average*	*SD*	*average*	*SD*
Experimental	26,94	3,76	28,45%	2,22%	105,69	7,93
TST	26,79	1,22	28,34%	0,03%	100,61	5,01
err%	0,57%		0,55%		4,81%	

Table 4.4.3 – Averaged performance parameters for experimental and simulated WBT

All parameters perfectly fall in the same range, and experimental errors are largely negligible. It can be concluded that this first attempt at extending the heat and mass transfer model into a TST provides very promising results, although a deeper analysis of mass transfer in the boiling region should be performed in order to strengthen the theoretical basis of the tool. Notice also that the variability of all simulated parameters is lower than the corresponding experimental value, even if variability in the simulated mass of water vaporised was larger than experimental. This is consistent with what discussed in *sub-section 4.3.3*, *viz.* that vaporisation variability alone is not responsible for all variability in testing, as other sources of variability are tester behaviour and fuelwood inhomogeneity.

4.4.1.3 EPTP simulation

The EPTP high-power phase is performed with a floating layer of closed-cell foam insulation above the liquid surface, therefore, changes shall be introduced to the model in order to simulate this configuration. The insulating layer prevents water evaporation, but also strongly limit other thermal losses from the top surface; all types of closed-cell foam (neoprene, polyethylene, polystyrene *etc.*), in fact, are very low emitting materials, thus radiative losses are also negligible. A small temperature gradient will be still present between the external surface of the insulating layer and ambient air, but the resulting convective losses will be much lower than for the case of free liquid surface.

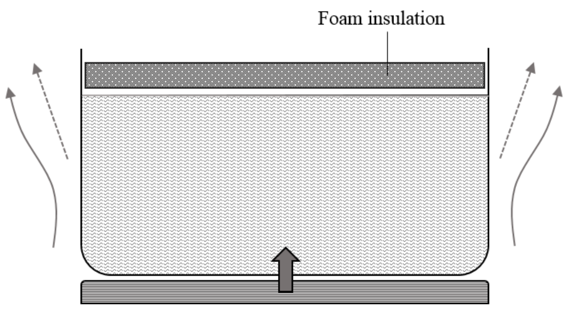

Figure 4.4.4 - Sketch of the heat transfer model for an EPTP procedure.

The temperature of the external surface of the insulating layer can be calculated following the conceptual scheme highlighted in *Figure 4.4.5*.

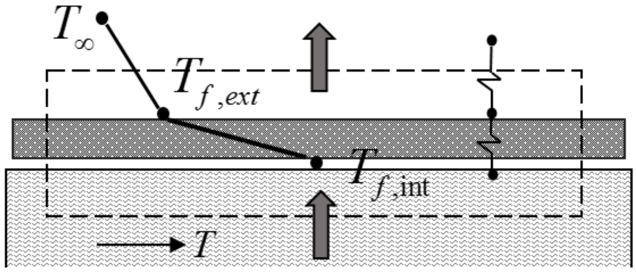

Figure 4.4.5 – Heat flux and temperatures between the water surface and the insulating layer.

For a rigorous approach, also transient phenomena should be considered, but for a first approximation the external surface temperature can be calculated for steady state conditions. The temperature of the internal surface ($T_{f,int}$) is assumed to be equal to the temperature of the water surface.

A system of equations can be formulated:

$$\begin{cases} \dot{Q} = \dfrac{T_w - T_\infty}{R_{tot}} \quad [W] \\ \dot{Q} = \dfrac{T_w - T_{f,ext}}{R_{foam}} \quad [W] \end{cases} \tag{4.4.1}$$

$$\Rightarrow T_{f,ext} = T_w - \dot{Q} \cdot R_{foam} \tag{4.4.2}$$

With:

$$R_{tot} = R_{foam} + R_{conv} = \frac{1}{A}\left(\frac{t}{k_f} + \frac{1}{h}\right) \quad [W/K] \tag{4.4.3}$$

Where k_f is the thermal conductivity of the insulating layer and t its thickness. Notice that the *system of equations (4.4.1)* is implicit, as R_{tot} is a function of h, which must be in turn derived from empirical correlations for free convection (*Equation (4.2.27)*) as a function of $T_{f,ext}$. Assuming polystyrene properties, an ambient temperature of 18°C and the whole range of water temperatures from 20 to 90°C, the external temperature of the insulating layer ranges from 19,4°C to 25,9°C, resulting in a small temperature gradient that will be still taken into account.

To perform a simulation, ambient temperature, pot dimensions, water volume and power input need to be set. Since the purpose of this demonstration is comparing results with those from the Clean Cooking Catalog, similar conditions should be imposed. Unfortunately, information from the catalogue are incomplete; however, it can be assumed that indications from the EPTP were rigorously followed, and thus that testing was performed for a large pot (about 7 L volume) with a water content of about 5 L. Lab temperature is set to 18°C, as for the WBT, even if a better strategy could be simulating different replicates for a range of reasonable ambient temperatures; to do so, real-time fluid properties could be implemented into the TST by means of specific software, which is left to future developments. As for the fuel, fir wood is assumed, as it is frequently used for lab testing and to keep uniformity with the WBT simulation; in this case, in fact, the same *FP* and $\dot{Q}_{input}$ can be used. Results follow in *Table 4.4.4*.

	η	SC [g/l]
EPTP	*average*	*average*
Catalog	30,2%	-
TST	30,8%	60,15
err%	1,3%	-

Table 4.4.4 – Averaged performance parameters for catalog and simulated EPTP.

Considering the impact of the missing information on the simulation precision, the output is incredibly close the exact value (standard deviations are not available from the catalog output). In this case, the simulation cannot reproduce any variability due to evaporation, as it is completely avoided; still, variability could be simulated accounting for different ambient temperatures, when not specified, by means of real-time fluid properties implementation. Also, it could be interesting to consider the implementation of different fuel types, resulting in different firepowers.

4.4.2 Prediction of different configurations

4.4.2.1 WBT vs EPTP

It would now be interesting to discuss the differences in Envirofit-Econofire performances as predicted by the two simulated protocols. To do so, a second simulation of the EPTP is performed setting identical pot dimensions and water content (2,5 L) to those used for the WBT. Results are shown in *Table 4.4.5*.

	η	SC [g/l]
2,5 L	*average*	*average*
WBT	28,34%	100,61
EPTP	29,69%	62,30

Table 4.4.5 – Comparison of WBT and EPTP performance evaluation referred to an Envirofit Econofire

If thermal efficiencies are comparable, specific fuel consumption is completely different. This is due to the different task performed in each procedure. In fact, as shown in *Figure 4.4.6*, the time interval needed to achieve the last 10°C ΔT in the boiling region (WBT) is much wider than the corresponding interval at lower temperatures, leading to a greater fuel consumption even if the stove has the same Burning Rate in both cases. Performance parameters like *SC* are therefore expected to vary substantially between procedures like WBT and HTP or EPTP that avoid the boiling region. This is the key reason why the WBT rejects moving away from an approximation of a cooking task; however, the fixed WBT approximated task cannot either encompass the variety of tasks potentially performed in a real context of use. The solution, as diffusely discussed in *section 3.8*, could be performing an IHT but under a culturally relevant burn cycle, as proposed by the WHT. In other words, if the real average burn cycle (in terms of time and power levels) is followed under an IHT procedure (*viz.* with a temperature limit below 90°C and the lid on), the pot can be regarded as a heat sink and has no impact on fuel consumption nor on the testing time, as no "task" is actually performed.

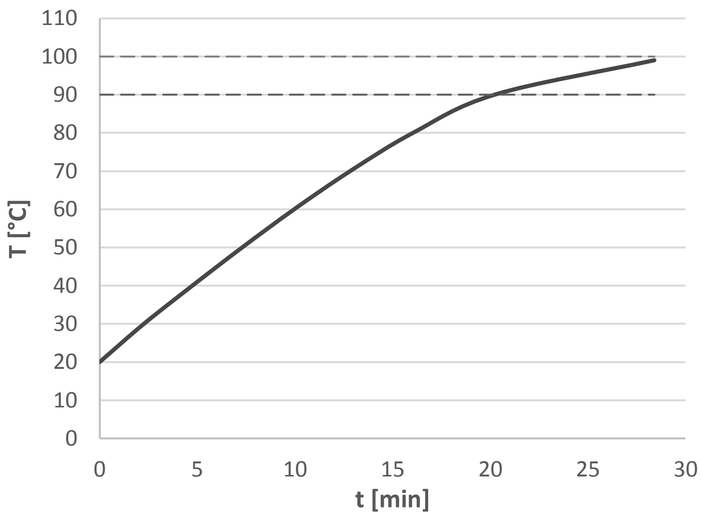

Figure 4.4.6 – Temperature trend over time for water in a cooking pot heated by a constant heat source, with no lid or any other form of insulation.

4.4.2.2 The TST as an improvement to the WHT

A simpler solution than actually reproducing the real burn cycle with a WHT procedure, would be testing ICS performances with an IHT for each required power level for a single fuel/pot combination and subsequently reproducing a desired burn cycle by means of the TST (simulating also the same pot used in the field and the same local ambient condition). For example, considering again the sample burn cycle in *Figure 3.7.4*, it could be easily reproduced by means of a weighted proportion of TST performances for high, medium and low powers.

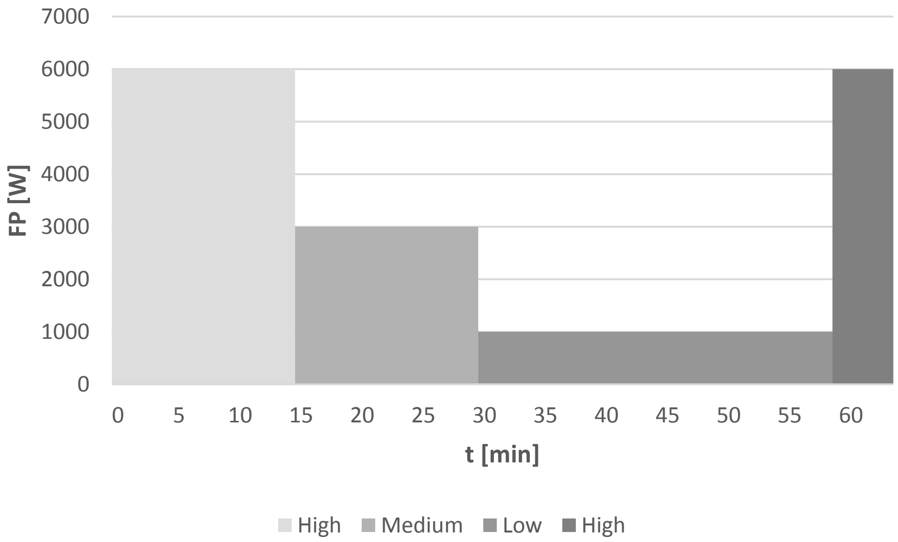

Figure 4.4.7 – Example of a burn cycle resulting from the combination of two cooking tests, adapted from Pemberton-Pigott [83]; high, medium and low represent firepower levels.

This could help strongly reducing the testing time in the lab needed to perform a complete WHT procedure; a short IHT experiment for each power level would be enough to simulate the whole procedure. Furthermore, if future developments will allow to virtually simulate different fuels, TST input parameters derived from a single set of IHT procedure replicates could be used to simulate not only one specific burn cycle, but any desired burn cycle referred to any target population. The major limitation of the WHT procedure would be thus solved, and a few experiments, combined with the knowledge of representative burn cycles and fuels, could be used to simulate stove performances in different contexts of use. Also, the "time to boil", often considered as the most important parameter by stove users [70], could be virtually simulated on the basis of IHT data for any external condition, any pot dimension or water content.

Conclusions

The ultimate aim of this thesis work was to identify the main criticalities related to current Improved Cooking Stoves (ICSs) testing methodologies and to provide indications for a better testing approach. The unreliability of current testing protocols is, in fact, a key challenge for the success of stove dissemination programs and carbon-financed projects. A critical issue is represented by the dominant practice of solely relying on lab protocols as performance indicators, regardless of their lack of reliability and their disregard for the final context of use. Different attempts at addressing the problem have led to the diffusion of a variety of protocols, though none of them has been able to emerge as an accepted standard, further complicating the framework.

Therefore, the analysis focused firstly on a comprehensive and **critical review** of all existing lab protocols, trying to highlight strengths and weaknesses of each approach and to draw conclusions for an effective solution; the literature, in fact, seemed to be missing a specific study in this direction. The review work also benefited from the author participation to the 2016 ETHOS Conference, which allowed to include a discussion of protocols under development by the ISO Technical Committee 285. Findings from the review confirmed that current lab protocols, and Tiers of Performance based on their output, should not be viewed as technology selection tools, as they carry little information about actual average field performances. In fact, as more and more studies seem to demonstrate, performance evaluation is not merely concerned with the stove, but rather depends on an integrated Cooking System, composed of: stove design, fuel and moisture content, burn cycle and type of pots used. The concept that relying on a fixed testing procedure it is possible to predict performances of a specific stove in any circumstance is totally misleading. This should be better highlighted to avoid serious implications on stove dissemination programs and climate impact estimates.

Furthermore, the review analysis seems to suggest that current testing protocols may also provide misleading guidance about stove designs; in fact, no design assessment can be considered as generally valid, as stoves do not have intrinsic performance characteristics, but are rather dependent on local circumstances, particularly as regards fuel consumption and emissions. Most of current protocols perform design comparisons by fixing at least the burn cycle, whilst a reliable design assessment should be able to capture stove performances over a broader range of conditions. Accordingly, it has been suggested that better testing might be achieved by firstly identifying a repeatable and scientifically validated procedure, in terms of metrics and thermodynamic hypothesis, and subsequently by integrating it with considerations on the fuel, the pot and the burn cycle that are relevant to the final users. This should reduce the gap between lab and field performances while allowing for a significant and reliable design comparison. Similar indications also seem to be in agreement with the current path of the ISO process. However, the review study did not provide sufficient indications to identify the requirements needed by a testing procedure in order to be regarded as repeatable and scientifically validated.

With the aim of drawing definitive conclusions about requirements for repeatability, a **theoretical and experimental study** concerning the main sources of variability related to lab testing was performed; vaporisation and uncertainty in thermocouple reading in the boiling region were considered. Although previous studies in the literature already tried to address the issue, they were based on a few empirical observations and lacked a solid and detailed theoretical background. In this case, the principle of falsifiability was followed: solutions were firstly analytically derived and subsequently tested against empirical observations. Accordingly, an effective theoretical model for water vaporisation up to 90°C was defined, implemented in Excel, and optimised through a comparison against experimental data; this restricted model allowed to demonstrate that the rate of vaporisation, assuming fixed pot diameter and lab setting, is only influenced by ambient air relative humidity. Secondly, the vaporisation model was integrated into a generalised heat and mass transfer model, considering the whole heat-source/cooking-pot/ambient system and again implemented in Excel, allowing for any kind of sensitivity analysis. Sensitivity simulations suggest that the total mass of water vaporised may be affected by significant variability due to uncontrolled and natural fluctuations of indoor relative humidity in a realistic range; furthermore, variability rapidly increases with water temperature. Most important, as vaporisation affects in turn the test ending time through the thermal power balance, any testing output is directly or indirectly influenced by this variability. As a demonstration, the theory of combined uncertainty was applied to common performance parameters (thermal efficiency and specific consumption), showing that at 90°C vaporisation-related variability may be responsible for relevant uncertainties in those outputs. Placing a lid on the pot would result in an optimal control of the evaporation phenomenon; a few grams of water would vaporise before saturating the control volume and arresting the process, regardless of any further increase of water temperature. A second source of uncertainty was also theorised in the form of thermocouple reading fluctuations in the boiling region; this could not be eliminated unless setting a limit to the water temperature before the appearance of boiling phenomena.

Theoretical findings were subsequently tested against empirical observations based on experimental testing on an electric heater. Experimental evidence corroborated previous results showing an increasing variability of vaporisation with temperature and an even larger variability in the boiling region, which was theoretically predicted even if not simulated due to model constraints. When testing with a lid on the pot, instead, no statistically significant differences were observed in the total amount of water vaporised at different temperatures. The impact of thermocouple fluctuations at 95°C was also separately evaluated, and found to be statistically significant ($p < 0,05$). It is thus concluded that a reliable and scientifically validated procedure should be performed with a lid on the pot and setting a limited maximum temperature before the boiling region (any temperature up to 90°C might be chosen). This has been defined an *Ideal Heat Transfer* (IHT) procedure.

To provide a reliable assessment of ICS performances, however, the IHT procedure should still be integrated with considerations about the Cooking System. The WHT, among the promising protocols under development, suggests to realise such integration by testing the stove over the typical burn cycle of the target population and using similar fuel and pots. However, a much more cost-effective and simple solution could be represented by testing a stove in the lab with an IHT procedure for a single fuel/pot combination and then performing an analytical simulation of all the different conditions and pot dimensions needed. To realise that, an extended version of the model was proposed and called the ***Testing Simulation Tool*** (TST). Although a complete development of the TST is left to further studies, first changes were implemented to demonstrate the tool potentiality to simulate ICS performances in different conditions with good approximation, based on a single lab experience. A simple procedure to implement cookstoves into the model was defined, and a demonstration study was carried out for an Envirofit-Econofire ICS model. In order to have comparison criteria, the TST was set as to reproduce five Water Boiling Test (WBT) replicates performed by the author at Politecnico di Milano and Emissions & Performance Testing Protocol (EPTP) results from the Clean Cooking Catalog; changes were introduced to extend the evaporation model to the boiling region and to simulate the EPTP configuration. Simulated results showed a very good consistency with experimental data for both WBT and EPTP. Furthermore, the tool was used to simulate equivalent results for different pot dimensions and water volumes, highlighting the limitations entailed by procedures that are based on an approximation of cooking tasks. These promising results seem to encourage a further development of the TST.

A completely developed TST, based on a few IHT reliable experiments and combined with the knowledge of representative burn cycles and fuels, could be used to simulate stove performances not only for one specific burn cycle, but for any desired burn cycle referred to any target population, thus solving the major WHT limitation. It could reproduce any kind of ambient condition, possibly further reducing the gap between lab and field performances. Also, the "time to boil", often considered as the most important parameter by stove users, could be virtually simulated on the basis of IHT data for any local specific condition: external ambient conditions, pot dimension or water content. Further studies should be therefore dedicated to the implementation of the Ideal Heat Transfer procedure into the tool and subsequently to a final evaluation of the TST effectiveness against field performances for a selected case-study.

The main findings are hence summarised:

1. Current testing protocols carry little information about actual average field performances and might provide misleading guidance about stove designs;
2. A better approach could be represented by the integration between a repeatable and validated procedure and the representative Cooking System;
3. This procedure should be an *Ideal Heat Transfer* (*IHT*), performed with a lid on the pot and with a limited maximum water temperature (any temperature up to 90°C could be chosen), as theoretical analysis and testing proved those practises effectively reduce thermodynamic uncertainties;
4. A *Testing Simulation Tool* was created with the aim of simulating the integration with any kind of Cooking System in any desired external condition, based on a single *IHT* lab experience for each required power level.

Appendix

This section is dedicated to further details about the laboratory equipment used to perform the evaporation experiment (*paragraph 4.3.2.1*) and the Water Boiling Test (*paragraph 4.4.1.1*). Characteristics of pots, stove and electric heater are not here reported as already presented in the mentioned paragraphs.

Evaporation experiment

A portable temperature data logger was used to measure water temperature, namely *Delta OHM HD 9016 Digital Microprocessor Thermometer*. The instrument was equipped with a K-type thermocouple, specifically tared at Politecnico di Milano – Department of Energy for the whole range considered (18÷100°C).

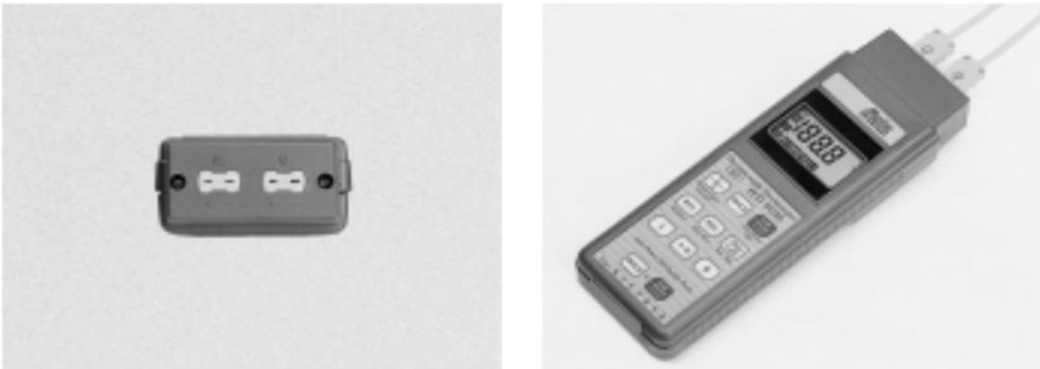

Figure A 1 – Delta OHM HD 9016 Digital Microprocessor Thermometer; source: Delta OHM [102].

Instrument resolution: ≤ +199.9°C (+199.9°F) 0.1°C (0.1°F);
≥ +200°C (+200°F) 1°C (1°F).

Instrument precision: From 0°C to +199.9°C (+199.9°F) ±0.1% of reading ±0.4°C (±0.7°F) ±1 digit;
From 200°C (200°F) to full scale or from -0.1°C (31.8°F)

to -200°C (-328°F) ±0.2% of reading +1°C (+1.8°F) ±1 digit.

This precision applies to an environment temperature of 25°C ±5°C.

Water Boiling Test

Laboratory performances of cookstoves were evaluated by means of the *Portable Emissions Monitoring System* (PEMS), purchased from *Aprovecho Research Center* [103]. PEMS is primarily designed for measuring emissions and includes a portable hood with a fan for collecting and measuring CO_2, CO and PM, but is also equipped with a thermocouple for water temperature measurement. A "Sensor Box" receives instrumentation signals and calculates data. The Sensor Box is connected to the computer through a specific software, allowing for real-time display and record of data (*Figure A 2*).

Figure A 2 – PEMS Sensor Box and real-time data output to the computer.

Figure A 3 – PEMS in use at Department of Energy, Politecnico di Milano.

Although emissions performances were not part of the experiments performed for this thesis work, all the PEMS internal sensors are presented below:

- CO (carbon monoxide) sensor, electrochemical cell. The conductivity between two electrodes in the cell is proportional to the CO concentration.
- CO_2 (carbon dioxide) sensor, NDIR (non-dispersive infrared). Measures CO_2 concentration.
- PM (particulate matter) sensor, scattering photometer. Includes both a laser and a light receiver. When smoke enters the sensing chamber, particles of smoke scatter the laser light into the receiver. More light reaching the receiver indicates more smoke in the chamber.
- Pressure transducer, outputs a signal based on the pressure drop measured across the flow grid. The flow grid is an amplified pitot tube that provides a low pressure drop through the system and a strong differential pressure signal, averaged across the entire duct cross-section. Flue gas velocity, and volume and mass flow rate within the duct, are measured and recorded using the Magnesense® pressure transducer.
- Analogue pressure measurement, provided by the Magnehelic® sensor. Measuring in parallel to the pressure transducer mentioned above, the

Magnehelic sensor provides a calibration to the Magnesense for each test.

- Flue gas temperature sensor, provides real-time data required to calculate the density of exhaust air and in turn the mass flow of emissions.
- The thermocouple (TC) temperature sensor is used to record the water temperature of the pot. The thermocouple temperature output is linear up to 400°C, and the thermocouple probe provided with the PEMS is rated for temperatures up to 250°C. Precision is ±0,1°C.

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