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SCUOLA DI INGEGNERIA INDUSTRIALE
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EXECUTIVE SUMMARY OF THE THESIS

Sustainable solar roasting of coffee beans

TESI MAGISTRALE IN FOOD ENGINEERING

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1. Introduction

Coffee is one of the most traded commodities in the world with a global consumption estimated at over 3 billion cups per day and a continuing growing demand.

Coffee industry generates, in global terms, an annual income of $200 billion USD according to International Coffee Organization (2020).

There are different stages that form the coffee making process: growing, harvesting, hulling, drying and packing, blending and roasting. The entire supply chain is further extended by several intermediaries, including global transporters as well as exporters and retailers.

Manage a complex and global supply chain in a sustainable way became nowadays a focus for coffee producers. The multiple actors involved in the supply chain need to establish concrete actions or strategies to address the principal sources of emissions. The use of efficient technologies will reduce the relation between energy consumption and the impact associated to its energy footprint, mainly if it is opted, as far as possible, take advantage of solar energy or other alternative energies, although this may initially affect the intensity of production [8].

Performing a life cycle assessment of coffee production, the results show that the majority of carbon was produced in the exportation phase when coffee beans are transported from the country of origin to the country of consumption.

Besides transportation, the most impactful operation, find out through a logistic free analysis of coffee supply chain, is the roasting process.

So alternative solutions can be investigated to perform more sustainable coffee roasting process.

2. Scope of the study

The scope of our study focuses on the simplified mathematical evaluation of the feasibility of solar roasting models as a replacement for the traditional process . The aim is to understand whether the use of a renewable source such as solar energy can partially or totally replace the use of fuel in the coffee roasting process in a way that makes it more sustainable. The analysis wants to establish if the individual design, characterized by physical equations describing its dynamics, can bring the coffee bean to temperatures capable of causing the second crack (220-240° C) in reasonable roasting time. The results obtained were then commented on, and the procedural feasibility was accompanied by the pros and cons of each model.

3. Roasting process

In the processing chain from the ripe coffee cherry to roasted coffee, roasting presents the most important step, whose main objective is to produce the desired aroma and taste, making coffee beans suitable for brewing [2, 8].

Roasting is an intense thermal treatment during which coffee beans are heated at high temperatures (160–240 °C) for times ranging between 5 and 20 min depending on the desired taste of the final product.

Roasting is a complex process involving both energy and mass transfer responsible for the main changes of the coffee beans in terms of weight, density, moisture, colour and flavour [7]. Endothermic process and reactions occur in the first stages of the roasting, while the undesirable exothermic pyrolysis of saccharides may occur at the latter roasting stages.

Traditional roasting technology consists in a forced flow of hot gases produced electrically or by burning oil or fuel gas in air, that pass through a moving bed of coffee. The heat is transferred from the hot gas to the bean by convective mechanisms and/or direct contact with the walls of the roaster. The motion of the beans is either produced by rotation or by flow of roasting gases.

Rotating drum roasters are the most employed equipment for batch or continuous processes. In this case beans are mixed with hot gases in a horizontal rotating drum (with or without perforated walls) or in a vertical fixed drum roaster with paddles. Among the others kind of roasters, fluidized bed and spouting bed roasting facilitate roasting for short time periods with low gas temperatures. The higher gas velocities in the roasting processes fluidized bed and spouted bed lead to a better heat transfer.

Physical and chemical properties of roasted coffee are highly influenced by process conditions during roasting, in particular by the time–temperature and time-moisture conditions within the coffee.

Thus, for the process optimization the moisture and temperature evolution in coffee beans during the roasting process need to be studied and modelled.

In this way, some researches have been investigated about the heat and mass transfer during drying of green coffee [11]. Schwartzberg, was the first to develop a semi-physical model to evaluate coffee bean temperature and moisture content during the roasting. Using the equations proposed by Schwartzberg (2002), a theoretical analysis of heat and mass transfer to evaluate the coffee bean's temperature and moisture content in bed batch system including the internal distribution was carried out by Hernandez et al. (2007), and Bottazzi et al. (2012). The latter proposed also a detailed heat transfer coefficient evaluation that include also the performance of the coffee roasters. Alonso Torres et al. (2013) also used the Schwartzberg (2002) model and solve it on a single bean using the finite volume technique in CFD. Fabbri et al. (2011) develop a numerical model, based on a 3D digitized geometry, able to describe the heat and moisture transfer inside the bean during roasting under natural convection. Also, Hyed et al., (2010) proposed a dynamical model, which takes in account heat and mass transfer at the surface and inside of the bean and validated it with a spouted bed pilot roaster.

4. Traditional roasting model

The heat and mass transport mechanisms during batch roasting using a hot air flow are described by the following mass and energy balance equations.

Moisture loss is controlled by the diffusive water transport in the bean as

$$m_{bd}\frac{dX}{dt} = -A_{gb}\rho_b k_w^{liq}\left(X - RH\frac{MW_W}{MW_b}\right) \tag{1}$$

X is the average mass fraction of water inside the beans and $k_w^{liq} = 15\, D_{eff\,w}/d_b$ is the mass transfer coefficient.

The beans temperature rise is given by the energy balance as

$$m_{bd}C_b(1+X)\frac{dT_b}{dt} = GC_g\left(T_{gi}-T_{go}\right) + \\ +m_{bd}\Delta H_{eva}\frac{dX}{dt} \qquad (2)$$

According to [17] the difference $(Tgi - Tgo)$ was calculated as

$$T_{gi} - T_{go} = \left(T_{gi} - T_b\right)\left(1 - e^{-\left(\frac{h_{eff}A_{gb}}{GCa}\right)}\right) \qquad (3)$$

Heat transfer coefficient h_{eff} between hot air and coffee beans was calculated as

$$h_{eff} = h_e/1 + 0.3Bi \qquad (4)$$

where A_{gb} is the area across which air to beans heat transfer occurs, h_e is given by the Ranz-Marshall equation [1] and the specific heat capacity as indicated in [1]:

$$C_b(1+X) = 1{,}009 + 0{,}007T_b\ [°C] + 5X \qquad (5)$$

The proposed model was solved through an Eulero forward approach simulating a roaster loaded with 4 kg_{dm} of coffee beans with an initial moisture content of 0.105 $kg_w/kg_{drymatter}$. The calculated water content and temperature profiles are shown in Figure 1 and 2.

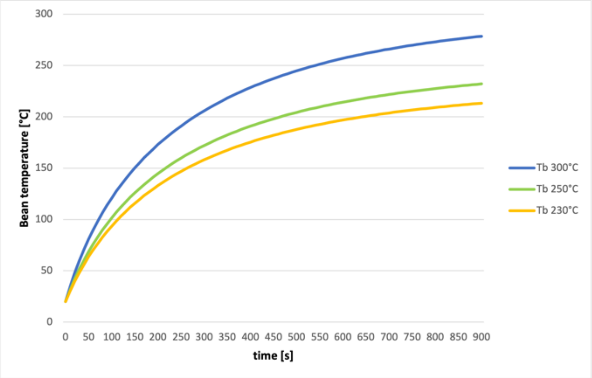

Figure 1: Bean temperature profile of traditional roasting for three imposed roasting temperatures

The T_b vs time profile shows a right trend although the heat generated by exothermic reaction is not included.

The curves show the strong relationship between hot air temperature and time necessary to achieve a complete roasting (240°C).

The moisture content simulation follows the usual process findings since in 900s of roasting the final moisture content reach the desired value of 2%.

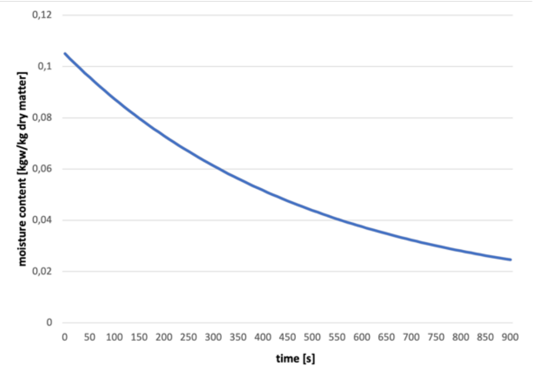

Figure 2: Bean moisture profile of traditional roasting

To validate the proposed model it is possible to compare the temperature trend of the roaster T_r, measured by a thermocouple, with that reported in the reference literature [3]. The T_r profile is given by

$$\frac{dT_r}{dt} = K_t(T_b - T_a) \qquad (6)$$

K_t is the thermocouple coefficient calculated as $K_t = {h_tA_t}/{m_tC_t}$[3].

The comparison is shown in Figure 3 where the orange line corresponds to the predicted T_r in [3], the blue line is the experimental one and the green line is the T_r referring to the model.

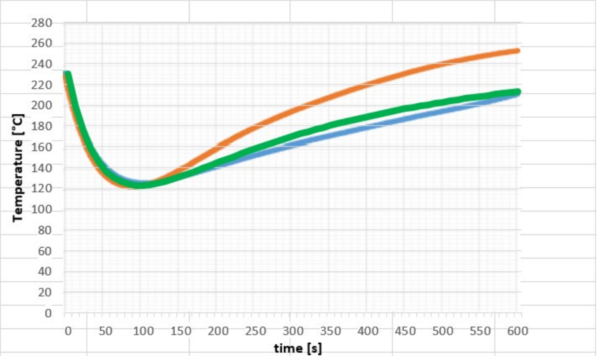

Figure 3: Comparison between model T_r and referencing T_r.

4. 1 Sensitivity analysis

In industrial applications, more than 4 kg of coffee are processed. To perform a scale up to roast larger batch it can refer to the process index as the first approximation. The PI is defined as

$$PI = \frac{G \times t_R}{m_b} = \frac{C_b(T_{bF} - T_{bo})}{C_a(T_{gi} - T_{go})} \qquad (7)$$

It has three degree of freedom, this allow to have an estimation of one variables parameters once the others are fixed. The reference PI used is calculated with data of a small batch analyzed in [3]. The sensitivity analysis on the traditional roasting process provides the results reported in the Figure 3, 4 and 5

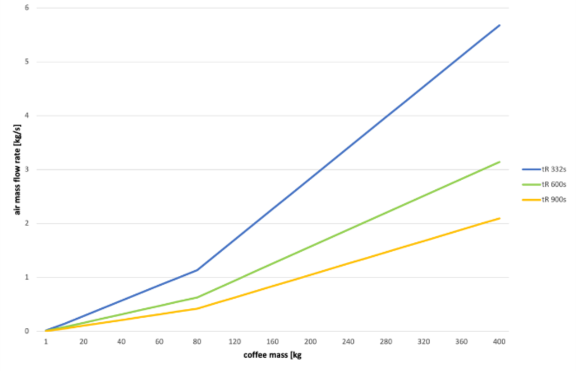

Figure 3: G variation compared to different amounts of coffee to be roasted in different roasting times (5,10 and 15 min)

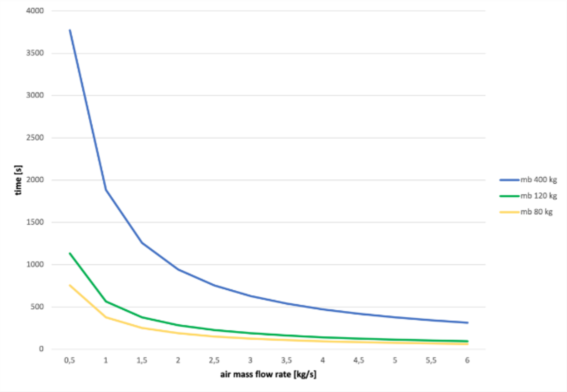

Figure 4: Variation of roasting time depending on the mass air flow rate used for different process batches.

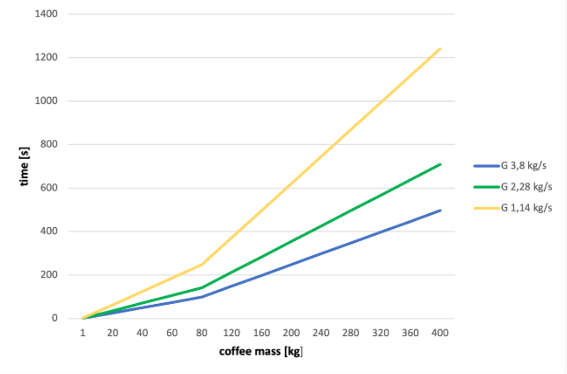

Figure 5: Variation of roasting time depending on the mass bean loaded at different G.

5. Traditional process with solar energy

The first proposed model aims to simulate the traditional roasting by heating air through a tube with sunlight. To do this, linear solar concentrators are required.

The energy and mass balances are the same as in the previous paragraph, since the process is identical (hot air on grain) and can be descripted by the roasting model reported in chapter 4. To verify the feasibility, however, it is necessary to evaluate the length of the tube needed to bring the air temperature to the value of interest. It is possible to calculate the pipe length Z as

$$\rho_a v A_p C_a \frac{dT_a}{dZ} = n_s \phi F \frac{dA_r}{dZ} - Q_{loss} \qquad (8)$$

where $dA_r = d_t \times dZ$ and n_s is the concentration ratio of the parabolic trough. The Q_{loss}, in first approximation, can be neglected, assuming that the receiver is well insulated [22].

The integration of the Eq. (8) leads to the plot shown in Figure 6 where the relationship between the length at the final air temperature is reported for multiplier n_s equal to 10.

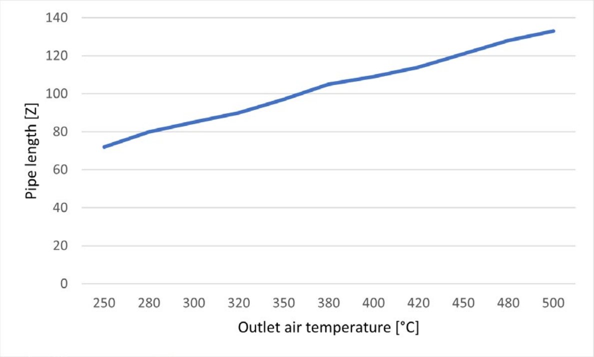

Figure 6: Relationship between temperature and pipe length.

The air flow rate passing through a single tube, given by G=$\rho_a v A_p$, is not enough to perform roasting on large scale, hence, more than one row of parabolic trough have to be used.

The total area required by this system is defined as

$$A_{tot} = S_{col} + (n° \; of \; rows - 2) \times Z \times d \; rows \qquad (9)$$

where the total collector surface is given by

$$S_{col} = n° \; of \; parabolic \; trough \; per \; row \; \times n° of \; row$$

$$\times\, area\ of\ one\ parabolic\ trough \qquad (10)$$

The number of rows can be estimated as the ratio of the total air flow required over the air flow in a single tube while the number of parabolic trough per row is obtained dividing Z for the length of a single device.

6. Roasting process with direct solar energy

The second proposed model uses solar energy with direct contact on the beans. Unlike the traditional and the previous case, in this case the temperature of the beans is greater or equal to that of the air that surrounds it depending on the roaster configuration chosen. The analysis is conducted on a perforated rotating drum coated with insulator.

6.1. Open drum

In the first configuration the opening hole of the drum is not closed, so as to put in direct contact the surrounding environment with the inside of the roaster. In this way you can approximate the temperature of the air in the roaster equal to the external one T_{amb}. The general energy balance on the system is

$$m_b C_b \frac{dT_b}{dt} = Q_{in} - Q_{loss} + Q_{eva} + Q_{react} \qquad (11)$$

The term Q_{loss} is given by the heat loss from beans and from the roaster; this last one is much lower so can be neglected. The reactions in beans start at temperature around 180-190°C and the heat generated by them (Q_{react}) become significative at higher T, so can be neglected.

Substituting all the terms in (11), the (12) is obtained

$$m_{bd} C_b (1+X) \frac{dT_b}{dt} = n_c \Phi A_c - h_{ba} A_{ba} (T_b - T_{amb}) + m_{bd} \Delta H_{eva} \frac{dX}{dt} \qquad (12)$$

The mass balance is given by the Eq. (4).

The specific heat C_b of the bean can be estimated accordingly to (5) while the convective heat transfer coefficient h_{ab} can be calculated by (4).

Solving the system of equations the temperature profile is

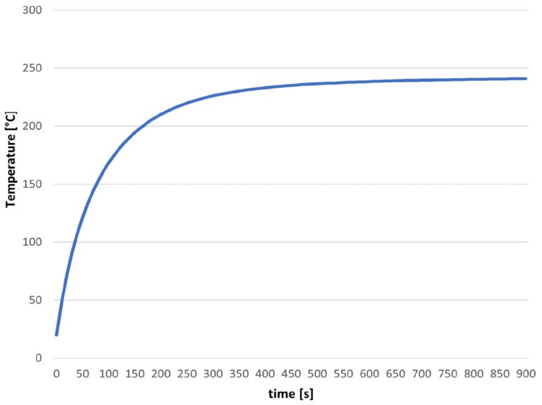

Figure 7: Bean temperature profile of open drum.

while the moisture profile is

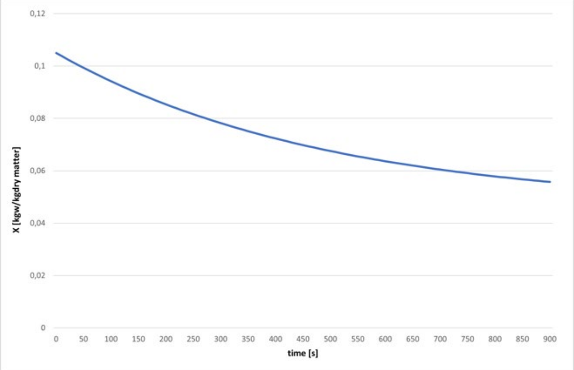

Figure 8: Bean moisture profile of open drum.

6.2. Closed drum

In this configuration the system is completely insulated, capping the opening hole with a glass cover that allows the transmission of the light coming from the panel. It is therefore no longer possible to consider the air temperature as the ambient temperature. For small drums, such as laboratory drums, instead consider that the temperature of the entire system (roaster, air and grains) is the same T_b. With this assumption, the energy balance becomes

$$m_{bd} C_b (1+X) \frac{dT_b}{dt} = n_c \Phi A_c \gamma_r - Q_{loss} + m_{bd} \Delta H_{eva} \frac{dX}{dt} \qquad (13)$$

where γ_r is the reflectivity of glass.

The Q_{loss} term refers to the heat losses from the roaster as $UA_d(T_b - T_{amb})$. Instead, the Q loss by convection air to bean is zero ($T_b \cong T_a$ at the same time).

Also in this model, the mass balance is given by Eq. (4) and C_b is estimated by the Eq. (5).

The bean temperature and moisture profile are reported

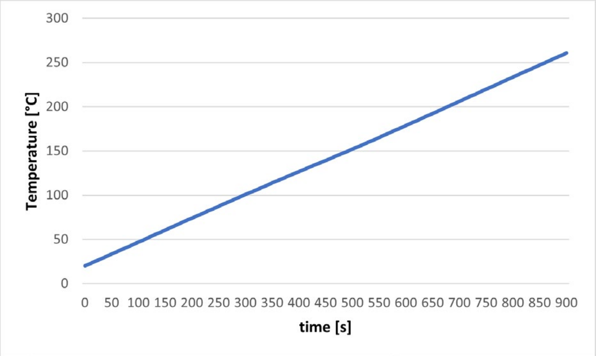

Figure 9: Bean temperature profile of closed drum.

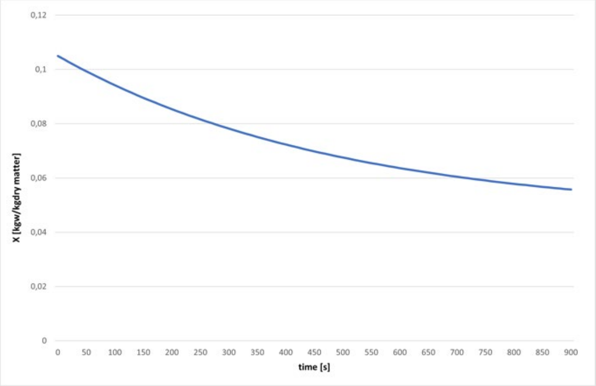

Figure 10: Bean moisture profile of closed drum.

As you can see, the temperature profile of the bean in this case differs greatly from the previous one. In fact, the heat losses from the roaster are very small and the asymptotic stagnation temperature, reached when $Q_{loss} \cong Q_{in}$, is decidedly high above 700° C.

7. Conclusions

The analysis carried out on the roasting process with the use of renewable solar energy, starting from the traditional model that approximates the results obtained by the cited authors, highlights how it is a valid alternative to fossil fuels. With appropriate systems, the proposed models give acceptable results in terms of temperature and time, less in moisture values reached by the grain due to the relative humidity of the surrounding environment. Although the results are encouraging it is good to keep in mind the criticalities of these models, on all the discontinuity of sunlight during the day that varies from latitude to latitude and depends on the conditions of cloudiness and the need for spaces and plants completely different from those in use. This study, however, is a starting point for a more detailed evaluation of the alternatives proposed both from the point of view of experimentation, essential to compare the theoretical results with the real ones, both from the point of view of the analysis of the olfactory and gustatory quality of the final product.

Nomenclature

Variable	Description	SI unit
A_{ba}	bean-air contact area	m^2
A_d	drum surface	m^2
A_{gb}	gas-bean contact area	m^2
A_p	passage área	m^2
A_r	receiver area	m^2
C_a	air specific heat	J/kgK
C_b	bean specific heat	J/kgK
C_g	gas specific heat	J/kgK
d_b	bean diameter	m
D_{effw}	effective water diffusivity	m^2/s
d_t	tube diameter	m
G	gas mass flow rate	kg/s
Gr	Grashof number	
G_{tot}	total gas mass flow rate	kg/s
h_{ba}	bean-air heat transfer coefficient	W/m^2K
h_e	heat transfer coefficient	W/m^2K
h_{eff}	effective heat transfer coefficient	W/m^2K
k_w^{liq}	water-bean diffusion coefficient	m/s
K_t	thermocouple constant	
m_b	beans mass	kg
m_{bd}	dry beans mass	kg_{dry}
n_{rows}	number of rows	
n_s	concentration ratio	
PI	process index	
MW_b	bean molecular weight	g/mol
MW_w	wáter molecular weight	g/mol
Q_{eva}	evaporation heat	W
Q_{react}	reaction heat	W
RH	relative humidity	
S_{col}	total collectors surface	m^2
t	time	s
T_a	air temperature	K
T_{amb}	ambient temperature	K
T_b	bean temperature	K
T_{bF}	final bean temperature	K
T_{b0}	initial bean temperature	K
T_{gi}	inlet gas temperature	K
T_{go}	outlet gas temperature	K
T_r	roaster temperature	K
t_R	roasting time	s
v	velocity	m/s
X	bean moisture content	kg_w/kg
Z	tube length	M
γ_g	glass reflectivity	
ΔH_{eva}	latent heat of evaporation	kJ/kg
ρ_a	air density	kg/m^3
ρ_b	bean density	kg/m^3
Φ	solar power per m^2	W/m^2

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