POLITECNICO DI MILANO

Facoltà di Ingegneria Industriale

Corso di laurea in ingegneria aeronautica

The Ignition of Gas Turbine Engines at High Altitude

Relatore: Prof. Aldo Coghe

Co-relatore: Prof. John J. Witton

Tesi di Laurea di:

Mattia VINCENTI

Matricola 754841

Mattia Vincenti

POLITECNICO DI MILANO

Facoltà di Ingegneria Industriale

Corso di laurea in ingegneria aeronautica

The Ignition of Gas Turbine Engines at High Altitude

Relatore: Prof. Aldo Coghe

Co-relatore: Prof. John J. Witton

Tesi di Laurea di:

Mattia VINCENTI

Matricola 754841

Acknowledgments

I want to start thanking Professor John Witton for all his support during my seven months in Cranfield University. He was my reference point when I started my thesis and he was also very patient with me when something didn't work. He continued in following me even after my departure and I appreciated it a lot.

Thanks to professor Coghe, that helped me once back in Italy with precious suggestions.

I took this long road alone six years ago, moving from my small village in Salento, Specchia, where I left my family and my old friends, in order to take the degree in this very difficult faculty in an amazing city like Milan.

During these years I met hundreds of people and it's quite difficult to thank all of them, so I will try to make a good summary!

First of all I have to thank my awesome parents, Pina and Aurelio, for their economical and moral support. They helped me in every possible and sometimes even impossible way! In my opinion it's very difficult to thank them for everything they have done for me in just few words..I hope that they will understand what I mean and that I love them more than my life. The same is for my beautiful sister, Eva..she's the most important person in my life and I lost the count of how many times she helped me and listened to my stupid problems just because she wants me to smile everytime..I know she's very smart and I know that she is going to do something wonderful in her life and I wish her all the best because she sincerely deserves it..

Now it's friends time..and the list here is very very long..I don't have a precious order in my head so I'm gonna thank them as they come in my mind but if I forget someone is just because I can't write 10 pages of aknowledgments!!

Let’s start with my old friends Luca, Carlo, Giovanni, Pierpaolo, Peperone, Marta, Alessandra, Simone, Becchiotto, Francesco, and all the others that asked me millions of times “How is it going dude??” or “no worries..you are a genius(???), you’re gonna pass this stupid exam easily!!”..all in rigorous Salentino dialect..Everytime that I came back in the south they were there to make me understand that nothing was changed and that they would have been ready to have fun and play football with me as always..!!Fortunately even after 20 years they are still my friends and I don’t wanna miss them never in my life!!

Then there are my “University” friends Palermitano, Peppe, Compà, Liotta, Chindemaccio, Sardo, Jacopo, Cuore, Presidente..T, ecc. ecc…..maybe “University” friends doesn’t give the idea of how important they have been and currently are for me..We shared an unrepeatable experience like University life.. we shared joys and sorrows together..everytime smiling..because smile is the first rule to live well! I lost the count of how many nights we shared partying and sleeping till midday the days after! My head is full of memories that I will never forget..I don’t have words to thank you guys..you have been fundamental to me!!!

Now it’s “sport” time..and it’s not easy as well to say thanks to the fantastic, amazing, incredible Bovisa calcio!!and so Ignazio, Corbo, Cortina, Gibe, Lo sordo, Paolino, Pasqualcol, Davisino, Gara, Zeno, and also Sam, Ale, Enea and many others.. We spent lots of nights on ridiculous pitches playing what we love more than anything else..football! We shared “international” tournaments in Ibiza, Poitiers and Toulouse with unforgettable memories of every type.. Guys sincerely you were very very important to me..and even if I didn’t win anything but I just lost some final matches..It’s been a pleasure to have met you and an honor to have played with you!!!

Now it’s “colleagues” time..Alberto, Jury, Giulio, Giada, Giuse, Sarah, Nonno, Mari…here again the name doesn’t say the truth..they have been more than simple colleagues but friends that helped me many times in this jungle that is our university..Thank you guys, I’m very happy to take the degree with some of you..it’s a circle that is closing today..Congrats to all of you and all the best for your future!

Another important section is the Cranfield one..well spending seven months abroad didn't scare me because I thought that I would have met new friends there and I was fortunately right! Let's thank Keeper, Michi, Iole, Antonio, the Tower, Filippo, Fede, Dagnele, Dani, Qbeda, Kingsley, Stefan, Rohan, Nour, Jason, Agata, Vag, and many any others..that made my English experience awesome and full of amazing memories..all the best guys..I hope to see you soon!!!

In the end I want to thank myself, because, although all the people just cited, many times I was alone, full of "problems" or things to do..and I spent lots of nghts awake just because I want to do it! Because I love what I do and I want to do it in the best way I can! So..Thank you Matty!! All the best, congratulations!

Thank you for your attention..now it's better to start talking about serious topics!

Table of Contents

Figure Index

Table index

Abstract

This work deals with one of the most important requirements that a gas turbine engine has to fulfil: its altitude relight capability.

Relighting this kind of engine at high altitude is more challenging than at sea level because of adverse temperature and pressure conditions. Furthermore the combustion efficiency is very low due to the poor fuel atomization quality, leading to slow shaft acceleration rates.

All the processes, parts of the engine and phenomena connected to the ignition are described, starting from a description of the most important engine's components, till atomization, evaporation and ignition process, with also some digressions about fuel properties and different kind of atomizers and igniters.

In the last chapter a preliminary analysis is developed, trying to give a global vision about the ignition process and the flame stabilization. The results are then compared to the ones found by Ballal and Lefebvre in their work about the influence of flow parameters on minimum ignition energy.

The purpose of this master thesis is to make the first move towards the construction of a box of conditions that allow the gas turbine engine restart at any altitude.

Keywords: Gas turbine engine, Ignition, Atomization, Evaporation, Quenching distance, Minimum ignition energy

Sommario

Il lavoro di tesi riguarda una delle richieste più importanti che un turbogetto deve soddisfare, cioè la sua capacità di riaccendersi in quota.

La riaccensione di questo tipo di motore ad alta quota rappresenta una sfida più difficile rispetto all'accensione al livello del mare, a causa di valori di temperatura e pressione sensibilmente minori. Inoltre la bassa qualità del processo di atomizzazione inficia anche l'efficienza di combustione, comportando ratei di accelerazione minori dell'albero.

In questo lavoro sono descritti tutti i processi, le parti del motore e i fenomeni connessi all'accensione di un turbogetto, a partire da una descrizione dei componenti più importanti del motore, fino ai processi di atomizzazione, evaporazione e ignizione, con alcune digressioni a proposito di vari tipi di atomizzatori e accenditori che potrebbero essere utilizzati.

Nell'ultimo capitolo inoltre è stata sviluppata un'analisi preliminare e semplificata che riguarda l'accensione e la stabilità di fiamma all'interno della zona primaria della camera di combustione di un turbogetto. I risultati ottenuti sono stati poi confrontati con quanto ottenuto da Ballal e Lefebvre nel loro lavoro riguardante l'influenza di alcuni parametri sull'energia minima di ignizione.

L'obiettivo principale di questo lavoro di tesi è di compiere il primo passo verso la costruzione di un "box" di condizioni all'interno del quale è possibile ottenere la riaccensione di un turbogetto.

Parole chiave: Turbogetto, Ignizione, Atomizzazione, Evaporazione, Quenching distance, Energia minima di ignizione.

Indice dei capitoli

Capitolo 1

Gas Turbine Engine: Applicazioni e componenti.

Il primo capitolo di questo lavoro di tesi riguarda in linea generale il ruolo del turbogetto in ambito aeronautico e la descrizione dei suoi principali componenti, in modo da sottolinearne la loro importanza nell’ambito della riaccensione in quota.

Capitolo 2

Windmilling.

Il secondo capitolo riguarda il Windmilling.

Il Windmilling è uno dei problemi più importanti cdi cui bisogna tener conto in fase di progetto del motore, in modo da poterne garantire la riaccensione in quota, quando le condizioni di pressione e temperatura rappresentano un forte ostacolo.

In questo capitolo è quindi presente una descrizione del fenomeno, con caratteristiche tipiche e possibili soluzioni.

Capitolo 3

Combustion Process.

Il terzo capitolo analizza nel dettaglio il processo di combustione, fornendo dettagli dal punto di vista chimico che potrebbero risultare utili per comprendere i problemi relativi ad una riaccensione in quota.

Capitolo 4

Fuel Properties.

Se si vuole ottenere una buona atomizzazione e un’affidabile riaccensione, soprattutto ad alta quota, è importante notare come molte proprietà del combustibile scelto possano influenzare questi processi.

Questo capitolo si propone quindi l’obiettivo di descrivere le proprietà più importante del combustibile, come queste vengono misurate e come possano influenzare atomizzazione e ignizione, il tutto supportato da grafici e tabelle contenenti i valori standard per combustibili differenti.

Capitolo 5

Atomization Process.

Il quinto capitolo è molto importante in quanto si occupa del processo di atomizzazione, e quindi di uno dei processi principali che possono influenzare la riaccensione in quota di un turbogetto.

Il processo di atomizzazione riguarda trasferimento di massa e calore, ed è influenzato sia dalle proprietà del gas che da quelle delle particelle liquide.

In questo capitolo è presente un’analisi dettagliata del processo, con inoltre una descrizione dei principali atomizzatori utilizzati e delle dimensioni tipiche delle gocce di combustibile da essi prodotte.

Capitolo 6

Evaporation Process.

L’evaporazione delle goccioline di combustibile presenti nello spray è un passo fondamentale per la loro seguente combustione, soprattutto nel caso trattato in questo lavoro di riaccensione ad alta quota.

Il processo di evaporazione riguarda il trasferimento di massa e di calore,ed è influenzato sia dalle proprietà del gas che da quelle delle particelle liquide di combustibile.

In questo capitolo sono descritti diversi modelli che descrivono il processo, analizzati nel dettaglio e confrontati.

Capitolo 7

Ignition Process.

In questo capitolo il processo di ignizione è analizzato in tutte le sue sfaccettature, con una descrizione dei parametri fondamentali come la quenching distance o l'energia minima di ignizione, e le loro dipendenze dalle condizioni operative, dalle proprietà del combustibile e da altri parametri.

In particolare diversi lavori, soprattutto di Ballal e Lefebvre, sono stati ripresi in modo da fornire grafici e risultati sperimentali di assoluta importanza nell'ambito della riaccensione di un turbogetto, con inoltre numerose correlazioni per i parametri fondamentali che descrivono il processo di ignizione.

Capitolo 8

Ignition Systems.

Questo capitolo presenta una descrizione di differenti tipi di accenditori, analizzati attraverso i rispettivi vantaggi e svantaggi, che sono o potrebbero essere utilizzati su un turbogetto.

Capitolo 9

Simplified analysis about ignition and flame stabilization for a simple turbojet.

In questo capitolo è stata sviluppata un’analisi preliminare e semplificata riguardante l’accensione di un turbogetto e la stabilizzazione della fiamma ad ignizione avvenuta.

Sulla base di alcune ipotesi semplificative è stata ricostruita la zona primaria della camera di combustione, con annesso vortice di ricircolo per la stabilizzazione della fiamma, ed un’analisi dei dati ha portato al calcolo del rapporto aria/combustibile in diverse zone della camera di combustione in modo da determinare la zona che favorisce l’ignizione della miscela.

I dati ottenuti sono stati confrontati con alcuni risultati sperimentali ottenuti da Ballal e Lefebvre.

Capitolo 10-11

Conclusions and Future Goals.

Negli ultimi due capitoli sono presenti le conclusioni e gli sviluppi futuri che questo lavoro può comportare, a partire da risultati e conoscenze ottenuti e dalle semplificazioni fatte per l’analisi sviluppata al capitolo 9.

Table of Chapters

1. G.T. Engines: Applications and components

The first chapter of this thesis deals with the role of G.T. Engine in aeronautic field and gives a description of its most important components, trying also to underline their roles in the ignition process.

2. Windmilling

During the design of an engine, one of the most important problems that has to be faced is to guarantee a reliable relighting of the engine under windmilling conditions, in particular at high altitude, where temperature and pressure conditions can be an obstacle to the ignition process. In this chapter a description of this relevant phenomena is provided, with typical characteristics and prospective solutions.

3. Combustion process

The third chapter analyzes in details the Combustion Process, giving some chemical details that could be useful to understand some problems related to the ignition process.

4. Fuel Properties

In order to obtain good atomization and reliable ignition, in particular at high altitude, it is important to note that some fuel properties can influence these processes.

This report is written to provide a description of these relevant properties, how they are measured and how they can affect atomization and ignition, all supported by tables containing some standard values for different kinds of fuel.

In order to be consistent, other properties are reported, although they are less relevant than the others for the purpose of this work.

5. Atomization Process

The fifth chapter deals with the atomization process, one of the most important processes that characterize the G.T. Engine. In this part that process is analyzed in details, with a great attention to the most used kinds of atomizers and their typical mean drop size.

6. Evaporation Process

Spray vaporization is a fundamental process in combustion, in particular if dealing with the problem of engine ignition and relighting. The liquid process involves mass and heat transfer, and is influenced by both gas and drops properties. In this chapter, different models of approaching this process are provided, with an analysis of the different choices to describe it.

7. Ignition Process

In this chapter the ignition process is described in all its facets, with a description of fundamental parameters like the minimum ignition energy and the quenching distance, and all their dependences on operating conditions, fuel properties and other variables.

8. Ignition Systems

This chapter deals with all the different ignition systems that could be chosen for a G.T. Engines, with all their advantages and disadvantages.

9. Simplified analysis about ignition and flame stabilization for a simple turbojet.

In this chapter an analysis regarding a simple turbojet is presented. This kind of analysis is simplified by using hypothesis that are validated by the experimental experience, and deals with the ignition of the engine at different altitudes, with the position of the igniter and with the stabilization of the flame once the combustion is started. The results are then compared with some experimentale ones found by Ballal and Lefebvre.

1. G.T. Engines: Applications and components

1.1 Introduction

The Gas Turbine Engine is one of the most important engines, used to drive different applications. Its most important components for an aeronautical engine are:

- Compressor
- Combustion chamber
- Turbine
- Nozzle

The air at ambient conditions is forced to pass through the compressor, that increases its pressure. The pressurized air flows in the combustion chamber where is mixed with fuel in order to start the ignition. In this way a large increase of temperature of the combustion products is obtained. The exhaust gases pass through the turbine, where expansion reduces their temperature, accelerating the combustion products towards the nozzle. In this way the turbine obtains the energy to drive the compressor. The accelerated exhaust gases flow in the nozzle where are further accelerated and expelled, obtaining thrust.

This is only a brief description about the principle of operation of a gas turbine engine in aeronautical environment, but other applications are also driven by this kind of engine, in order to obtain thrust or power, like the automotive application, the marine one or the power generation and the industrial mechanical drive applications. In some of these cases the first competitor is the Diesel Engine, because of its better SFC and start time, but also the G.T. Engine is characterized by important advantages, like high torque,

lower weight and volume per unit power, lower maintenance cost, longer time between overhaul and lower emission of pollution.

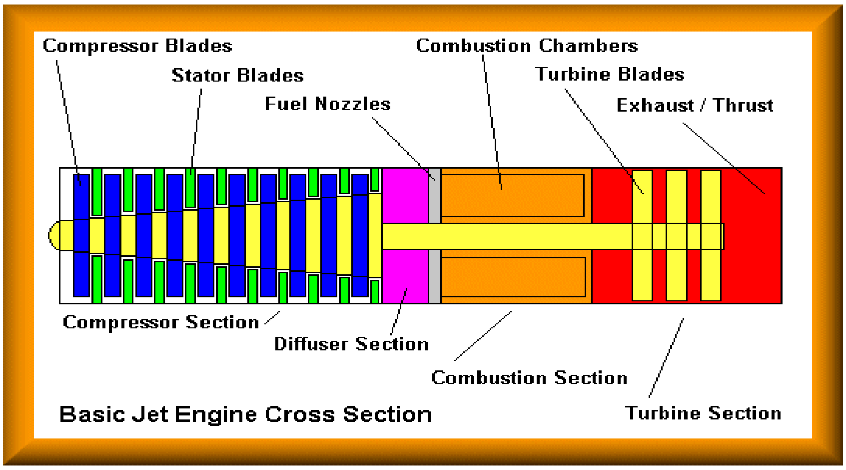


Figure 1 Gas turbine engine section

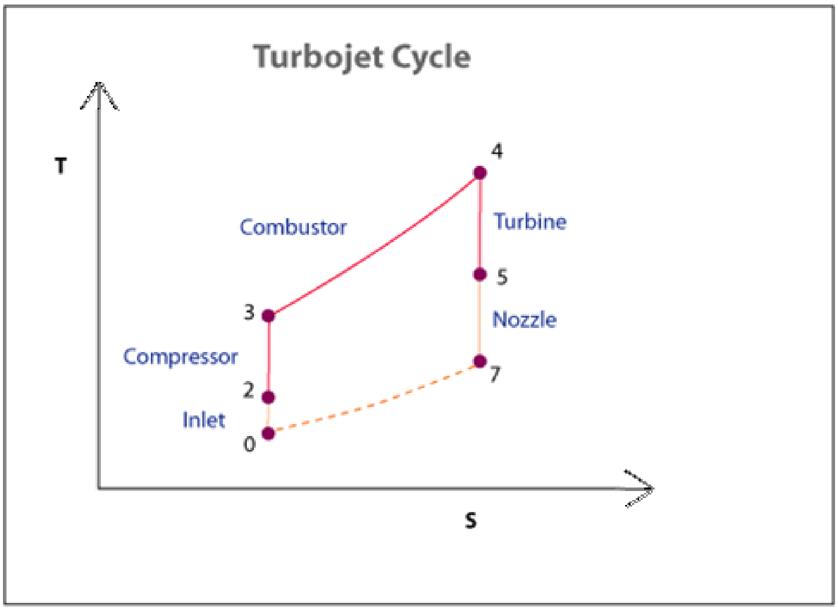


Figure 2 Ideal turbojet cycle

1.2 Aircraft Applications

Since the aeronautical environment is characterized by key parameters like SFC, weight, frontal area and cost, the G.T. engine is the most used, also because of other advantages like an acceleration time of 5 seconds for civil and 4 seconds for military engines. To estimate the suitability of an engine configuration for a particular flight mission, the most used parameter is the Range factor, that represents the ratio of the weight of fuel and engine to the engine net thrust less pod drag, for a range and flight speed.

It's important to make some considerations about the flight Mach number M:

- $0.3 < M < 0.6$, the turboprop is the best powerplant, because it has a high propulsive efficiency and so better fuel consumption than a turbojet or turbofan.
- $0.6 < M < 0.8$, also turbojet and turbofan are good powerplants, and the choice depends on the kind of application.
- For $M = 0.8$, the high bypass ratio engine is the best powerplant.

1.2.1 Turboprops and Turboshafts

Turboprops characterize the fixed wing aircraft. In this kind of application the G.T. engine provides shaft power to drive a propeller. The engine is typically of free power turbine configuration with a single spool, and compressor can be centrifugal or axi-centrifugal, while turbine involved is usually axial. Typical pressure ratio between 7:1 and 10:1, and SOT between 1250 and 1450 K.

Turboshafts characterize the rotary wing aircraft. In this field the engine is usually single spool, since rotor pitch may be varied to change load at constant speed. Typical pressure ratio 17:1, and typical SOT: 1500 K.

1.2.2 Turbofans, Turbojets

These kind of applications are used in different aircraft, like UAV, long range cruise missiles, subsonic commercial aircraft, military trainer, supersonic civil transport and advanced military fighter.

For UAV the most important thing is to achieve the minimum cost, and so it’s typical to use single spool turbojets, in particular with a centrifugal compressor, characterized by both lower cost and weight. Typical pressure ratio between 4:1 and 8:1, with SOT around 1250 K (typical value for uncooled turbine blading).

Large range cruise missiles are characterized by medium bypass ratio turbofans with centrifugal compressor, a pressure ratio of 10:1 and a value of SOT around 1250 K.

Subsonic commercial aircraft use turbofans (SOT around 1650 K), while for military trainer both turbojets and turbofans compete.

Turbojets and turbofans with bypass ratio less than 1:1 are the typical engines for supersonic civil transport, with a pressure ratio of 14:1 and SOT level over 1600 K.

For the advanced military fighters low bypass ratio afterburning turbofans are used, with pressure ratio of 25:1 and SOT over 1800 K.

1.2.3 Auxiliary Power Unit

In the aeronautical field, auxiliary power unit (APU) is an important device, used often for the main engine starting but also to supply cooling air for aircraft secondary systems, and electrical power when main engines are shut down. This kind of device usually uses simple cycle gas turbine, with centrifugal compressor, with a pressure ratio of 4:1 and SOT around 1250 K. APUs can be pneumatic, if supplying high pressure air to the main engine, or jet starters if they apply torque directly to the main engine HP shaft.

1.3 Gas Turbine Engine Components

Since this project deals with ignition of gas turbine engines, it is useful to analyze the main parts that compose such engine, to understand how these components can affect the ignition process. Therefore compressor, burner, and turbine are described below.

1.3.1 Compressor

The compressor is one of the most important component of a gas turbine engine. Its main purpose is to increase the total pressure of the air stream that flows in the combustion chamber, by absorbing the minimum shaft power possible. It's driven by turbine.
There are two different kinds of compressor, the axial and the centrifugal.
The main parts of the axial compressor are a row of rotor blades and a row of stator blades, even if sometimes outlet guide vanes (OGVs) are used to carry structural load and to straighten the flow from the compressor, or variable inlet guide vanes (VIGVs) and variable stator vanes (VSVs).
A single spool compressor is composed by one rotor assembly and stators with different number of stages, depending by the desired pressure ratio, while a multi spool compressor is composed by more rotor assemblies each driven by their own turbine, in order to obtain a higher pressure ratio and more flexible operation.

It is very common to scale a component's design of a GT Engine, whose characteristics are represented by proper scaling factors. In case of an axial compressor it is important to know that while pressure ratio, efficiency, blade speeds and velocity triangles are unchanged, rotational speed changes inversely proportional to the linear scale factor and flow changes proportional to the linear scale factor squared.
As hinted previously, a compressor is also characterized by an efficiency. It is useful to describe the two different efficiencies that are common for a compressor, the polytropic and isentropic ones:

- Isentropic efficiency represents the ideal specific work input (or total temperature rise) for a given pressure ratio, divided by the actual.

- Polytropic efficiency is characterized by the same definition of the isentropic one, but referred to an infinitesimally small step in the combustion process. This kind of efficiency is very important, since it enables the comparison between different compressor pressure ratios, but it’s not used directly in design point calculations.

An axial compressor is characterized by different key parameters, like rotational speed, aspect ratio, mean inlet Mach number and surge margin, and once it is been designed, it may be tested on a rig, before being built into an engine.

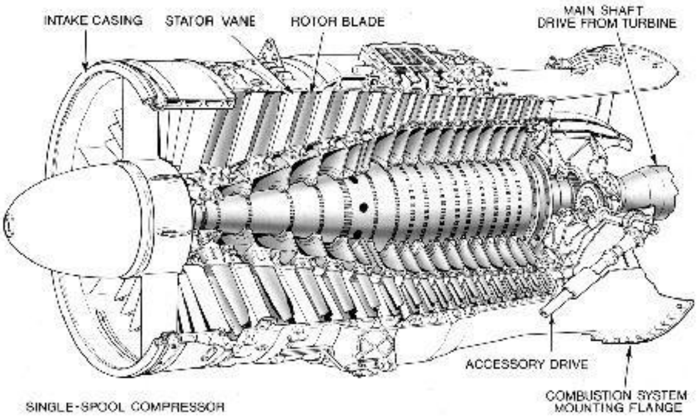


Figure 3 Multistage axial flow compressor (Rolls-Royce, 1992)

The centrifugal compressor is composed by a single or two stage unit, characterized by the use of an impeller to accelerate the air and a diffuser to produce the desired pressure increase. The impeller is supported in a casing, that also contains a ring of diffuser vanes. This kind of compressor is featured by a pressure ratio of 9:1, thanks to an area ratio greater than the axial compressor one.

The definitions of the two kind of efficiency of the axial compressor are the same for the centrifugal one.

Some key parameters for the centrifugal compressor are the mean inlet mach number, the rotational speed, the pressure ratio and also the impeller length.

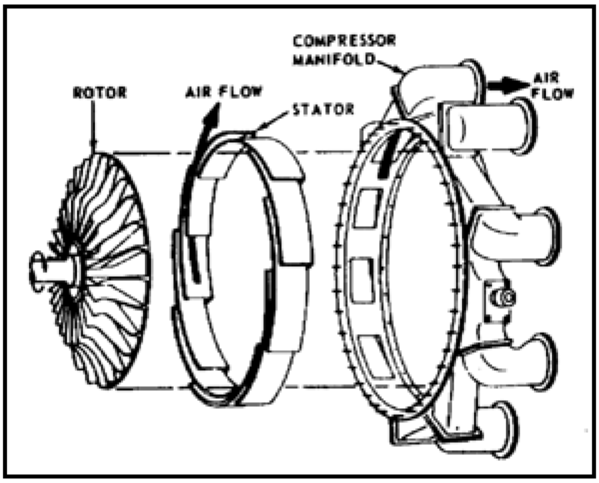


Figure 4 Centrifugal compressor

These kinds of compressor are very different, e.g. the axial compressor is the only choice at large sizes, and it is usually used in systems characterized by low frontal area and weight, and also high efficiency, while the centrifugal is used in systems featured by small size, where unit cost is fundamental.

The design of a compressor is based on fixing its geometry at the design point. Once completed this task it is fundamental to analyze the performance of the device at conditions also far from the design point. This purpose can be achieved by defining the compressor map, where pressure ratio and isentropic efficiency are plotted versus referred flow, for a series of lines of constant referred speed. The compressor map is characterized by a limit line, called *surge line*, that represents the regime in which the blade stall becomes so important that the blading can no longer support the adverse pressure gradient, making the flow suddenly breaking down. In this very dangerous regime, if action is not taken immediately, a surge cycle occurs, producing damages to the engine.

Another important margin that has to be considered, is the *choke* one. This limit condition is reached with the achievement of the maximum flow, that cannot be exceeded for each referred speed.

Further the blade stall, there are other secondary order phenomenon like rotating stall and locked stall.

The rotating stall consists of single or a number of stall pockets on the front stages rotating at between 40% and 70% speed in direction of rotation, while locked stall may occur when a channel of stall rotating in the direction of rotation remains instead of a surge cycle.

The compressor map is unique for a fixed compressor geometry and the operating point, characterized by a unique velocity triangle, and is influenced by the components surrounding it. In order to plot the map, two out of these parameters, pressure ratio, $cp\frac{dT}{T}$ and efficiency may be used as the ordinates for the map. The map is subject to changes if linearly scaling is applied to the compressor, but if it is plotted with dimensionless parameters, it is unique for different fluids and all linear scales.

A compressor map can have some problems in being read, since sometimes the speed lines can be vertical, or there could be two values for corrected flow at a given pressure ratio. So auxiliary coordinates called beta lines are introduced, which intersect the speed lines. This allows he map to be read independently from the shape of the speed lines. Beta lines are arbitrary lines, drawn approximately equispaced and parallel to the surge line.

Once introduced the compressor map, it is important to note that in this work it is going to be analyzed what occurs outside the wide envelope described by the map, where the engine is not operating as a propulsion device, with consequential alterations in flow, pressure and temperature characteristics.

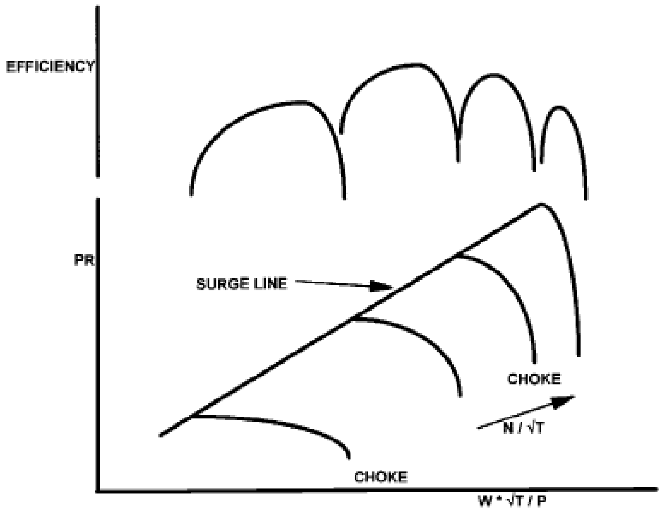


Figure 5 Typical compressor map

1.3.2 Fan

The fan is the first compressor in a turbofan engine. It is always axial flow, since it could be very difficult to use a centrifugal compressor for the diameter and downstream ducting required. After the fan, the flow is split into the cold or bypass flow, and the hot or core one. A fan is composed by rotor blades followed by fan tip and root stator blades, usually put downstream of the splitter. About the fan efficiency, it’s important to note that if clappers or snubbers are used to control blade vibrations, the efficiency level is reduced by around 1.5% points.

The typical bypass ratio for long range civil turbofans is between 4 and 6, while for shorter range turbofans, the typical value is between 1 and 3, though modern designs are tending to higher values. For supersonic military engines, bypass ratio is between 0.5 and 1.

Typical key parameters for a fan are mean inlet Mach number, rotational speed, axial velocity, axial velocity ratio, and surge margin pitch/ chord ratio.

About the fan off design performance, all the items described before are the same. It is important to note that there are different map for each bypass ratio, while in off design modeling phase a single map, as for a compressor, may be used for all bypass ratios, assuming equal tip and root pressure ratio and efficiency. Fan root efficiency and pressure ratio are evaluated with computer codes.

It is worth to point out that the cold flow is not supplied to the core of the engine and so does not participate in the process described by this work.

Figure 6 Fan with low pressure compressor

1.3.3 Combustor

The combustor has the fundamental task to burn large quantity of fuel to produce heat and hence power, reducing the pressure loss. The fuel comes from the fuel spray nozzle, while the air is from the diffusers after the compressor, that bring the Mach number of the air from the compressor exit value of 0.2-0.35 at the value of 0.02-0.07 in order to reduce the pressure loss, and to help the ignition system, that makes the combustion process starts.

The key parameters of the combustor are loading, residence time, fuel air ratio, outlet temperature distribution, local Mach number and combustor system areas.

In scaling the combustor it is important to note that fuel air ratio, air and gas velocity, percentage pressure loss are unchanged, while flow change is proportional, residence time is directly proportional and combustion loading and intensity are inversely proportional to the scale factor.

As for the compressor, also the combustor is characterized by an efficiency. The combustion efficiency is defined as the ratio of fuel burnt in the combustor to the total fuel input. A typical value is over 99%, and values less than 90% are not tolerable.

Even if the combustion process could be considered as adiabatic, the combustion chamber provokes a pressure loss. There are two different kinds of pressure losses, the cold and the hot one. The cold loss is due to the dump of air being ejected through the wall while the hot, or fundamental, loss occurs in the combustion section of the flame tube, due to combustion.

A combustor is typically divided into three parts:

- *Primary zone*: This is the first part, where most of the combustion occurs. Here only about the 20% of the total amount of the air from the compressor goes in to support the combustion process and also to stabilize the flame. The maximum temperature is about 2300 K. The tasks of the primary zone are to guarantee the ignition, to anchor the flame and to guarantee sufficient residence time, temperature value and pressure value, such to complete the combustion process. The stability of the flame and liner diameter are optimized by using opposing jets (a), swirl (b), or a mix of swirl and opposing jets (c).

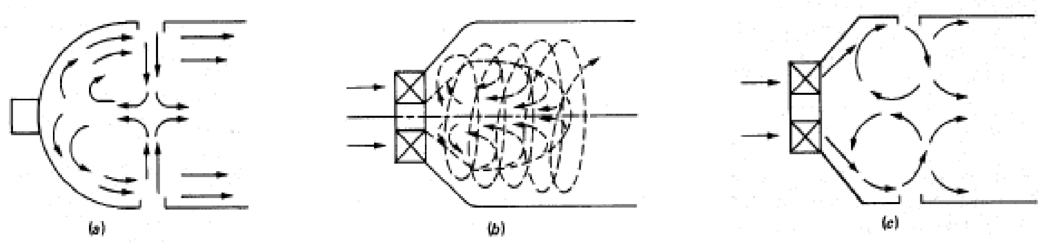


Figure 7 Methods for the liner diameter optimization

- *Secondary/intermediate zone*: Since the high value of the primary zone's temperature can cause CO_2 dissociation in CO and O, if the hot gases pass directly to the dilution zone, the composition would be frozen and the heat from the fuel inefficiently used would be lost. So the secondary zone is very important to complete the combustion process, in particular at high altitude, and hence at low pressure, when the reaction velocity is slower. For the combustion another 20% of the air from the compressor is used.

The length of the secondary zone is typically 50%-70% of the liner diameter. It is a compromise between a length long enough to ensure a good residence time, and a high value of the combustion efficiency.

- *Dilution zone*: The task of the dilution zone is use the last 20% of the air (since usually about 40% is used to cool the liner walls) to decrease the temperature value of the hot gases, in order to avoid damages to the turbine's blades. The length to liner diameter ratio is 1.5-1.8.

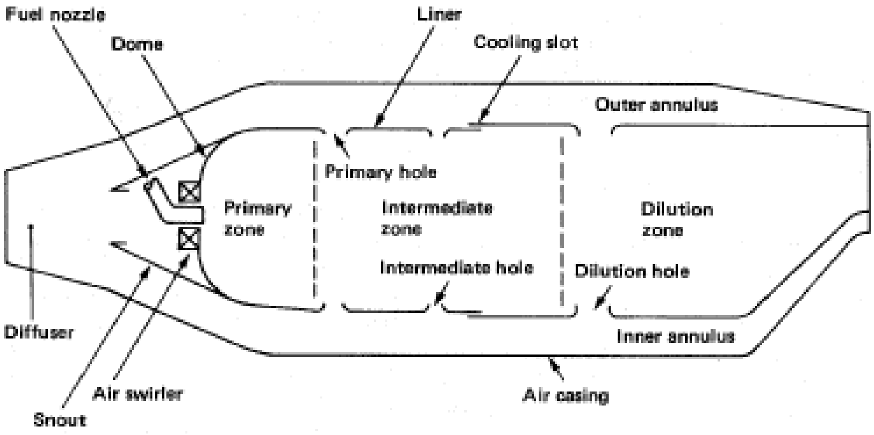


Figure 8 Simple view of a combustion chamber section

There are different kinds of combustors: annular, tubular and tubo-annular:

- *The tubular or multiple combustion chamber* was used in particular with the centrifugal compressor and was a development of the Whittle combustion chamber. With this kind of combustor, the chambers are disposed around the engine, with a flame tube per each. The separate flame tubes are interconnected in order to operate at the same pressure.

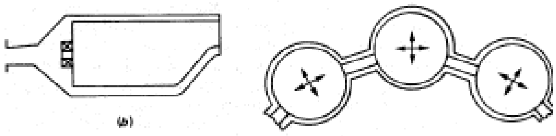


Figure 9 Tubular combustion chamber

- *The tubo-annular combustion chamber* is a tubular one, where the flame tubes are fitted with in an annular casing. This is a kind of

mixture between the tubular and the annular combustor, and it was used in the early aircraft engines, but due to its higher diameter and higher weight, and also a higher surface to be cooled, it was substituted by the annular combustor.
Since in the industrial field the frontal area and weight are not such important issues, this kind of combustor is used.

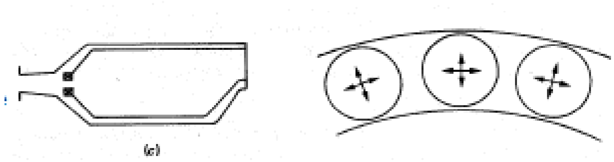


Figure 10 Tubo-annular combustion chamber

- *The annular combustor* is the most used in aeronautical field, due to its low frontal area and low weight for a given volume. Its composed by a single flame tube, contained in a inner and outer casing. This kind of combustor is characterized by several advantages, such a less length than the tubo-annular for the same power output, or the elimination of combustion propagation problems between two chambers. Due to its less wall area than the tubo-annular one, it needs a less amount of air to cool the system and hence the combustion efficiency is higher.

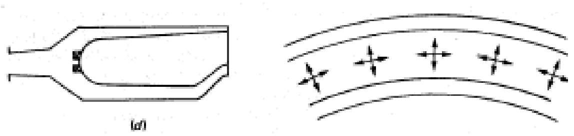


Figure 11 Annular combustion chamber

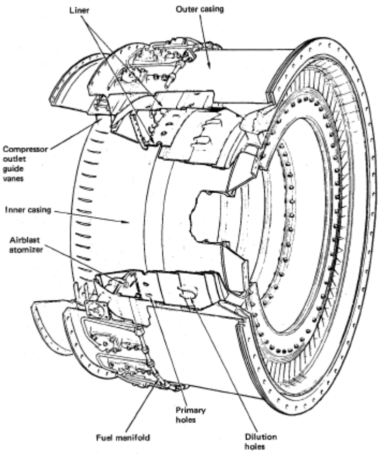


Figure 12 Another section of an annular combustion chamber

Combustion emissions

An important task for the combustor is to reduce pollution, and low emissions of NOx, CO and unburned hydrocarbons have become essential for combustion systems. Since the formation of CO is aided by low value while the formation of NOx by high value of temperature, it is important for the primary zone, to burn weak at about 1700-1800 K, instead of 2300 K

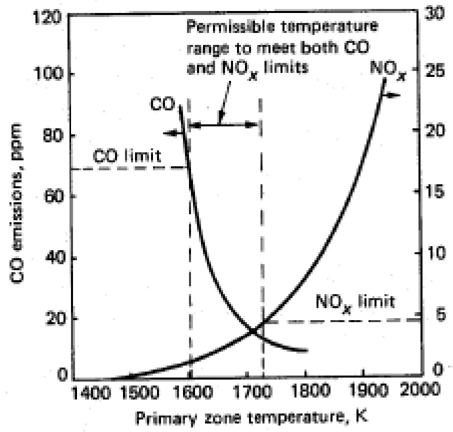


Figura 13 Emissions of NOx and CO with temperature variation

Combustor Off-Design Performance

Combustion stability

The combustion stability is one of the most important topic that an engineer has to deal with, in order to avoid phenomena like flashback or blow-off. While flashback is promoted by low velocity and high temperature, blow-off is easier with non-stoichiometric mixtures and high velocity.

Stability is aided by low velocity and by high inlet pressure and temperature. For any kind of combustor it is important to draw the stability loop, by carring out some extinction tests. Once ignited the mistures of fuel and air at predetermined pressure and temperature, the fuel is gradually reduced until the weak extinction limit is reached, then combustion is re-established and the fuel flow is increased, until the rich extinction occurs. This process is then repeated at increasing levels of air mass flow until the complete stability loop can be drawn.
Typical values can be noted in the following figure:

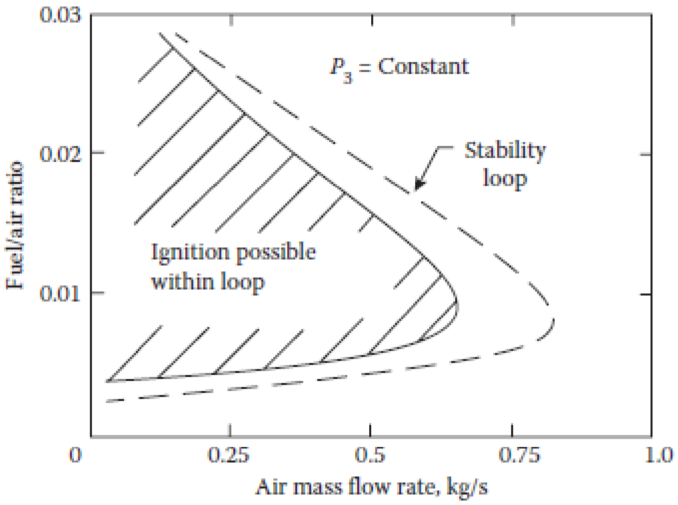


Figure 14 Ignition and stability loop

The region of stability decreases if the velocity is increased.

Also the ignition process is characterized by weak and rich limit of fuel-air ratio, and these limits form a stability loop that lies within the stability loop of the combustion process.

If flame extinguishment occurs, for an aircraft it is very important to be able to relight the engine. This is a very difficult challenge at high altitude and low Mach number, since loading (i.e. the measure of how much work is demanded of the compressor or stage) is high due to the low inlet pressure and temperature, as it can be noted from the following formula:

$$LOADING = \frac{C_p * (T_o - T_i)}{U^2}$$

Where C_p is the specific heat at constant pressure, T_o is the outlet temperature and $T_i$the inlet temperature, and U^2 the blade speed.

So altitude relight performance is measured in a rig test program, that is absolutely prior to any development engine testing. This kind of test must develop the combustion efficiency vs loading and fuel-air ratio, combustion rich and weak boundaries, combustor wall temperature and emissions level.

1.3.4 Axial Flow Turbine

The task for a turbine is to extract power from the gas stream, in order to drive either compressor or a load such as a propeller or electrical generator, in case of a power turbine.

A turbine is composed by a row of nozzle guide vans (NGVs), followed by a row of rotor blades mounted on a disc. The use of shrouded blades, often interlocked, is typical to reduce clearance losses, despite the increase in stress level.

For a multistage turbine the blading is arranged sequentially in an annulus, such as a drum. The total pressure and total temperature are reduced across the turbine and everything described about the scaling for the axial compressor is the same, like the definition of the two efficiencies. The key parameters for a turbine are inlet Mach number, rotational speed, axial gap, axial velocity ratio, final stage exit Mach number and final stage turbine swirl angle.

About the turbine off design performance, there are the same considerations made for the axial compressor, but, furthermore, it must be considered that each NGV angle represents an unique geometry, and so a different turbine map. For the turbine it is rather important to note that at low speed, during starting or windmilling, there is not any kind of abnormal behavior.

Turbine rig tests, before engine testing, are made only for the highest technology engines.

Figure 15 Axial flow turbine

2. Windmilling

2.1 Phenomen's description

When a shutdown occurs in flight the turbine is no longer fed with heat energy, and this leads to a relevant decrease of the rotational speed of the compressor and possibly of the fan. Nevertheless the relative wind will continue to make the compressor rotate. The direction of rotation is determined considering the resultant aerodynamic torque acting on the rotor blades. Since the blade's airfoil is designed to overcome the engine friction, then with relative wind the direction of rotation remains the same as for the working engine. There are two kinds of windmilling: the free windmilling, where the engine spools are free to rotate, and the locked rotor one, where the HP spool is mechanically prevented from rotating. For single spool engines with a locked rotor compressor delivery temperature is equal to the ram temperature since the compressor is acting as a cascade with no work extraction.

Obviously this is typical of bigger engine, like turbofan, composed with both LP and HP compressor.

When windmilling, typical of aircraft engines (and rarely of marine engines), occurs, both compressors and turbines work far away from their design point, and so also their efficiency is very low. Therefore this phenomenon has to be analyzed during the engine design and development. It is fundamental to ensure successful lighting or relighting of the engine, since otherwise the engines produces drag, due to an exit flow velocity lower than inlet one.

Some important information during windmilling:

- The compressor continues in absorbing power and the turbine is able to supply the compressor input power, and this proves that there is however an expansion ratio above all the losses.
- Combustor and other ducts are characterized by drop in pressure but not in total temperature, while the expansion ratio across the nozzle is quite small and the total temperature is lower than the ram temperature.
- Since the nozzle is not choked, the standard thrust relationship is simplified, since the term about pressure is reduced:

Typical relationship $F = \frac{1}{g_c}(\dot{m}_e V_e - \dot{m}_0 V_0) + A_e(P_e - P_0)$

Simplified relationship $F = \frac{1}{g_c}(\dot{m}_e V_e - \dot{m}_0 V_0)$

Ambient conditions have to be considered, since at high altitude the pressure reduction leads to a reduction of the referred parameters at a given flight Mach number, e.g. for a turbojet, a 5000m increase in altitude leads to a reduction of about 1% of referred speed at 0.8 Mach number.

In the following figures is shown the behavior of the typical non-dimensional relationship for the windmilling regime. It is relevant to note that:

- Mass flow increases with flight Mach number, since higher Mach number corresponds to higher referred speed.
- In the lowest part of the curves it is not possible to conduct operations because of the weak extinction of the combustor.

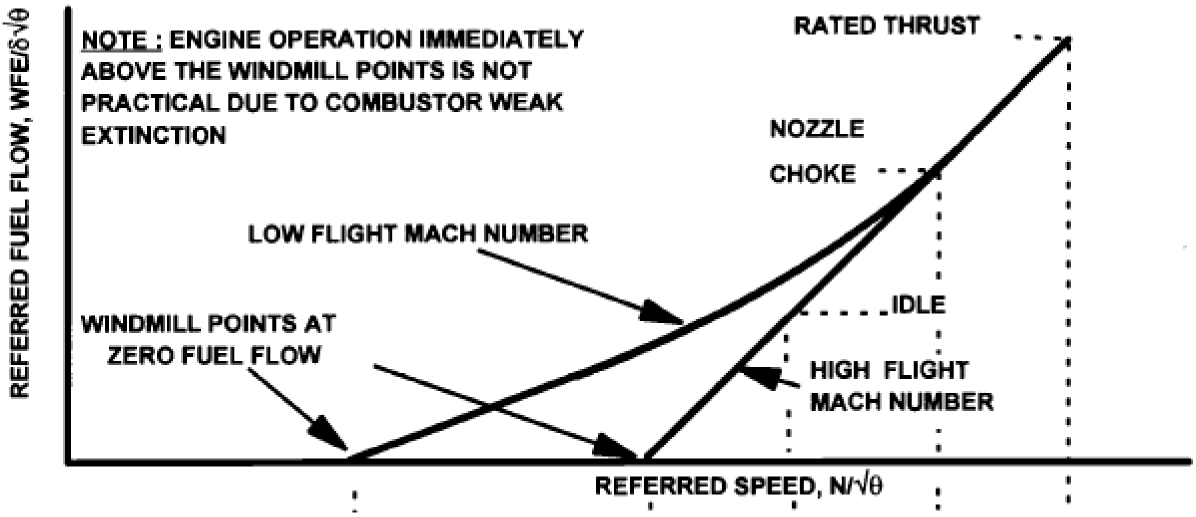


Figure 16 Referred fuel flow versus referred speed[3]

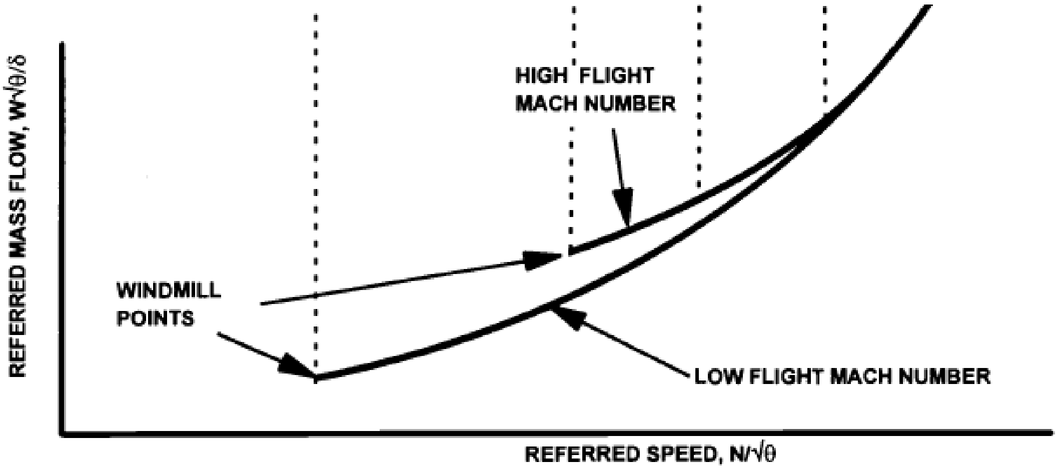


Figure 17 Referred mass flow versus referred speed[3]

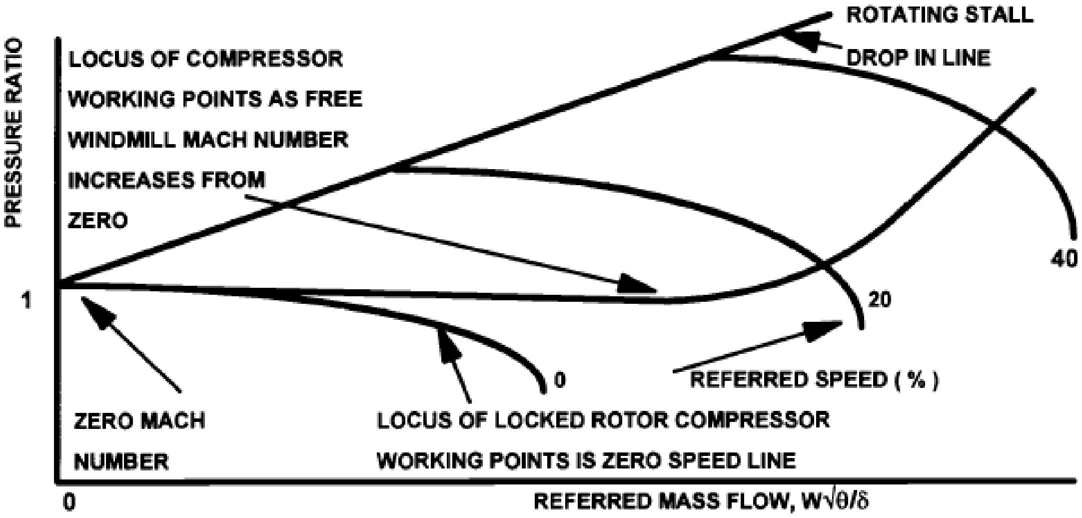


Figure 18 Compressor working points[3]

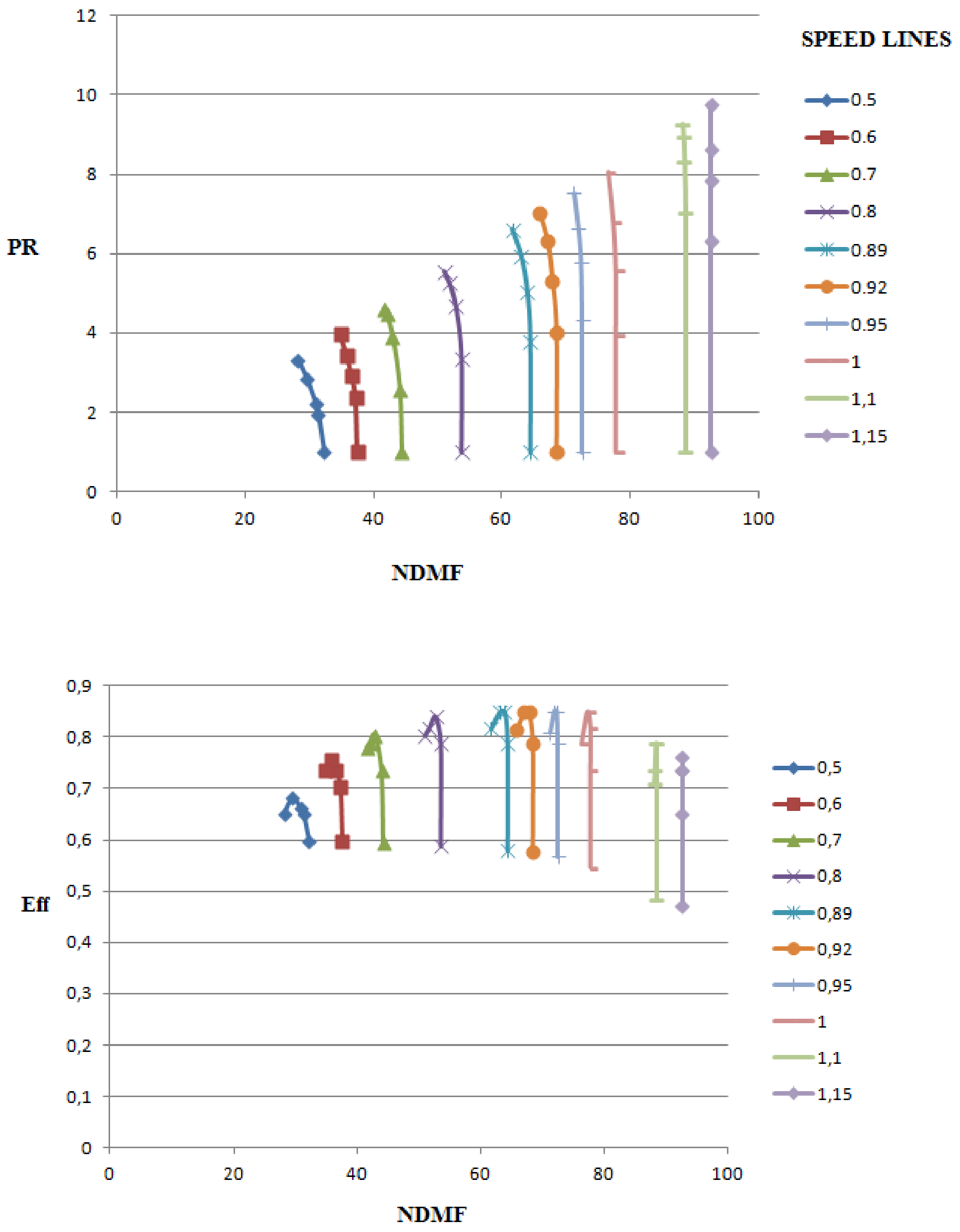


Figure 19 Compressor maps obtained with Turbomatch

The last two figures have been drawn with Turbomatch, a code developed at Cranfield University, able to analyze the engine performance and to draw the relative compressor maps. In this work, we are interested in a part of the maps that are not represented, i.e. the part at a very low velocity, so the previous figures represent just some examples of typical compressor maps at standard conditions.

About compressor, it is possible to note its dependence on the Mach number:

- As Mach number increases, pressure ratio starts decreasing, while temperature ratio remains greater than one.
- As Mach number increases further, pressure ratio increases as well and exceeds one. This peculiarity is different for centrifugal compressor, where pressure ratio is lower since there are not back stages able to operate normally.

In order to obtain accurate data for a given engine, a windmill test has to be conducted. Typical test is taken with a Mach number increment of 0.2 at two different altitudes, and derived referred parameters are plotted versus Mach number. Otherwise data are recorded during flight testing.
Windmilling may be also modeled by some off design codes, but the results have to be analyzed with attention if the model could not be calibrated with windmill test data, and components maps could cause mistakes at very low referred speeds.

Possible solutions

An interesting solution to relighting problem during windmilling could be the use of the fan, since it is an advantageous source of energy, because of its inertia and of the energy that could be extracted from the air passing through it. This could be achievable by transmitting power from the fan to the compressor, e.g. with a device comprising a differential that interconnects the two coaxial shafts (for fan and compressor), compensating for their different rotational speeds, and a braking system that slows down or stops the differential when turbojet shuts down, enabling the first shaft to entrain the second one, in order to reach a speed that help relighting the turbojet.

Other possible solutions could be the uses of hydraulic, electrical or pneumatic power generators driven by the fan, in order to transmit power to the compressor via a suitable device.[2]

Off-design performance

During the development of a gas turbine engine, each component is designed in detail, so that all the engine will give the required performance when operating at design point.

Design point (DP) is defined as the particular point of the operating range, when the engine operates at the particular pressure ratio, mass flow and speed for which the engine components were designed.

But apart from the design point performance, also the overall performance of the engine over the entire operating range of speed and power output has to be analyzed. This process is related to the Off-Design performance (OD). As written previously, this can be achieved by plotting data from rig tests or previous experience in a diagram to form a “component map”. It is relevant to note that when all the components are linked together, the range of operating conditions is considerably reduced.

When the engine is running at a steady state, the equilibrium running points of each components can be found, plotted on the compressor map, for a series of speeds, and joined up together in order to form the running line that has not to be displaced beyond the compressor surge line, to avoid unstable operation of the engine. Once established the operating conditions, performance curves for thrust, power output and SFC can be found.

The Off-Design performance is, therefore, relevant in the process of engine development. When OD performance is calculated, it is important to define an engine variable used as “handle”, that will be a variable that determines the matching conditions of the engine.

Typical handles are rotational speed N, Turbine Entry Temperature TET and exhaust gas temperature EGT. The procedure to define Off-Design performance consists of an iterative procedure, where several trials are conducted in order to ensure that all the engine variables are consistent with the “handle”.

The following figure represents the effect of an increasing flight speed on the equilibrium running line. Carrying out the same procedure but for different values of the flight Mach number M_a, it is found that the different running lines of constant M_a merge into a single running line at higher compressor speeds (nozzle choked). In this work more attention will be given to the unchoked condition due to the values of pressure, temperature and flow speed, that lie in the lowest part of the map.

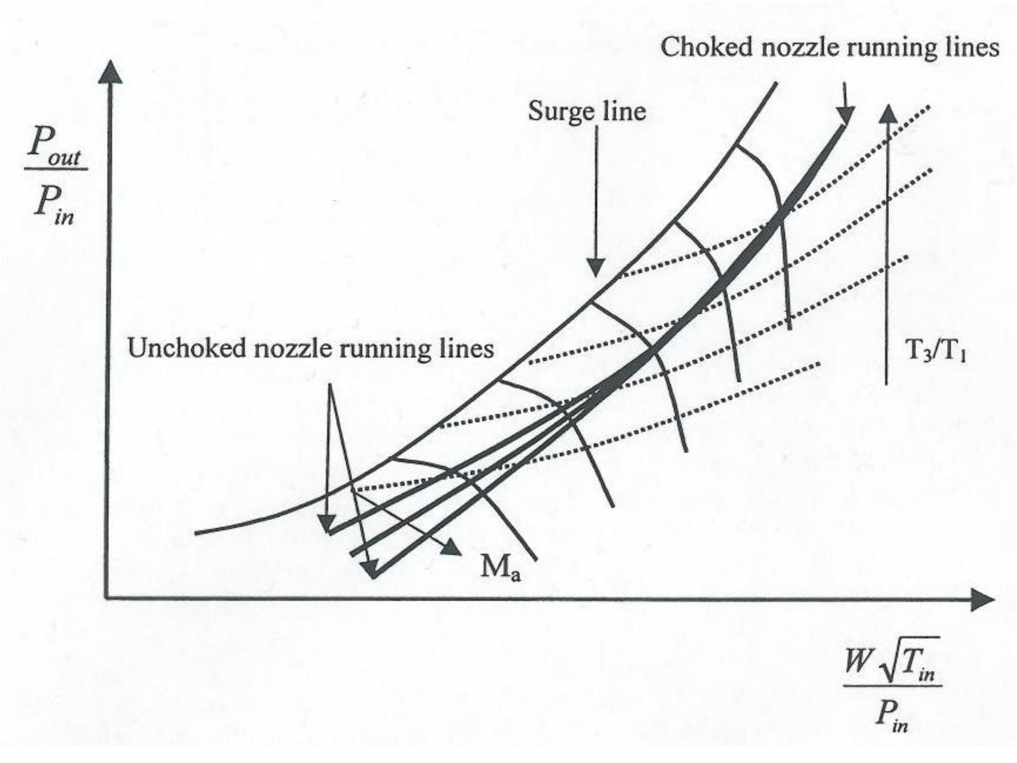


Figure 20 Effect of an increasing flight speed on turbojet running line

3. Combustion Process

The key requirements in the combustion process of a gas turbine engine are:

- Adequate mixture preparation
- Stabilization of the flame
- Non luminous flame (nice to have but difficult to achieve with liquid fuels)
- Control of the turbine blades temperature by dilution of the exhaust gases with air
- Minimum variation in temperature across outlet cross-section (in fact, a uniform temperature profile in the radial plane may not be helpful as it can overheat the blade and nozzle platforms, so it is usual to consider temperature variations in two planes, radial and circumferential, with the radial profile that can be quite highly shaped to avoid platform overheating)

- Maximum combustion efficiency
- Minimal combustion pollutants

While the typical problems are:

- Radiation from the atoms of carbon that heats the combustor liner reducing the engine life
- Impingement of fuel on the liner walls causing carbon deposition and possible mechanical failure
- Poor temperature distribution at the combustor outlet, causing additional thermal stress for the turbine
- Pollution

To deal with the combustion process it could be useful to describe some general introductive aspects, before introducing very important subjects like atomization and ignition process.

3.1 Introductive aspects

The law of mass action: A generic chemical reaction can be written in this way:

$$\sum_{i=1}^{N} \boldsymbol{\upsilon_i' M_i} \rightarrow \sum_{i=1}^{N} \boldsymbol{\upsilon_i'' M_i}$$

Where υ_i' e υ_i'' are the stoichiometric coefficients for the species *i*, while M_i is the *i-th* chemical species involved in the chemical reaction.

By introducing the reaction speed ω as:

$$\boldsymbol{\omega = \frac{\dot{\omega}_1}{(\upsilon_1'' - \upsilon_1')}}$$

where $\dot{\omega}_1$ is the variation speed rate of the *species 1* concentration, and it depends on reagents concentration, temperature, pressure, catalyst presence, radiant nature effects. It's measured in *mol/(cm^{3}s).*

It is now possible to define the law of action mass as:

$$\boldsymbol{\omega = k \prod_{i=1}^{N} c_i^{\upsilon_i'}}$$

where c_i is the concentration of the i-th species, and k is the proportionality factor.

The law of Lavoisier: The necessary energy to decompose a chemical species into its constituents elements is the same as the developed energy when a species is formed from its elements.

The law of Laplace: The energy associated with a chemical reaction in a direction, is exactly the same, but with opposite sign, as the energy associated to the same reaction in opposite direction.

The law of Hess: The energy associated to a chemical reaction, at constant pressure and constant volume, is the same if the reaction develops in one or more steps.

Flame Adiabatic Temperature: After a chemical reaction, the Flame Adiabatic Temperature is the temperature of the reaction's products, if all the heat is used to warm the products.

Chemical Balance: It's the condition in which the direct and inverse reaction velocity are the same. This is a dynamic condition, i.e. when the reaction is reversible. Once the chemical balance is reached, the concentrations remain constant. Furthermore, this condition can be reached faster by using a catalyst. A reaction at the chemical balance obeys to the mass action law and can be described by a balance constant, which is only function of the temperature.

Chemical kinetics: This subject studies the mechanisms by which it develops a chemical reaction, and the reaction velocity.

Chemical reaction: The essential requirement for an elementary reaction like

$$\boldsymbol{A + B \rightarrow C}$$

is that the two species A and B get in touch. So that the collision is efficacious, it should create the *activated complex*, that is a species characterized by a higher reactivity than the normal atoms, formed when the collision brings the two species to reach the *activation energy*.

It’s important to note that for exothermic reaction the reagents energy is higher than the products one, while for endothermic reaction the products energy is higher than the reagents one.

The law of Arrhenius: It’s the law followed by specific speeds of a lot of chemical reactions, where the kinetic data are plotted on a graph ln(k) – T1, on a straight line. What it means is that, in a assigned chemical reaction, the specific speed of the reaction doesn’t depend on the reagents concentration, but it depends only on the temperature T:

$$\ln(k) = \ln(A) - E_a/R_uT$$

where A is the collision frequency and E_a the activation energy.

Generally the Arrhenius equation is valid only in some temperature ranges.

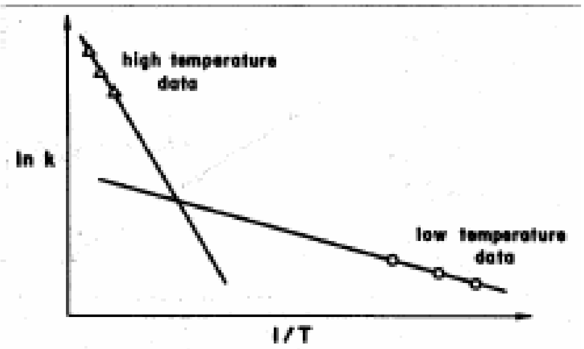


Figure 21 Arrhenius law: rates of temperature

There are two kind of reactions that don’t follow the law of Arrhenius:

- The reactions of free radicals with low activation energy.

- The reactions of radicals recombination.

Reactions: There are different kinds of reactions and to distinguish them it's important to know the global reaction order, introduced as *n* in this equation:

$$\frac{dc_i}{dt} \sim c^n$$

Where *c* is:

$$c = \sum_{i=1}^{N} c_i$$

So *n* is defined as:

$$n = \sum_{i=1}^{N} v_i'$$

1. *First order single step reactions* :

   - Molecule $\mathbf{A_2}$ decomposition: $\mathbf{A_2} \rightarrow \mathbf{2A}$
   - Molecule **AB** dissociation: $\mathbf{AB} \rightarrow \mathbf{A} + \mathbf{B}$
   - Bimolecular reaction: $\boldsymbol{A} + \boldsymbol{C} \rightarrow \mathbf{D}$

2. *Second order single step reactions:*

- $\mathbf{A + B \rightarrow AB}$
- $\mathbf{2A \rightarrow C + D}$

3. *Third order single step reactions:*

- Trimolecular reaction: $\mathbf{2}\boldsymbol{NO} + \mathbf{O_2 \rightarrow 2NO_2}$
- Third body reaction: $\mathbf{M + 2A \rightarrow A_2 + M^*}$ (used to model components unchanged by the chemical reaction but which absorb heat from the reaction of the other omponent, so for exaample it limits the flame temperature of air/fuel mixtures (where N_2 is the third body) compared to the same fuel mixed with oxygen (hotter as there is no third body).

4. *Consecutive reactions:*

- $\mathbf{A + B \rightarrow AB \rightarrow C + D}$

typical $\boldsymbol{C}$+$\boldsymbol{O}$→$\boldsymbol{CO}$, then $\boldsymbol{CO}$+$\boldsymbol{O}$→ $\boldsymbol{CO_2}$

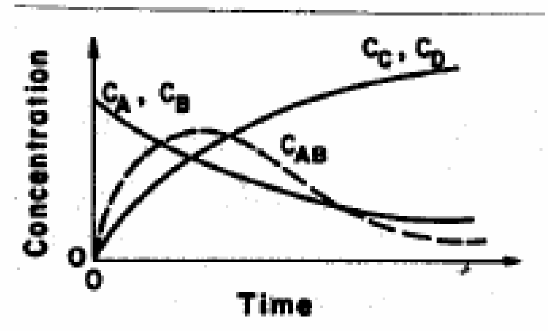


Figure 22 Concentrations trends in consecutive reactions

5. *Competitive reactions:*

- $$\begin{cases} \boldsymbol{A+B \rightarrow AB} \\ \boldsymbol{A+B \rightarrow E+F} \end{cases}$$

Which one of the two reactions is dominant depends on the specific reaction velocity constant, i.e. on a temperature's function. So it's possible that one reaction is dominant only in a specific range of temperature.

6. *Opposite reactions*

In general, the chemical reactions can occur in both the directions, forward, characterized by the forward constant k_f, and backward, characterized by the backward constant k_b.

The two constants are linked by the balance constant k_c:

$$\boldsymbol{k_c = \prod_{i=1}^{N} [M]_i \, (v_i'' - v_i')}$$

7. *Chain reactions*

The chain reactions are the most common ones and characterize the combustion process. They consist in a series of consecutive, competitive and opposite reactions with different reaction velocity constants.
A chain reaction is constituted by different steps:

- *Chain beginning*: production of free radicals.

- *Chain propagation*: series of elementary reactions of chain propagation.
- *Chain ramification:* series of elementary reactions that produce more free radicals than the number of free radicals in the reagents.
- *Chain extinction*: Destruction of free radicals.

Flames: A flame is a discontinuity surface (not in geometric sense) that separates reagents from combustion products, and where exothermic redox reactions occur. A flame is characterized by the capacity of self-sustaining and propagating itself, by burning fresh mixture.

There are different ways to classify different kind of flames:

- Homogeneous and heterogeneous flames (depending on the phase of the mixture)
- Laminar and turbulent flames
- Detonating (not used in GT Engines) and deflagrating flames
- Premixed (typical in GT Engines) and diffusion flames

In particular, the premixed flame is a flame where the oxidant has been mixed with the fuel before the flame front, while the diffusion one is a flame in which the oxidant combines with fuel by diffusion.

Typically, diffusion flames burn slower than the premixed ones, and they also produce more pollution since usually they do not have enough oxygen to complete the combustion process.

Below there are two picture about respectively premixed and diffusion flames.

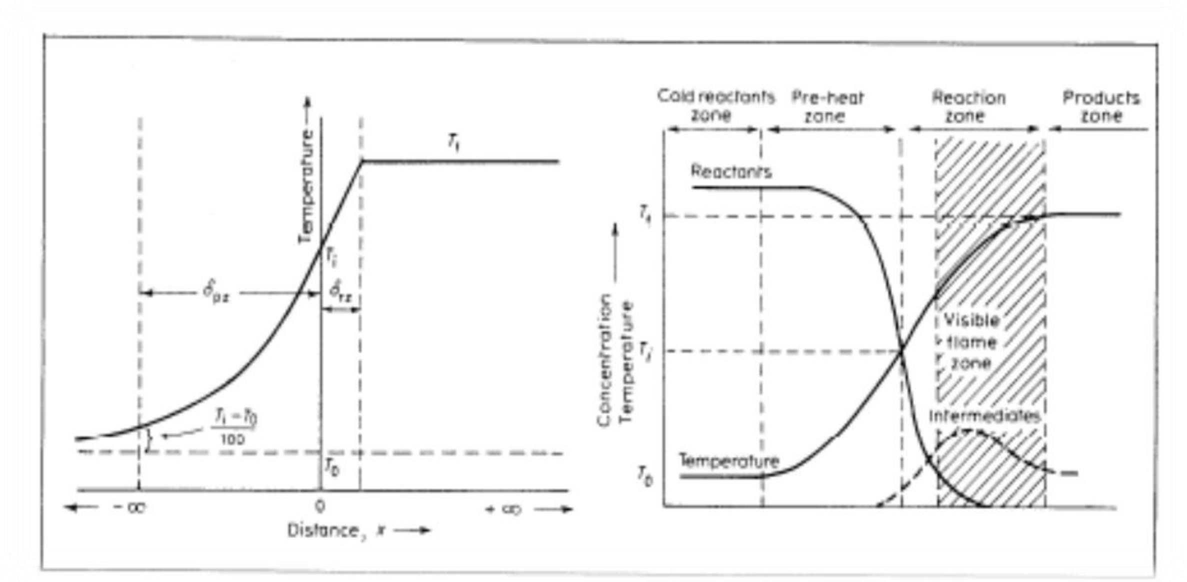


Figure 23 Temperature and reagents concentration plot for a premixed flame

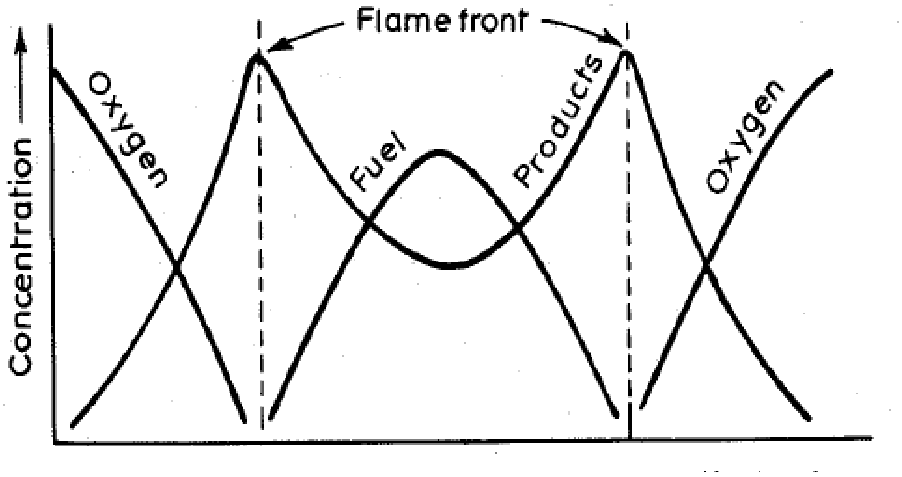


Figure 24 Reagents and products concentration plot for a diffusive flame

Pattern factor: It describes the temperature traverse quality at the outlet of the combustor (it can be radial and circumferential):

$$\boldsymbol{Pattern\ factor} = \frac{(\boldsymbol{T}_{\boldsymbol{max.exit}} - \boldsymbol{T}_{\boldsymbol{mean.exit}})}{(\boldsymbol{T}_{\boldsymbol{mean.exit}} - \boldsymbol{T}_{\boldsymbol{mean.inlet}})}$$

4. Fuel properties

4.1 Handling and Combustion Properties

Description of the properties that affect ignition and atomization processes. In the figures of this chapter, red lines are used to define the zone in which this work is interested.

4.1.1 Density

The density of a fuel is one of the most relevant properties.
The density relates to the molecular compostion of the fuel so, for many industrial fuels and most aircraft fuels, the density varies relatively little, and is a useful classifier for other properties. In fact it affects the mass of fuel carried, since for an aircraft the tank has a fixed volume, and all the most important processes like atomization, evaporation an ignition, as can be easily found even from all the equations that describe them. It is defined as the mass m contained in a unit volume V, and is measured in kg/m^3 :

$$\rho = \frac{m}{V}$$

In order to measure density, it is important to distinguish gaseous fuels and liquid fuels. In the first case it is typical to measure density by weighing a sample of fuel contained in a Chancel flask (Fig. 1), while for the liquid fuels, density can be measured from the depth of immersion of a glass hydrometer floating in the sample (apparatus in Fig.2), making right corrections for the possible temperature’s difference between the standard value and the test one (Fig.2).

Another system is to employ a digital density meter, where a small sample is introduced into an oscillating miniature glass. In this way is possible to measure density from the change in natural resonant frequency resulting from the change in overall tube mass.

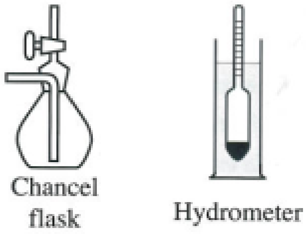


Figure 25 Some different apparatus to measure density [4]

It is also relevant to define relative density, and even though it is without physical meaning, it is widely used since it can help to quantify the buoyancy of a substance, or determine the density of an unknown substance from the known density of another. For liquid fuel it is defined as:

$$d_{T1/T2} = \frac{mass\ of\ given\ volume\ of\ sample\ at\ T1}{mass\ of\ equal\ volume\ of\ pure\ water\ at\ T2}$$

Where T1 is the temperature of the liquid fuel (typical at 15°C) and T2 is a reference temperature of water (typical at 15°C)

In case of gaseous fuels, relative density can be measured by timing the flow of equal volumes of sample and air through a fixed orifice, since it is possible to define relative density also as:

$$d = \left(\frac{sample\ flow\ time}{air\ flow\ time}\right)^2$$

Density gives information about the kind of fuel used, since its value is very different if fuel is e.g. hydrogen, propane or kerosene [tab 1]. Density also affects the droplet size [all forms for SMD diameter are function of the fuel density as can be noted in Atomization process chapter] and the quenching distance of the flame kernel, that could be defined as [Ignition chapter]:

$$d_q = \left[\frac{\rho_f D_{32}^2}{\rho_A \phi ln(1+B_{ST})} + \left(\frac{10\alpha}{S_L}\right)^2\right]^{0.5}$$

Where ρ_f is the fuel's density.

It is important to note that density is related by an inverse relationship to temperature, as can be noted in the following figure:

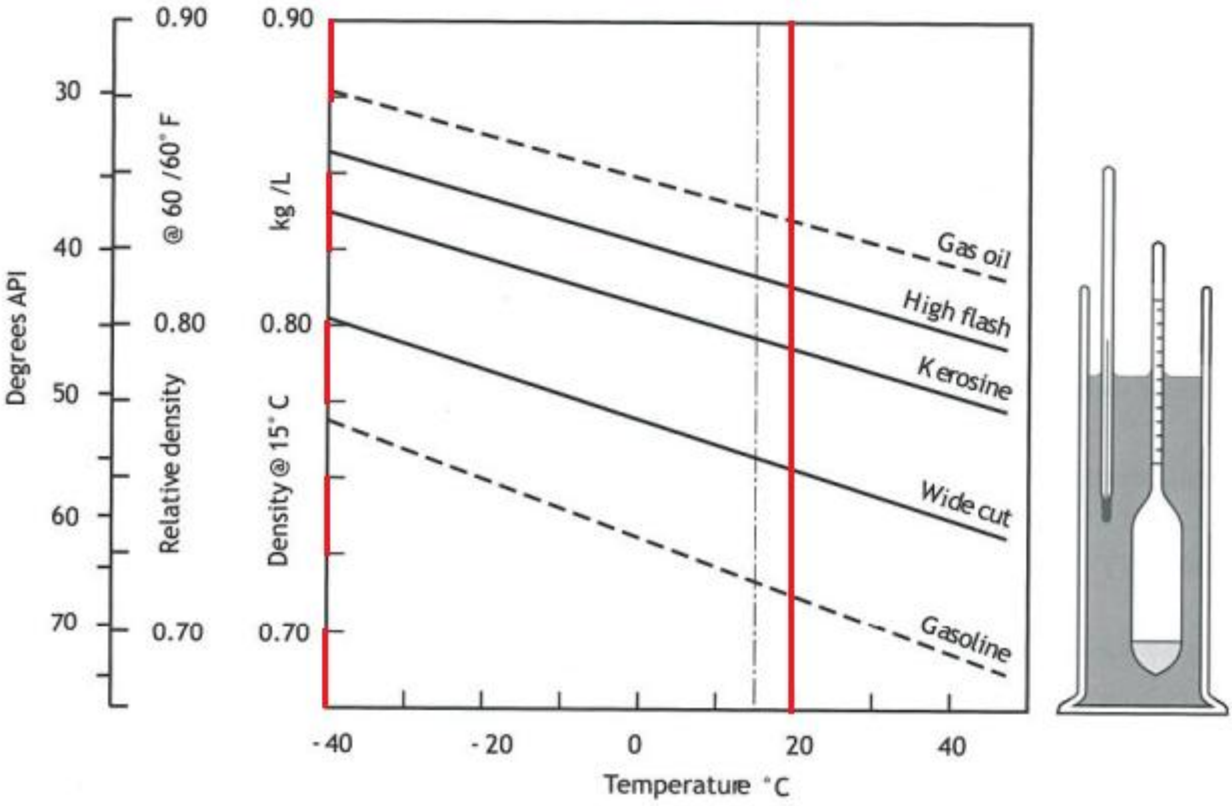


Figure 26 Variation of density with temperature, with schematic of apparatus [4]

4.1.2 Calorific Value

This value characterizes quantity of heat released during combustion, and can be related to either mass or volume basis. However it is quite widespread to use “specific energy” on a mass basis, and “energy density” on a volume basis:

- Specific energy: it is defined as the energy released on complete combustion in oxygen of unit mass of fuel. It is measured by locating a weighed fuel sample in a calorimeter filled with oxygen. Therefore once ignition is started and combustion complete, the heat is absorbed by the calorimeter, and knowing its temperature rise and its heat capacity, it is possible to know a gross value of the heat released. Then with some empirical relationships it is possible to derive the net value. Since sometimes this test is too expensive, some empirical equations are directly used.

- Energy density: it is defined as the energy release on complete combustion of unit volume of fuel. Once knowing the specific energy, it is possible to derivate the energy density with the following relationship that involves also density:

$$\mathrm{MJ/L} = \mathrm{MJ/kg} \times \mathrm{kg/L}$$

4.1.3 Viscosity

The viscosity of a liquid relates to its resistance to flow, and therefore it defines the frictional force between adjacent layers of the liquid. Viscosity in a liquid depends on the weak electrostatic forces acting between the molecules, and so it permits hydrocarbon fuels to exist in liquid phase.

It is possible to define two different viscosities, dynamic (μ) and kinematic (υ), related to each other by density, in particular:

$$\upsilon = \mu/\rho$$

To define dynamic viscosity you can consider two parallel planes of surface A, sliding one at a relative velocity, u, to the other, moved by a relative force F, and spaced by a distance y. Dynamic viscosity is defined as:

$$\mu = \frac{F}{A}\frac{\partial y}{\partial u} = \tau\frac{\partial y}{\partial u}$$

where τ is defined as shear stress between the two planes considered. μ is measured in [Pa·s], while υ in $[m^2/s\ ]$.

In the gas turbine engine, kinematic viscosity represents a key parameter, since it indicates the power required for pumping, filtration and spraying, therefore influencing atomization process and droplet size (high viscosities lead to larger droplets). Kinematic viscosity varies inversely with temperature (Fig.3).

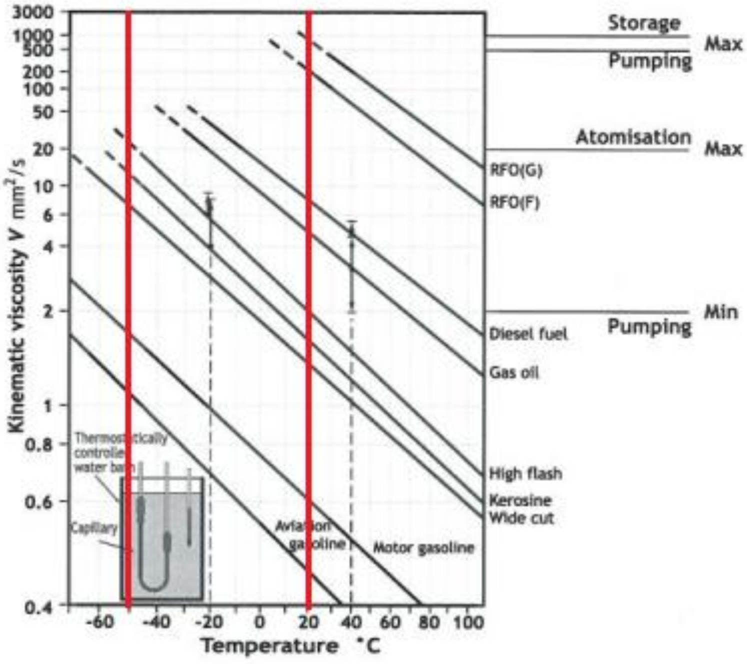


Figure 27 Variation of kinematic viscosity with temperature, with schematic of apparatus [4]

4.1.4 Volatility

Volatility is the tendency of a material to vaporize at given temperature and pressure. It is measured through True Vapor Pressure (TVP), that provides common measures of the volatility of petroleum distillate fuels. TVP is defined as the equilibrium partial pressure exerted by a volatile organic liquid as a function of temperature as determined by the test method ASTM D 2879. This test is applicable to liquids that have a vapor pressure between 133 Pa and 101.3 kPa at the selected test temperatures. The test method is suitable for use over the range from ambient to 748 K. The temperature range may be extended to include temperatures below ambient.

At a certain pressure for an individual material the boiling temperature is fixed, while for fuel mixtures it can vary from a minimum to a maximum value, depending on the kinds of hydrocarbon presented in the mixture. Therefore also volatility characteristics can vary in that range of temperature, as can be noted in Fig.5, since volatility is related to the vapor pressure of a liquid fuel. Vapor pressure is the pressure of a vapor in thermodynamic equilibrium with its condensed phase in a closed system, and it could be expressed as a ratio between the released vapor volume V and the unvaporised liquid volume L.

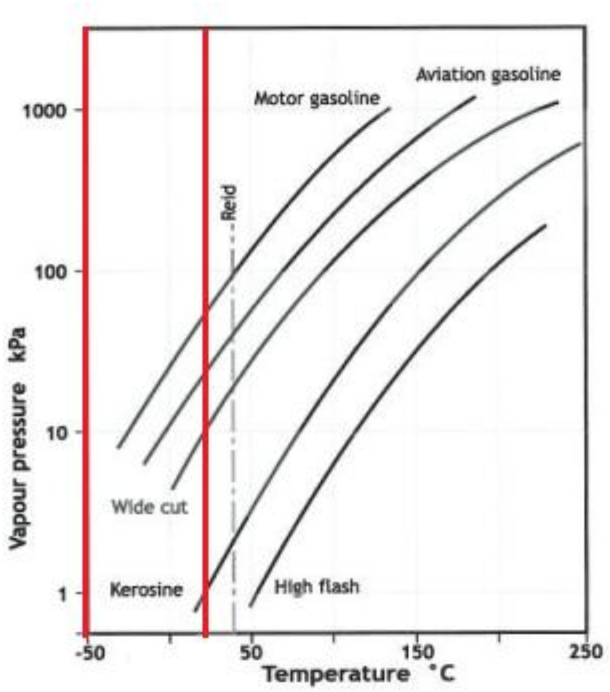


Figure 28 Variation of vapour pressure with temperature [4]

Volatility is an important property that controls the retention of the liquid phase at high temperature (*Fluidity*).

4.1.5 Surface Tension

Surface tension is represented by the symbol σ. It is a property of the surface of a liquid that allows it to resist an external force. It is measured in [N/m]. This property is very important in the atomization process, since it is part of the definition of Weber number We and of the maximum stable drop size D_{max} [chapter about atomization process]:

$$We = \frac{0.5\rho_a U_R^2}{\frac{\sigma}{D}}$$

$$D_{max} = 12\sigma/\rho_a U_R^2$$

4.1.6 Distillation

Distillation is not really a fuel property, but is a process where fuel is heated and separated into its different fractions depending on their boiling points. The proportions of fuel that boil at a certain temperature define the fuel performance characteristics, e.g. the highest boiling point fraction is important for the exhaust pollutants, the middle one leads to the definition of general combustion properties and the lowest one defines the starting characteristics. The method of distillation is based on a heating process of the sample in a round-bottomed flask. This flask is connected to a metal tube that works as condenser, since it is cooled by a liquid contained in a tank surrounding the tube. In the flask there is also a thermometer, and the rate of distillation is controlled to a specified time schedule.

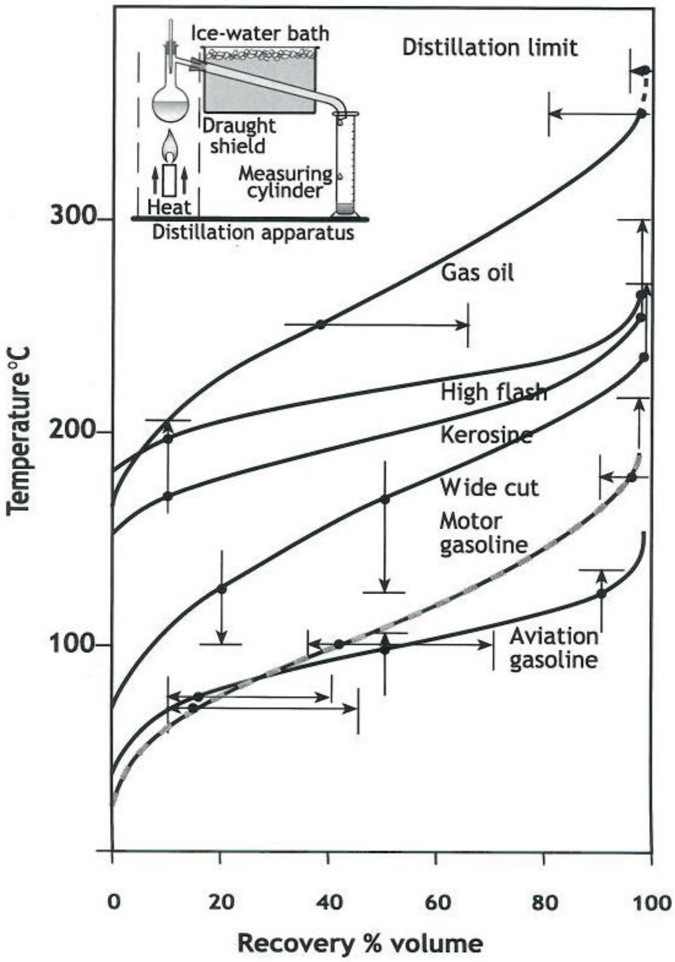


Figure 29 Distillation curves with schematic apparatus [4]

4.1.7 Fuel Solidification

This property relates to the temperature of solidification of fuels. With a progressive cooling, each component of the fuel starts crystallizing as wax, then viscosity rises and relative movements are limited. To measure this property a solution can be that adopted by Atkins and Ervin [3], i.e. a rectangular, optical cell, where fuel can be cooled below its freezing point. while images and temperature recorded provides information about crystal habit and crystallization behavior.

Other tests, that can be conducted, are in order to define:

- *Freezing point*: Temperature of a stirred chilled sample of aviation fuel at which a cloud of wax crystals precipitated on cooling just disappears on warming.
- *Cloud point*: Temperature of an unstirred chilled sample of aviation fuel at which a cloud of wax crystals precipitated on cooling just disappears on warming.
- *Pour point*: temperature typically 3K above the value of an unstirred chilled fuel sample that just fails to pour from a horizontal container.

These tests are typically conducted with fuel containers surrounded by refrigerants, where at determined intervals the samples are examined. A typical solidification temperature value (temperature at which solidification or freezing starts) for the international civil Jet A-1 is -47 °C, while for aviation gasoline is -70 °C.

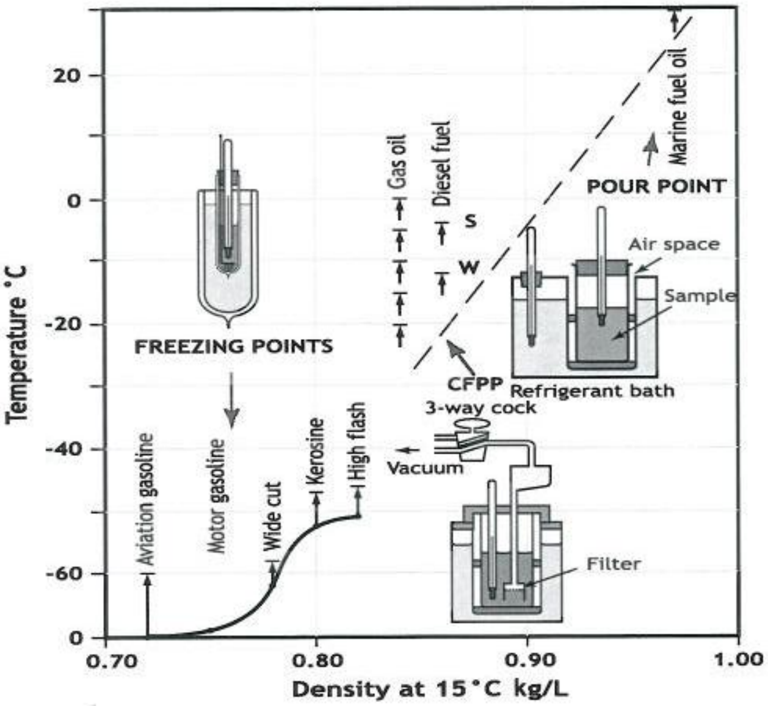


Figure 30 Relationship between density and solidification points, with schematic of apparatus [4]

Another arbitrary test that mimics operating conditions in aircraft is to define cold filter plugging point, i.e. the highest temperature at which 200 mL of the chilled fuel sample require more than 60 seconds to pass through a fine wire mesh filter under repeated pressure pulses.

4.1.8 Flame speed

It is a speed relative to the fresh mixture. It is a chemical-physical constant for a given mixture and it is proportional to the mixture that can be burnt, per time unit. The flame speed is an important parameter that influences the stabilization of the flame, it should be of the same order of the air speed in the combustion chamber to guarantee the anchorage of the flame and to avoid its extinction. Flame speed is subject to the changes of :

- temperature and pressure
- main stream velocity
- medium diameter of the fuel drops, in terms of SMD (Sauter Mean Diameter)
- the equivalence ratio
- kind of fuels

as it can be noted by the following pictures, representing some results of different experiments:

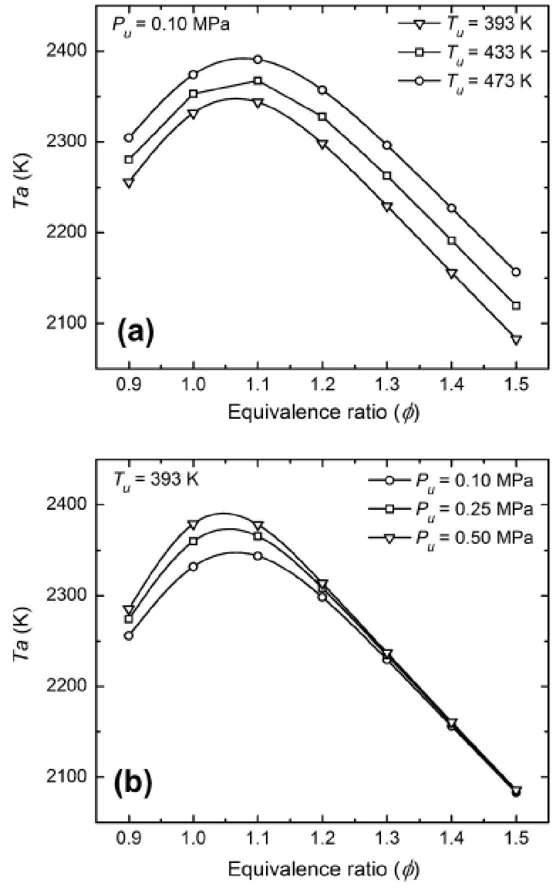


Figure 31 Flame speed's variation with equivalence ratio, temperature and pressure for an iso-octane blend [6]

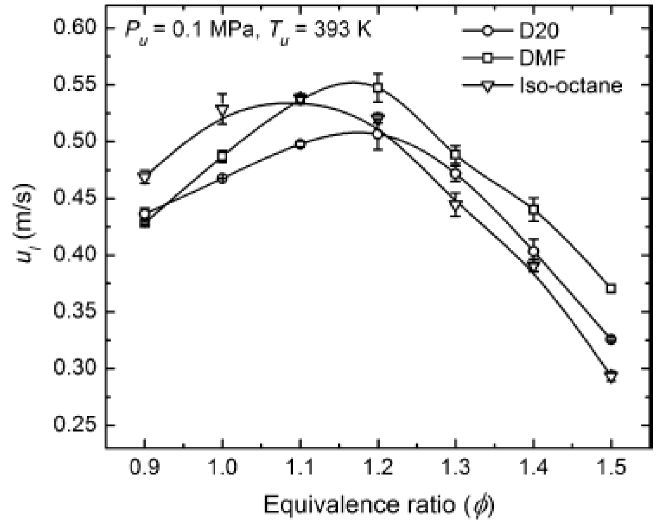


Figure 32 Flame speed variation with equivalence ratio and different kind of fuels [6]

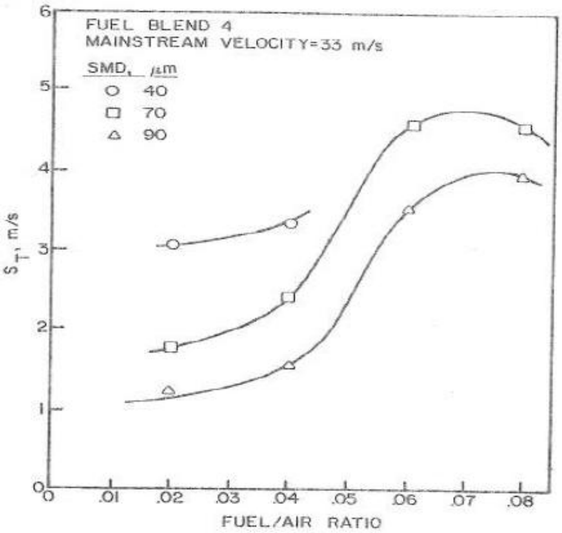


Figure 33 Flame speed variation with SMD and fuel-air ratio [5]

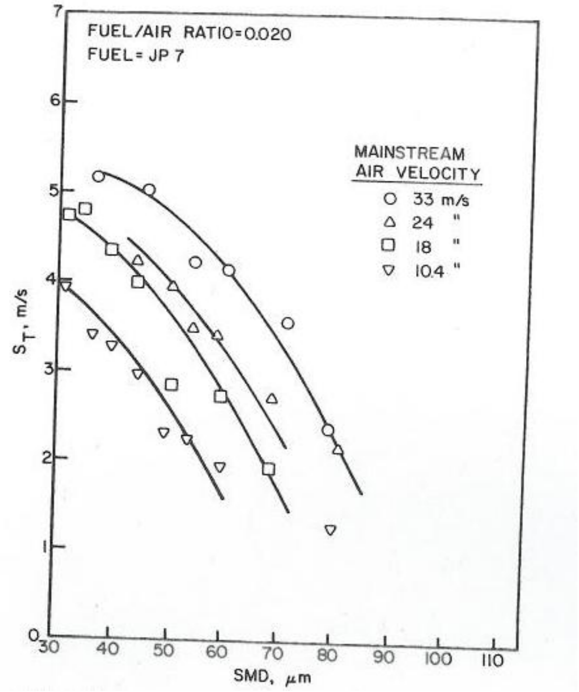


Figure 34 Flame speed variation with SMD and mainstream velocity [5]

4.1.9 Ignitability

To start the combustion process, it is necessary to achieve Minimum Ignition Energy [chapter about ignition process].
Ignition can occur in 3 different regimes:

- *Point Source of ignition*: It occurs when ignition is forced at a specific point, using a point-like spark discharge, i.e. a discharge of few microseconds generated between two electrodes spaced few millimeters apart.

- *Surface Ignition*: It occurs when ignition is forced from a small surface . In case of static gases, they go in contact with a heated surface. They start

to be heated till the achievement of minimum ignition energy that allows the beginning of the ignition process. In case of flowing gases, they flow on a heated surface where there is the formation of two boundary layers, an aerodynamic and a thermal one. Passage of mixture along a given streamline of both the boundary layers leads to deceleration, heating and partial or complete reaction.
Another way is the catalytic one, it is used in particular for afterburners, where ignition occurs using a catalytic surface to make the fuel burn.

- *Spontaneous Ignition*: In this case ignition is not controlled, since it arises spontaneously in the mixture when it is subjected to temperatures higher than the ambient one. This occurs because at temperature much above ambient, the more energetic molecules of fuel and oxygen crack and start a chain of preoxidaton reactions. When the energy reaches the activation level, ignition occurs.
The typical value of spontaneous ignition temperature for aviation kerosene is 254 °C.

4.1.10 Flash Point

Flash Point is the lowest temperature at which, in specific conditions, a quantity of vapor is produced such to form, with air, a mixture capable of being ignited with a proper ignition system. This property is important where the combustor inlet conditions are above flash point conditions, but it also indicates the fire explosion hazard, in particular if fuel has flash point below room temperature, it requires controlled ventilation in order to minimize fire risk.
Low flash point is index of presence of volatile constituents, and careful storage is required to avoid their evaporation.

4.1.11 Inflammability and Flammability Range

In general inflammability is related to the capacity of a fuel-oxidant mixture to sustain combustion after the ignition process, while flammability range is the range between the rich and the weak limits, in which combustion can occur.

Inflammability is often connected with flash point, and can be measured with some fire tests, i.e. with test where the behavior of the inflammable substance is checked, in presence of different quantities of air, in order to find also the limits of the flammability range, in terms of air to fuel ratio.

Flammability range is modestly affected by temperature (see figure below). Increasing pressure tends to increase the rich limit but has small effect on the weak one, while a reduction of pressure seems to have little effect on both the limits, but only until about 7 kPa, after which the flammability range decays to zero.

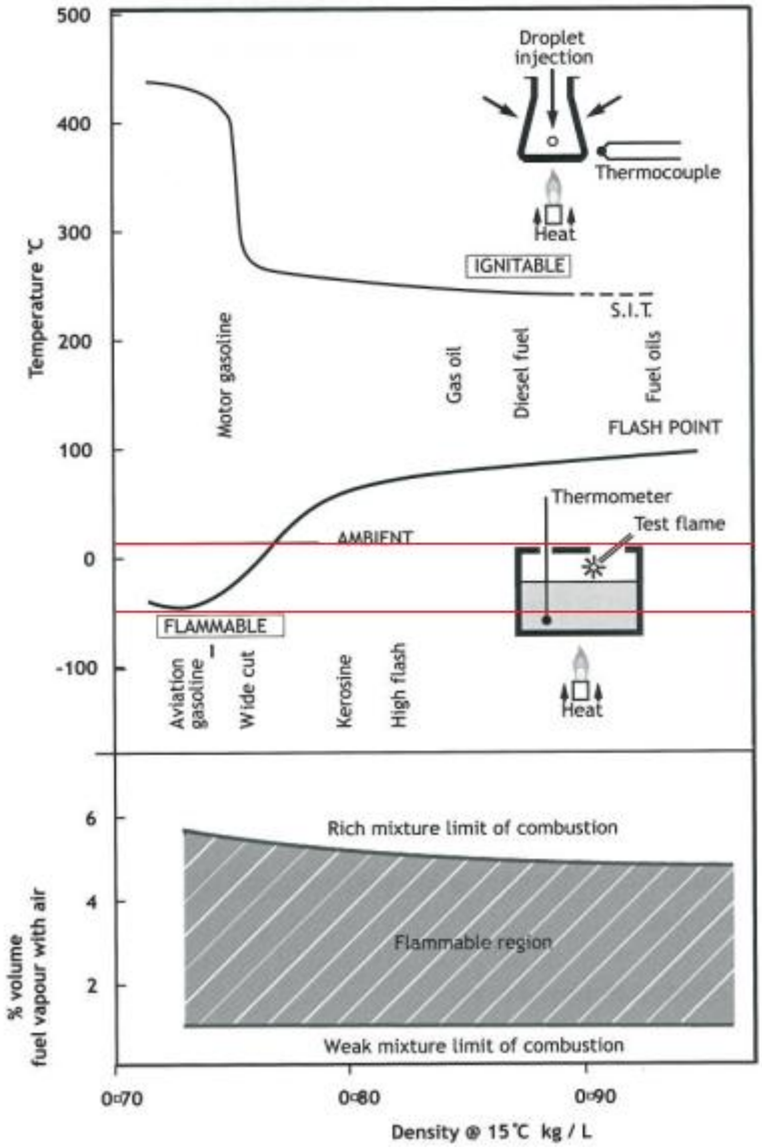


Figure 35 Levels of combustible mixture limit, flash point and spontaneous ignition temperature for petroleum fuels, with schematic apparatus. [4]

4.2 Other Properties

These properties are relevant in general for aeronautical fuel, but are less interesting for what concerns the atomization and ignition processes.

4.2.1 Thermal Stability

Problems of thermal stability are related to the presence of gum in aviation fuels. This is due to the presence of copper, olefins and other materials in the fuel that lead to an easiness of oxidation. Additional gums are produced during the storage phase. Therefore it is typical to conduct some test that indicate the “potential gum”, this is possible for gasolines but unfortunately not for kerosines, since no correlation was found with field storage trials, because of differences in fuel type, processing and field conditions. However with special treatments, that include the use of a metal deactivating additive such as a propanediamine, this problem can be overcome.
A test can be conducted in order to assess thermal stability. This test is called JFTOT (jet fuel thermal oxidation tester, Fig.8), and comprises an aluminium tube resistance-heated to 260°C,a heated stainless-steel cloth precision filter and a different gauge. The test is based on the fuel sample flowing laminarly along the outer surface of the tube, in order that any deposit can be examined visually. The presence of solid particulates is indicated by any pressure drop.

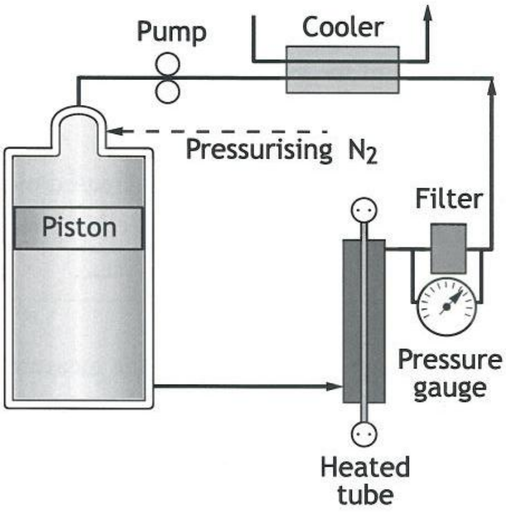


Figure 36 Schematic of JFTOT [4]

4.2.2 Smoke and Coke

The presence of combustion smoke is important for different reasons. First of all smoke is an index of pollution, but also coke, an aggregate of smoke and solid carbon particulates, is relevant because it could lead to deposition in the flame tube, and so to temperature differences. Another reason is that smoke emits infra red radiation, which is used as a homing signal by heat-seeking missiles, so it is important for military aircraft.

Temperature differences cause metal failure and therefore turbine blade damage. Smoke is sub micron sized, it represents a health hazard and it is also index, but in minor part, of combustion inefficiency.

A typical test that is conducted is for the tendency of the fuel to generate smoke. The maximum height to which a diffusion flame, wick fed from the fuel sample, can be adjusted without smoking is defined the smoke point. But this kind of test is far away from the usage in a combustor. Smoke production tends to be higher with higher aromatic content in fuel.

4.2.3 Electrical Conductivity

Electrical conductivity is not one of the most important properties for gas turbine engine fuels, since, because of their cleanness, is very low (1 to 3 picosiemens/meter for aviation kerosene). This property derives from the flow of the fuel through pipelines, when the presence of trace polar contaminations leads to the rise of ionization. This property has been considered dangerous in particular during aircraft fuelling, and therefore a number of rules, about pumping rates, line velocities, settling time and bottom loading, were adopted to avoid the generation of static electrical charges.

Sometimes this property is also useful in a combusting spray, since creating an electric charge after atomizer can improve droplets' distribution and penetration in the primary zone.

The following figure represents a composite plot for the major properties of petroleum fuels:

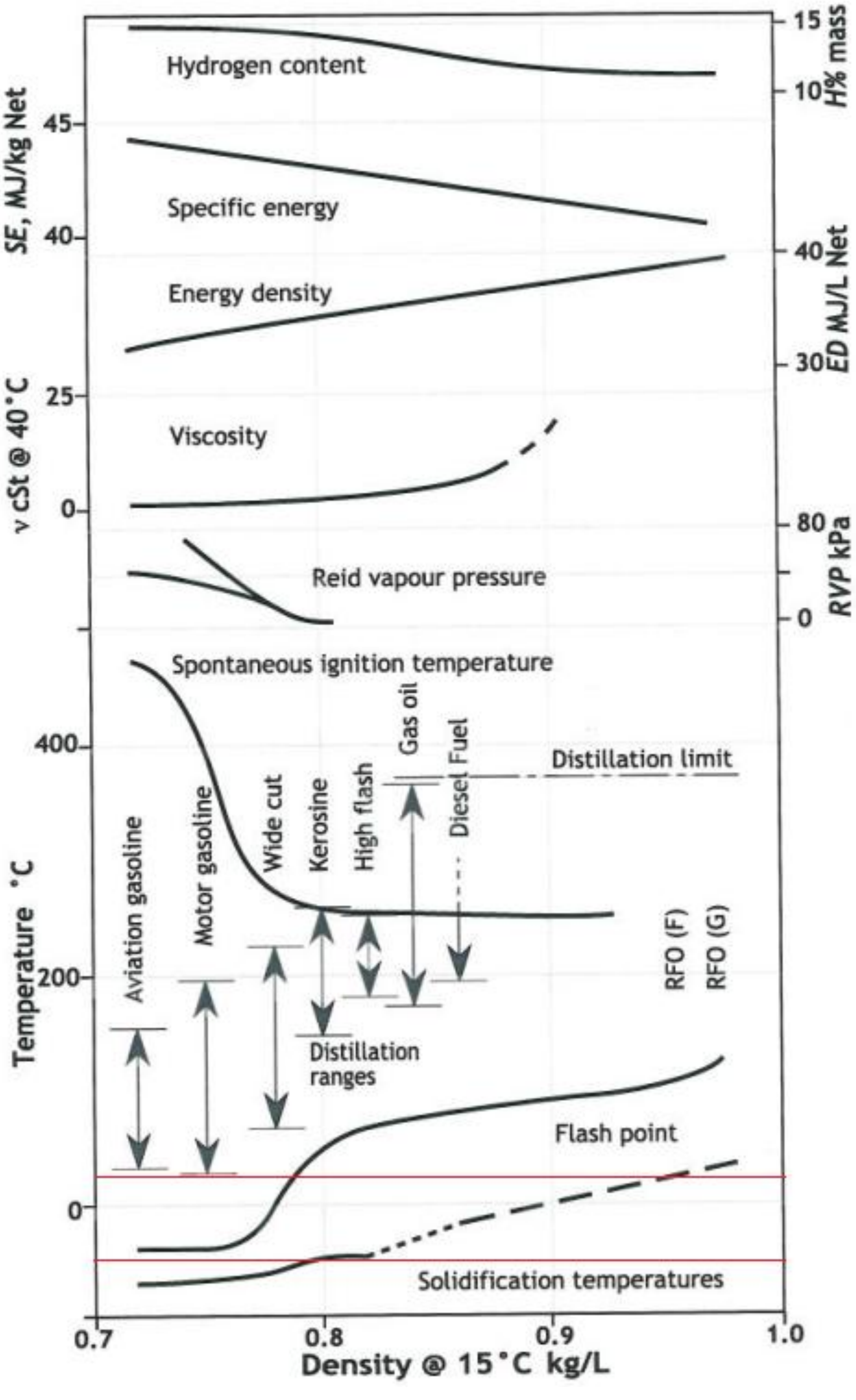


Figure 37 Composite plot of major properties of petroleum fuels

Fuel	Average Formula	Density [kg/L] At15°C	Distillation range [°C]	Kinematic Viscosity [cSt] At15°C	Solidification Temperature [°C]	Surface Tension [mN/m] At15°C	Flash Point [°C]	Calorific value [Mj/kg] fuel
Hydrogen	H_2	0.07^b	-253	-	-259	2^b	-	120.2
Methane	CH_4	0.42^b	-162	-	-183	-	-	50.0
Comml. propane	C_3H_8	0.51^v	-40	-	-186	-	-	46.5
Comml. butane	C_4H_{10}	0.58^v	-7	-	-140	12		44.2
Aviation gasoline	$C_{7.3}H_{15.3}$	0.72	46 – 145	0.5	-70^{fp}	21	-40	44.2
Aviation kerosine	$C_{12.5}H_{24.4}$	0.80	152 256	1.8	-52^{fp}	25	43	43.4
Jet A	-	0.775-0.840	-	8 at -20°C	-40^{fp}	-	38	42.8
Jet A-1	-	0.775-0.840	175-270	8 at -20°C	-47^{fp}	-	38	42.8
TS-1	-	0.774 at 20°C	-	8 at -40°C	-50^{fp}	-	28	42.9
Jet B	-	0.750-0.801	100-250	-	-51^{fp}	-	-	42.8

Table 1 Properties of different fuels [1]

With

b = 1 atm

v = under vapor pressure at 15°C

fp =freezing point

Fuel	Production % of CO_2	Production % of H_2O	Production % of N_2	Flammability limits in air a/f mass	T_{sp} [°C]	T^* [°C]
Hydrogen	0	34.7	65.3	34 - 5	574	2431
Methane	9.5	19.0	71.5	34 - 10	540	2246
Comml. propane	11.7	15.4	72.9	27 – 6	520	2273
Comml. butane	12.0	14.9	73.1	27 - 5	480	2275
Aviation gasoline	12.8	13.4	73.8	26 – 4	470	2298
Aviation kerosine	13.1	12.9	74.0	22 - 4	254	2295

Table 2 Typical combustion properties of conventional fuels [1]

5. Atomization Processes

5.1 Atomization

In a gas turbine engine liquid fuels are typically used, but since they are not volatile enough to produce vapor, they are atomized into a great number of droplets, increasing in this way the liquid surface area. As will be seen in the next chapter, the size of droplets influences many parameters, like stability limits, combustion efficiency, emissions level and also the rate of evaporation (in particular the smaller is droplet size, the higher is the evaporation rate).

Atomization uses the action of both internal and external forces in order to interrupt the influence of the surface tension, and hence it involves several interacting mechanism. A very important parameter that characterizes this process is the Weber number, We, defined as the ratio between the disruptive aerodynamic force to the surface tension force:

$$\boldsymbol{We = \frac{0.5\rho_a U_R^2}{\frac{\sigma}{D}}}$$

The higher We, the larger the deforming external pressure forces, compared with the surface tension forces.

Starting from the definition of We it is possible to define the maximum stable drop size as

$$\boldsymbol{D_{max} = 12\sigma/\rho_a U_R^2}$$

It’s possible to split the atomization process into two phases, primary atomization, where the fuel is broken into ligaments and shreds, and secondary atomization, where the products of the first one are broken into smaller droplets.
The process dealt with in this chapter is based on the breakup of fuel

drops, and this is possible only when the critical condition for drop breakup is reached. This condition is achieved when external forces (drag) equals the internal one (surface tension forces), and it's so defined:

$$\boldsymbol{C_D\left(\pi/_4\right)D^2 0.5\rho_a U_R^2 = \pi D\sigma}$$

Where C_D is the drag coefficient of the droplet.

By rearranging this equation it's possible to define the critical condition of the Weber number:

$$\boldsymbol{We_{crit} = {}^{8}/_{C_D}}$$

The influence of viscosity in atomization process is described by the Ohnesorge number ,Oh, defined as:

$$\mathbf{Oh} = {}^{(\mathbf{We})^{\mathbf{0.5}}}/_{\mathbf{Re}}$$

Where Re is the Reynolds number:

$$\boldsymbol{Re = \frac{\rho_l U_R D}{\mu_l}}$$

With the subscript L that indicates liquid fuel. The critical Weber number can be written with the effect of viscosity, as Brodkey suggested [1]:

$$\boldsymbol{We_{crit} = We_{crit_0} + 14\mathbf{Oh}^{1.6}}$$

Where $\boldsymbol{We_{crit_0}}$ is the critical Weber number for zero viscosity.

The atomization process is characterized by two different mechanisms, classical and prompt one.

- *Classical mechanism of atomization*: concerned with the formation of waves that can bring to the drops breakup by the action of small disturbances on the surface and/or in it.

- *Prompt mechanism of atomization*: it is a faster mechanism. Prompt atomization occurs when breakup takes place very rapidly, for example, where a high velocity air jet impinges the fuel jet or sheet. In this condition the fuel has not the time to form wavy structure and goes suddenly into droplets breakup. The size of such droplets is influenced by viscosity but also by the initial fuel dimension. It is very difficult that prompt atomization occurs with low Weber numbers, while it is dominant with high value of We.[1]

Breakup of fuel jets and sheets

This mechanism is typically used to realize the drops breakup of fuel jet or sheet, by introducing some disturbance on the liquid surface that lead to the formations of ligaments and then of drops.

Jet breakup

Rayleigh found that if a disturbance is introduced, characterized by a wavelength λ_{opt} so defined [1]:

$$\lambda_{opt} = 4.51d$$

with d initial jet diameter, it's able to bring the disintegration of the fuel jet into drops of diameter D=1.89d, accompanied by the formation of some satellite drops. The definition of λ_{opt} was then modified by Weber to introduce the viscosity effects:

$$\lambda_{opt} = 4.44d(1 + 3Oh)^{0.5}$$

It's also important to know that the velocity influences the atomization process because of aerodynamics interferences. As Weber found, an increase in jet velocity (from 0 to 15 m/s) led to a reduction of λ_{opt} to 2.8d, and so leading to a reduction of D to 1.61d, obtaining a smaller drop size.

If the velocity increases, the relative motion between the jet surface and the surrounding air improve atomization. So as the jet velocity increases, ligament diameter decreases and atomization is enhanced.
Therefore it is possible to describe four different mechanisms, depending on the velocity:

- *At low velocity*: drops formation caused by axisymmetric oscillations. Drop diameter almost twice the initial jet one.
- *At higher velocity*: the mechanism is the previous, but the λ_{opt} is reduced because of the interaction jet-surrounding air. Drop diameter the same of the initial jet one.
- *At an improved velocity*: droplets formation caused by unstable growth of small waves on the jet surface. Drop diameter smaller than the initial jet one.
- *At very high velocity*: atomization occurs rapidly. Drop diameter about 80 µm.[1]

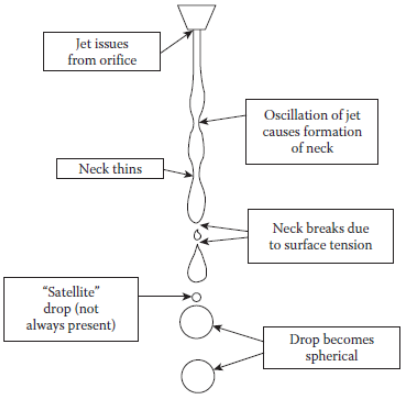


Figura 38 Fuel jet breakup mechanism

Fuel sheets breakup

With regard to the fuel sheet breakup, it's based on a wave motion caused by the interaction between fuel and surrounding air, that brings the sheet in being separated into ligaments. These ligaments then contract to form droplets of different sizes and velocities.

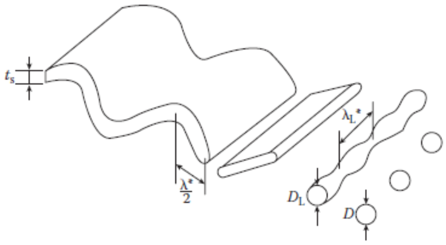


Figura 39 Fuel sheet breakup mechanism

What is possible to understand from what written so far is that the atomization process can be divided in two stages. The first, led by wave motion, is clearly deterministic, while the second, droplets breakup, is random and stochastic. [1]

For this stochastic process, to be described by probability density function, also called *pdf*. Different empirical pdfs were proposed, the most well-known are Rosin-Rammler and Nukiyama-Tanasawa correlations, but before arriving at that kind of correlations, in the last 20 years two analytical methods were proposed, the DPF method (discrete probability function) and MEP (maximum entropy theory). The first is based on a linear instability theory used to determine the most unstable wave to which the liquid is subjected. The coming droplet size is then related to the dominant wavelength resulting from the liquid bulk breakup. On the other hand, MEP is based on the concept of information entropy, used as a measure on uncertainty of a probability distribution.MEP is a method used to predict the least biased pdf that can satisfy properly a set of constraints like conservation of liquid mass, momentum and energy during atomization process, and also the interaction between atomizing liquid and surrounding gas.[2]

A good atomization process is fundamental to obtain ignition and a high combustion efficiency. This objective can be achieved with a proper mixing of fuel vapor with air. That mixing depends mainly on the rate of vaporization of fuel droplets that is improved by a good atomization process and depends also greatly by dispersion and penetration of fuel droplets in the stream of swirling air in the combustor. Some experiments were conducted about combustion and atomization, and they led to the dependence of penetration and vaporization of some parameters. These experiments brought some results that showed how an increase in spray cone angle, inlet air swirl and inlet air pressure and a decrease in air temperature bring a decrease of the spray penetration. [3]

5.2 Atomizers

There are different kinds of atomizers, every one characterized by some advantages and disadvantages, but that seek to provide the optimum atomization conditions across the combustor operating regime.

These devices are different in particular for the principle on which the atomization is based.

Pressure atomizers: for this kind of devices the atomization is based on the achievement of a high relative velocity between fuel and air, obtained with the conversion of liquid pressure into kinetic energy.

- *Plain Orifice*: This device is based on making a low-viscosity fuel pass through a small hole (typical circular, although attempts are made using shaped holes to produce asymmetric sprays), obtaining first of all a liquid jet that rapidly disintegrates into a well-atomized spray. This process is obtained by an increase in turbulence and in aerodynamic forces exerted by the surrounding sides, because of an increase in fuel injection pressure. This particular device is the most simply made and it’s typical of afterburners, since their typical fuel injection system is composed by circular manifolds supported by struts inside the jet-pipe.[1]

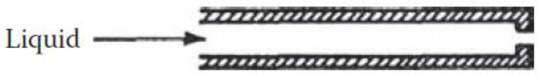


Figura 40 Plain Orifice Atomizer

- *Simplex atomizer*: This atomizer is able to obtain droplets breakup by forcing the fuel under pressure through a specially designed orifice. In order to minimize the combustor length, a spray cone of 110° is obtained by the introduction of a swirl chamber upstream of the orifice. This kind of atomizer is characterized by a problem, if the discharge orifice is designed to guarantee a good atomization at low fuel flow rates, then there will be some problems with high fuel flow rates, since the pressure required will be excessive, but however, if the atomizer is designed for high fuel flow rates, the atomization at low fuel flow rates will be not acceptable. This problem is solved by using a dual-orifice atomizer.[1]

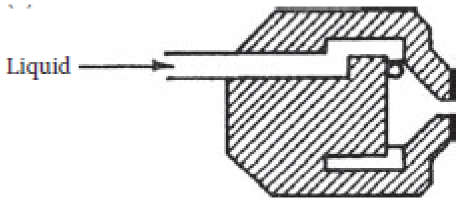


Figure 41 Simplex atomizer

- *Dual-orifice atomizer*: This kind of device is composed by two concentric swirl chambers, the pilot and the main one. With this disposition low fuel flows pass through the pilot swirl chamber that ensure a good atomization, when a pre-determined pressure is reached, a valve opens and fuel moves in the main chamber. Then it is necessary to augment the fuel flow, otherwise the low secondary fuel pressure will lead to a poor atomization quality.

This device is characterized by good mechanical reliability and by the ability to sustain combustion with low fuel flows, but however there is a fuel flow range in which the drop size is too large, in particular when the valve is opened, so a possible solution is to make the spray cone of the primary spray a bit larger than the secondary spray's one, in order to make the two cones interact and share their energy.[1]

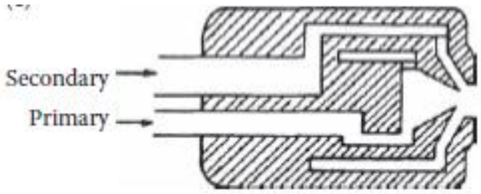


Figure 42 Dual-orifice atomizer

- *Spill-Return*: This kind of atomizer was one of the most used because it guarantees a very efficient atomization since of constant high fuel-injection pressure that it's able to maintain. This device is similar to a simplex atomizer but instead of having a solid rear wall of the swirl chamber, it contains a passage, through which the quantity of fuel that is more than requested for the combustion enters the spill and comes back again in the fuel tank. In this way a high fuel-injection pressure can be hold also with low fuel flow rate.

  Spill-return atomizers are also characterized by some disadvantages: high fuel-pump power requirements, large variation of the spray cone angle when fuel flow rate changes, more complicated problems of metering the fuel flow rate, the need of a larger-capacity pump to handle the large recirculation flow. For all these reasons the spill-return atomizer is not used anymore in gas turbine engines, but it is sometimes used in the industrial ones. There are also other issues with recirculated fuel flows; the generation and dissipation of heat in the recirculated liquid and the accumulation of electric charge in it. The latter is dealt with by 'earthing' (grounding in American) the fuel system.[1]

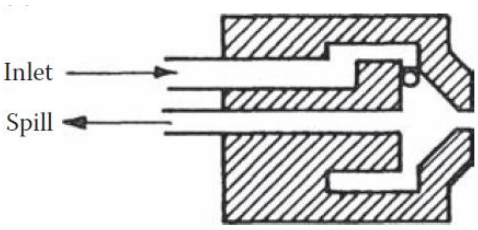


Figure 43 Spill-Return Atomizer

Rotary atomizers: In this kind of device fuel is supplied at low pressure, it's sprayed and dispersed through the discharge orifice of a hollow drum by centrifugal force of a rotating shaft. This device is characterized by simplicity, but it has some problems with igniter-plug location, and with relighting at high altitude. It seems good for small engines and low compressor ratio, it's relatively independent of fuel properties and requires lower pumping pressure. It's also efficient in terms of costs, weight reduction and ease to maintenance. The atomization process promoted by rotary atomizer could be divided into three phases: a liquid column breakup stage, a liquid film formation and a direct drop formation stage.[1][4]

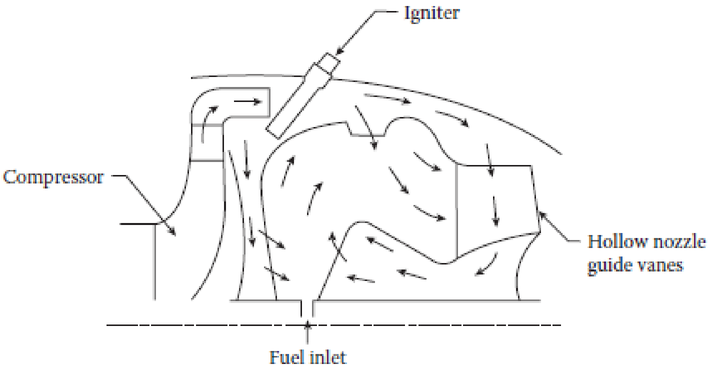


Figure 44 Rotary atomizer

Air-assist atomizers: This system represents another solution to the simplex atomizer's problem, since in this device the fuel ports are sized for the highest fuel flow rate, and then it uses high velocity air (or also other fluids) to augment the atomization process at low fuel flows. There are two different configurations of air-assist atomizers. The first one is the internal mixing, where air and fuel are mixed before exiting through the outlet orifice, while in the second configuration, the external mixing, fuel and air are mixed downstream the outlet orifice.

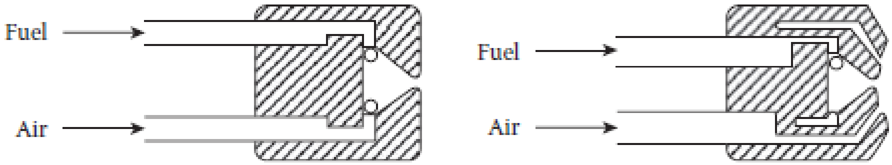


Figure 45 Air-assist atomizer : internal and external mixing

Airblast atomizer: This device is based on the principle that if fuel at low pressure is forced to flow over a lip, in a high velocity airstream, per each side, it is led to the droplets breakup, due to the stress forces. In this atomizer the air flows into the combustion chamber carrying the fuel droplets. The airblast atomizer is characterized some advantages due to its thorough mixing of air and fuel, like the absence of soot formation, furthermore the component parts are protected by the air from overheating, but on the other hand there are also some disadvantages like narrow stability limits and poor atomization quality at startup. This problems are solved with the introduction of an airblast atomizer with a pilot pressure-swirl atomizer. There are different kinds of airblast atomizer:

- *Plain-jet atomizer*: it features a round jet of fuel injected along the axis of a round jet of air.

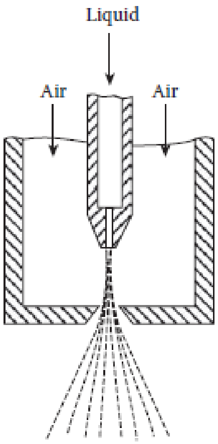


Figure 46 Plain-jet atomizer

- *Prefilming Airblast*: In this device the air is split through two concentric air passages, while the fuel flows on a prefilming surface before being discharged in the interface between the two airstreams. This is the most used atomizer now in service.

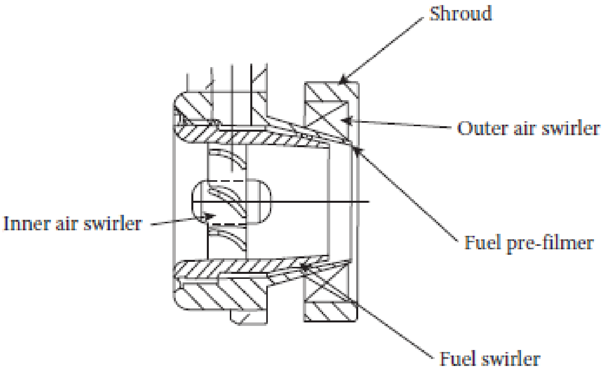


Figure 47 Prefilming airblast atomizer

- *Piloted airblast*: it’s an hybrid atomizer composed by a prefilming one with a simplex pressure-swirl nozzle placed on its centerline.

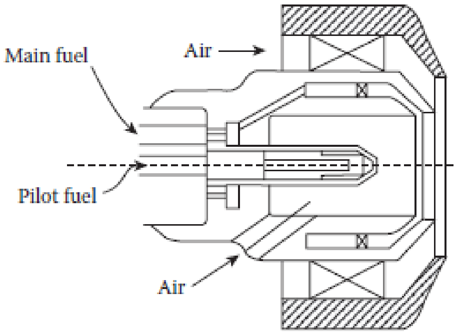


Figure 48 Piloted airblast

- *Airblast simplex*: it’s composed by a simplex pressure-swirl nozzle surrounded by a co-flowing stream of swirling air.

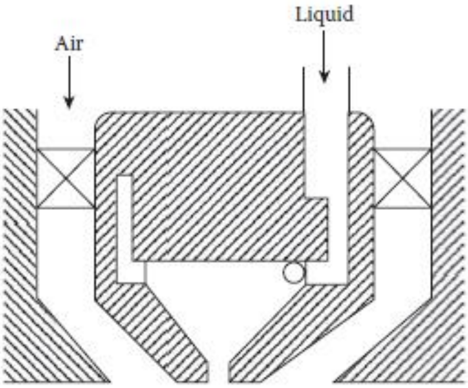


Figure 49 Airblast simplex

Effervescent atomizer: Another kind of atomizer is the effervescent one where the air is injected at low velocity in order to form bubbles that will lead to the droplets breakup of the fuel. It typically consists of liquid and gas supply ports, a mixing chamber and an exit port. The gas is supplied to an annular chamber surrounding the perforated central tube, with a pressure that is a bit higher than the liquid one.

Thanks to its higher pressure, the gas penetrates the liquid stream, forming bubbles. So the bubbly two-phase mixture flows towards the exit orifice, and in particular the gas phase forces the liquid to flow through a small fraction of the exit orifice, leading to the reduction of liquid shreds' and ligaments' size. Once outside the discharge orifice, the rapidly expanding gas leads to the liquid breakup into droplets.

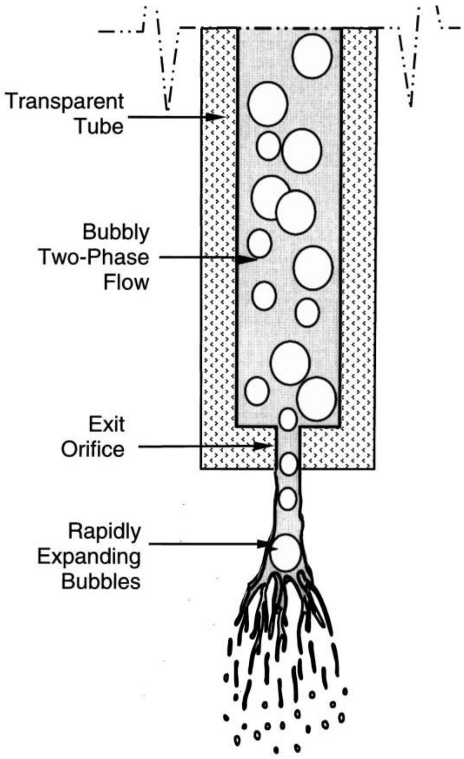


Figure 50 Schematic of the atomization mechanism for an effervescent atomizer

This device is very simple, rugged, reliable and ensures a good atomization, that can be achieved at injection pressures several times lower than those required by other types of atomizers. Furthermore this atomizer guarantees smaller drop size rather than the others with also lower pollutant emissions, gas flow-rates are smaller than those employed by other twin-fluid atomizers and mean drop size is relatively insensitive to liquid viscosity.

Another interesting data is about flow velocities in the discharge orifice, that are much lower for this kind of device than those encountered for conventional atomizers, since two-phase flows choke at lower velocities than single-phase flows. This leads to a reduction of orifice erosion.[12]

Vaporizer: Apart from the atomizers, another good way to obtain a good combustion is to use this kind of device. It is based on pre-heating of the liquid fuel above the boiling point, in order to make it completely vaporized before combustion. The typical architecture is based on the use some circular tubes immersed in the flame, installed longitudinally in the combustion chamber. The downstream ends of these tubes are bent through 180°. Liquid fuel is fed in their entrance ends, that are open and exposed to the air stream coming from the compressor. The mixture is then discharged in the flame tube in an upstream direction. The consequent flame promotes vaporizing and pre-heating of the rest of the mixture within the tubes.

Vaporizers have some advantages in terms of cost and low soot formation. A problem of this kind of device could be represented by the presence of tubes immersed in the flame, that in case of problems cannot be demounted without disassembling the engine. This problem could be overcome providing a vaporizer assembly mounted externally, on the peripheral wall of the combustion chamber, and that projects within it.[1][10][11]

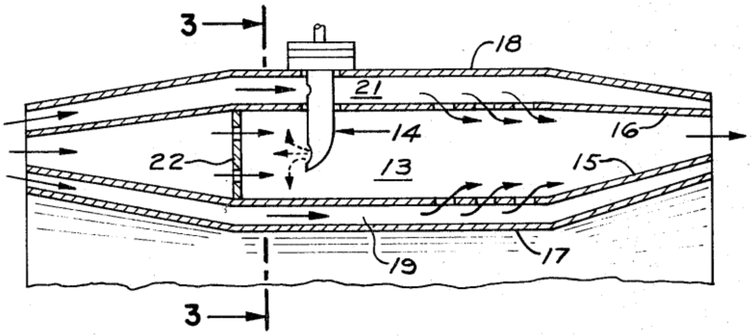


Figure 51 Fragmentary view of a cross-sectional elevation of a portion of a jet engine combustor engine with a vaporizer

5.3 Drop-Size Distributions

An important parameter to take in account about the atomization process is the drop-size distribution in the spray. It is typical to represent the distribution of drop sizes with a graphical representation, e.g. using histograms, where each ordinate represents the number of droplets that have dimensions between $D - \Delta D/2$ and $D + \Delta D/2$ (Fig. 53).

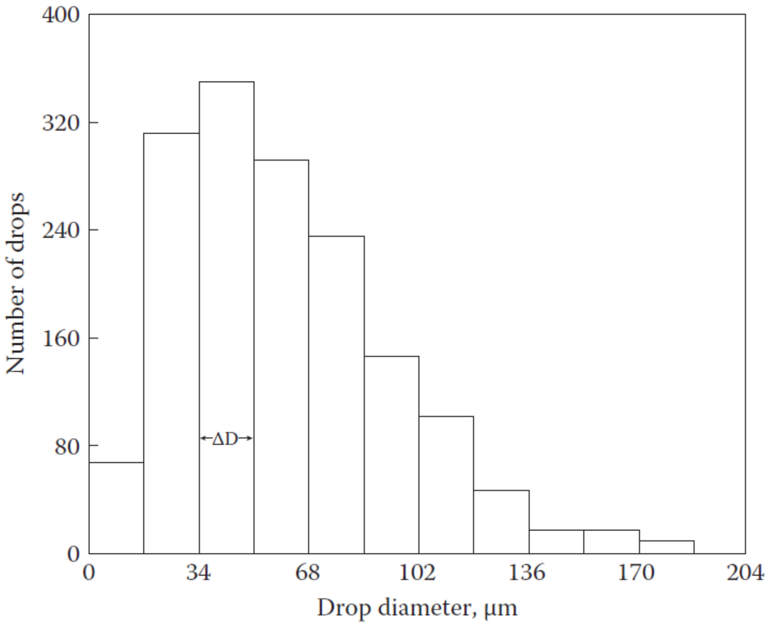


Figure 52 Typical drop-size histogram with ΔD=17 μm [1]

From Fig.53 is possible to note how the graph is quite similar to the form of a frequency distribution curve, as in Fig.54, if it is based on a sample large enough.

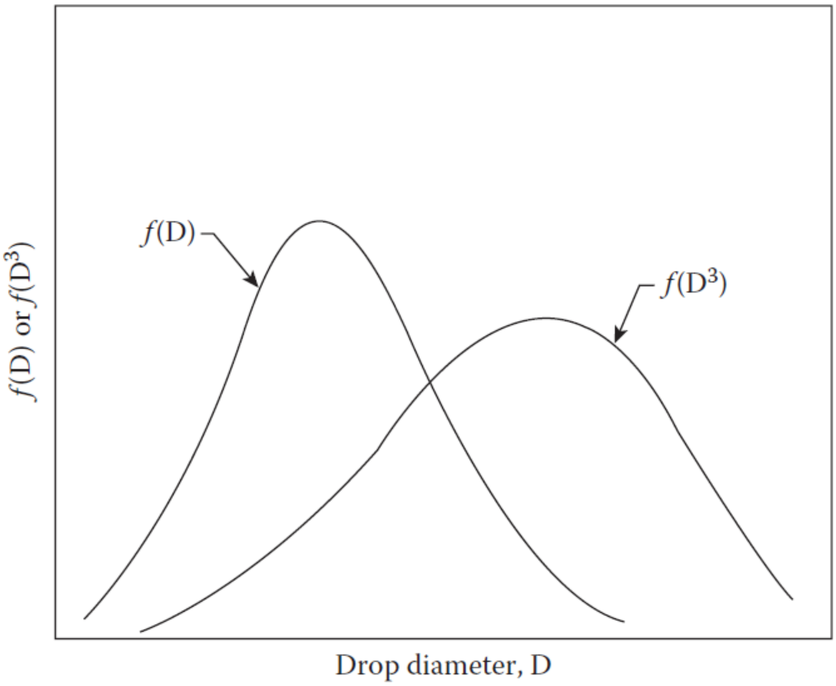


Figure53 Drop-size frequency distribution curves [1]

Another technique used to represent drop-size distribution is the cumulative distribution, i.e. a plot of the integral of the frequency curve (Fig.55).

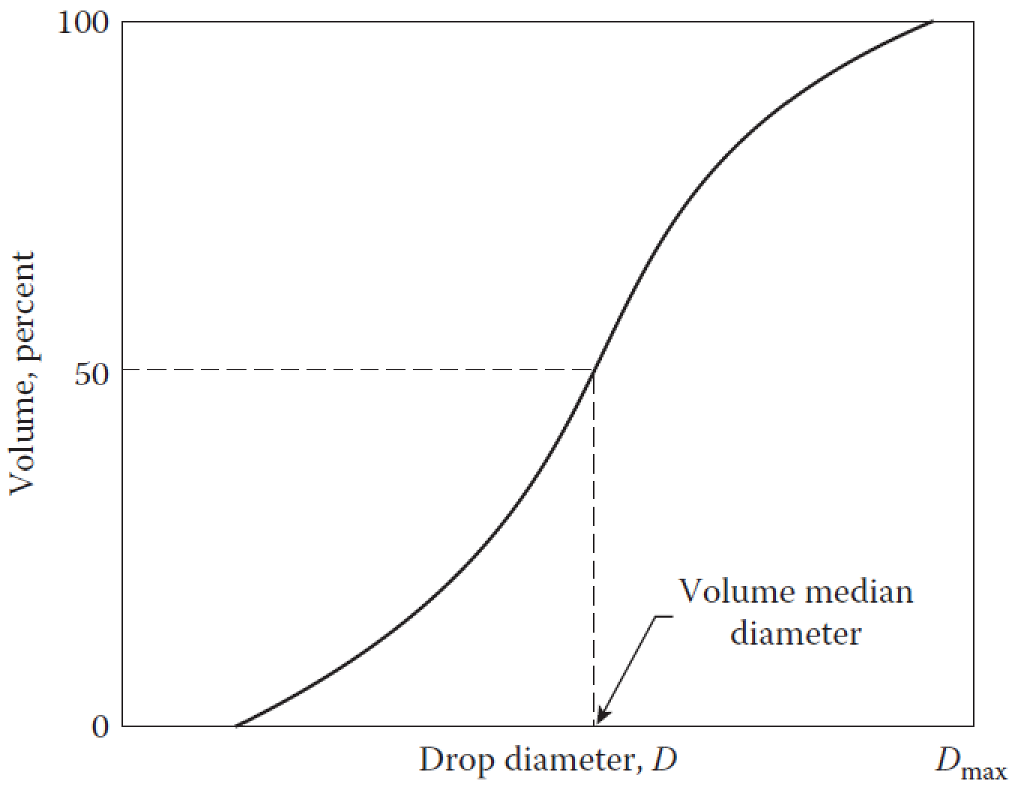


Figure 54 Typical curve of cumulative distribution [1]

Graphical representation has some disadvantages, e.g. it is laborious and related with difficulty to experimental results. This led some workers to develop mathematical distribution functions, that are typically based on empirical considerations. The most important is the Rosin-Rammler distribution function.

Rosin-Rammler distribution function

This widespread function is defined as:

$$1 - Q = e^{-\left(\frac{D}{X}\right)^q}$$

With

Q: fraction of the total volume contained in drops of diameter less than D.

X: constant determined experimentally.

q: constant determined experimentally, that provides a measure of the spread of drop sizes. In particular, the higher the value of q, the more uniform is the distribution. With q infinite, all the drops have the same size. Typical value of q for most practical sprays is between 1.8 and 3.

Rosin-Rammler distribution is quite simple and permits to extrapolate data into the range of very fine droplets.

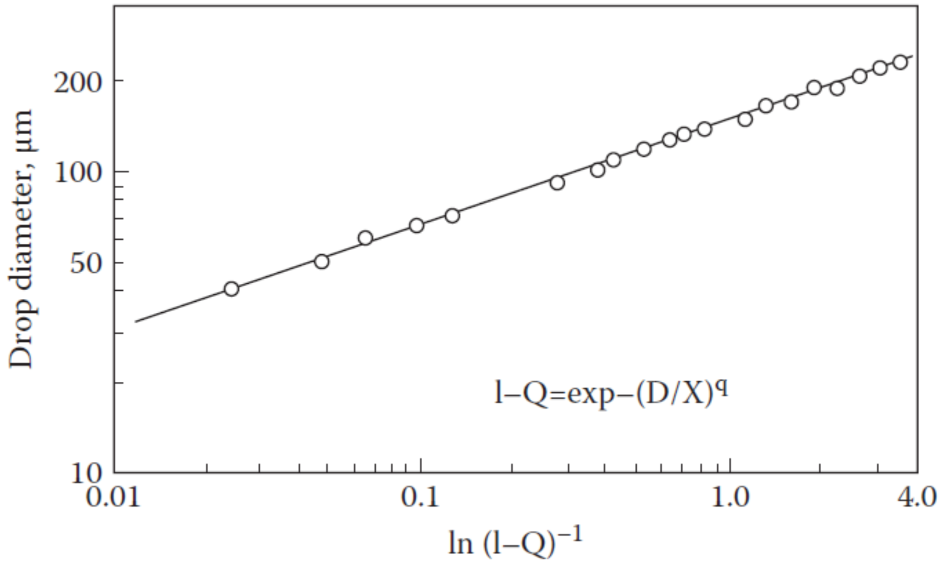


Figure 55 Typical Rosin-Rammler curve [1]

After some analysis, Rizk and Lefebvre suggested a change to the Rosin-Rammler distribution [13]:

$$1 - Q = e^{-\left(\frac{lnD}{lnX}\right)^q}$$

This change improved the relationship with experimental results, as it is possible to note from Fig.19:

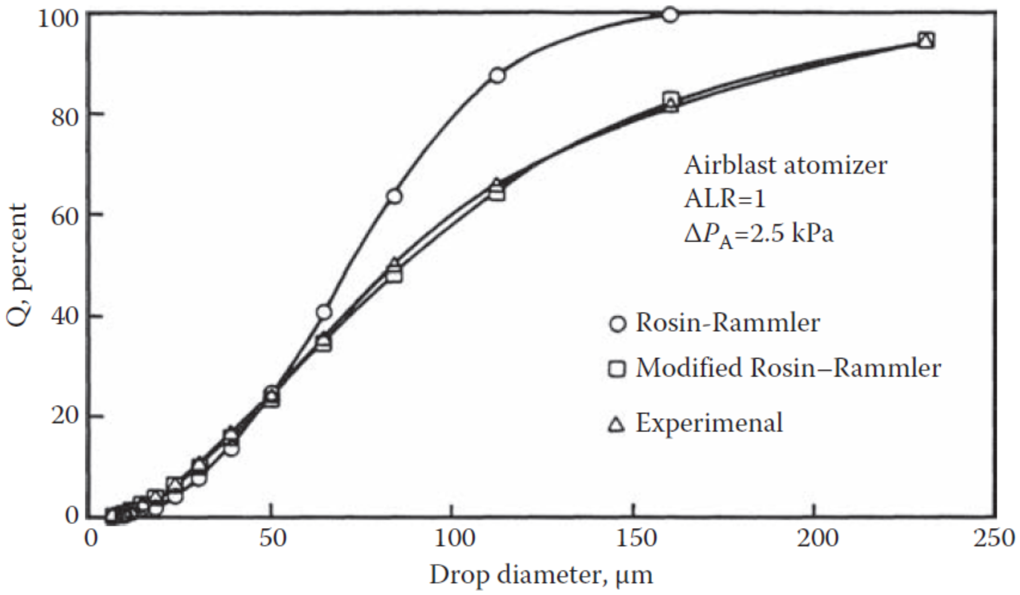


Figure 56 Comparison between Rosin-Rammler and Modified Rosin-Rammler plots, with also experimental results curve [1]

5.4 Mean drop diameter and typical SMD equations and values for different atomizers

Another relevant parameter is the mean drop diameter. There are many definitions of different mean diameters, as:

- $D_{0.1}$: drop diameter such that 10% of the total liquid volume is in drops of smaller sizes.
- $D_{0.5}$: drop diameter such that 50% of the total liquid volume is in drops of smaller sizes. Also known as volume, or mass, mean diameter VMD (MMD).
- $D_{0.632}$: drop diameter such that 63.2% of the total liquid volume is in drops of smaller sizes. This is X of the Rosin-Rammler equation.
- $D_{0.9}$: drop diameter such that 90% of the total liquid volume is in drops of smaller sizes.

Although these different definitions, the most relevant mean diameter is SMD, i.e. the Sauter mean diameter, also known as D_{32}, defined as the diameter of a drop within the spray, whose volume to surface area ratio is the same of that of the whole spray.

If the drop size data correspond to a Rosin-Rammler distribution, it is possible to relate all the diameters via q:

$$MMD = SMD(0.693)^{\frac{1}{q}}\tau\left(1-\frac{1}{q}\right)$$

Where τ denotes the gamma function.

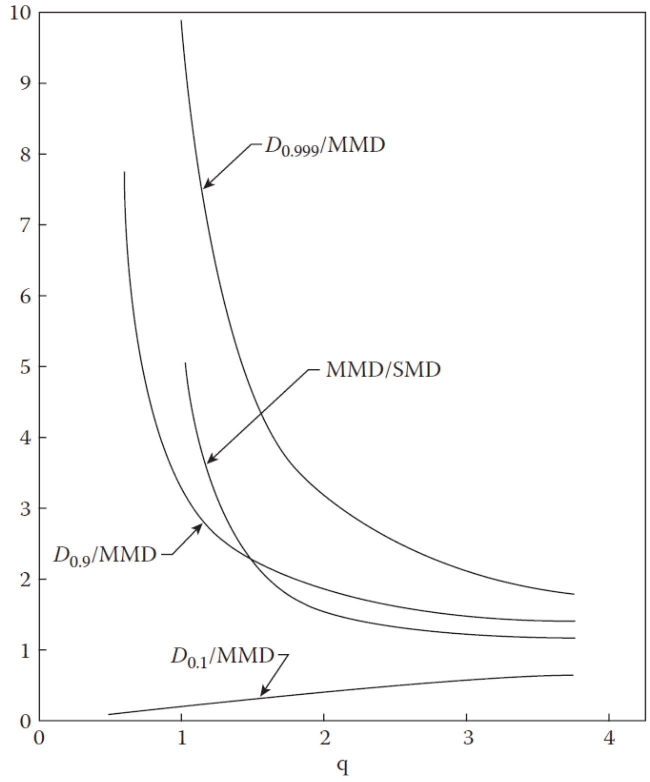


Figure 57 Relationship between Rosin-Rammler distribution parameter *q* and various spray properties [1]

5.4.1 SMD for pressure atomizers

Plain orifice

For this kind of atomizer there are not a huge number of equations, because of the difficulty in measuring the drop size, due to the big density of drops. According to Elkotb, a possible measure of SMD is:

$$SMD = 3.08 \upsilon_L^{0.385} (\sigma \rho_L)^{0.737} \rho_A^{0.06} \Delta P_L^{-0.54}$$

Pressure-swirl

This kind of atomizer is characterized by various complex phenomenon. The typical equation of SMD is:

$$SMD = constant\ \sigma^a \mu_L^b \dot{m}_L^c \Delta P_L^{-d}$$

The work of Jasuja led to:

$$SMD = 4.4\ \sigma^{0.6} \mu_L^{0.16} \dot{m}_L^{0.22} \Delta P_L^{-0.43}$$

Another equation, characterized by the advantage of being dimensionally correct, is [1]:

$$SMD = 2.25\ \sigma^{0.25} \mu_L^{0.25} \dot{m}_L^{0.25} \Delta P_L^{-0.5} \rho_A^{-0.25}$$

Lefebvre developed an alternative approach to derive SMD, based on some considerations on the role of velocity. For both pressure and airblast atomizers, both relative velocity between the liquid and the surrounding air and velocity of liquid injection are very relevant. In pressure atomizers two different effects have to be taken in account: first of all the role of the absolute velocity U_L, that can provoke turbulence and instabilities, and, secondly, the effect of the relative velocity U_R, that promotes the atomization mechanisms on the liquid surface. Starting from these considerations, Lefebvre divided the atomization process into two different phases, the first where instabilities are created on the liquid surface, and the second, where there is the conversion into ligaments and drops. This subdivision yields to:

$$SMD =$$

$$4.52(\sigma\mu_L^2/\rho_A\Delta P_L^2)^{0.25}(t\ cos\theta)^{025} + 0.39\left({}^{\sigma\rho_L}/_{\rho_A\Delta P_L}\right)^{0.25}(t\ cos\theta)^{0.75}$$

(1)

With t defined as the film thickness within the final discharge orifice, and θ as the half-angle of the spray. The value of 4.52 and 0.39 were found experimentally by Wang and Lefebvre. This investigation led to the results represented in the following graphs:

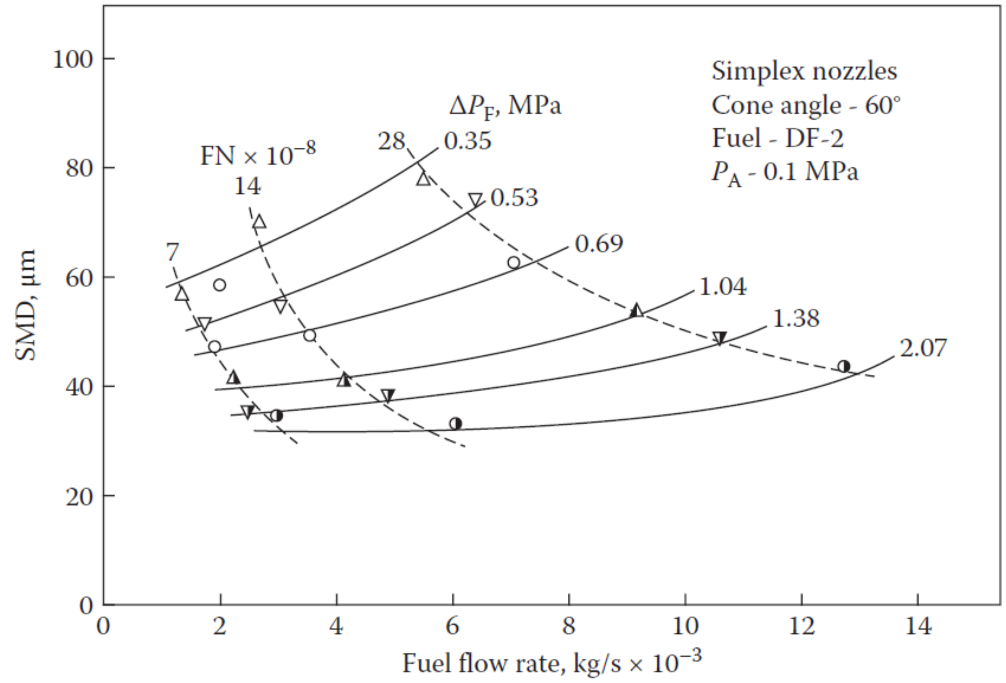


Figure 58 Relationship between SMD and nozzle operating variables, with spray cone of 60° , with diesel fuel no.2 (DF-2)[1]

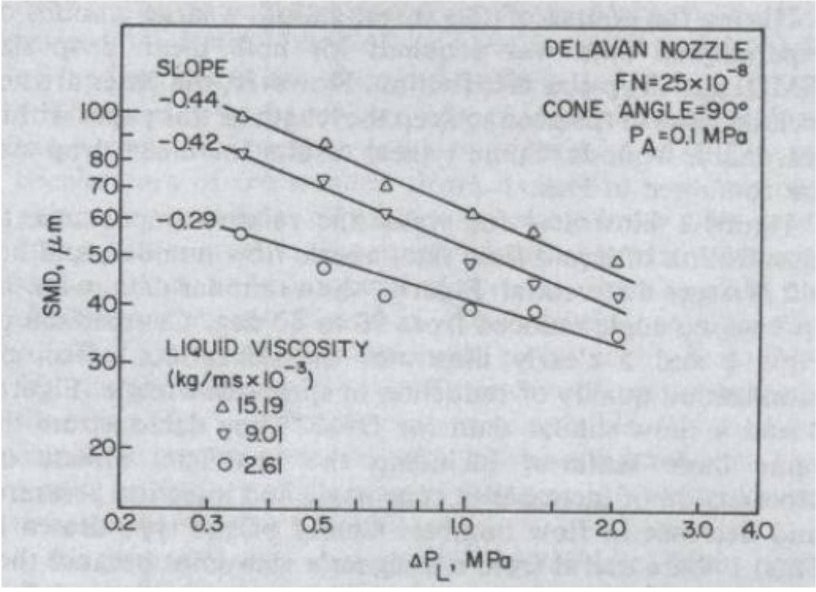


Figure 59 Influence of viscosity on SMD for a 90° cone angle [14]

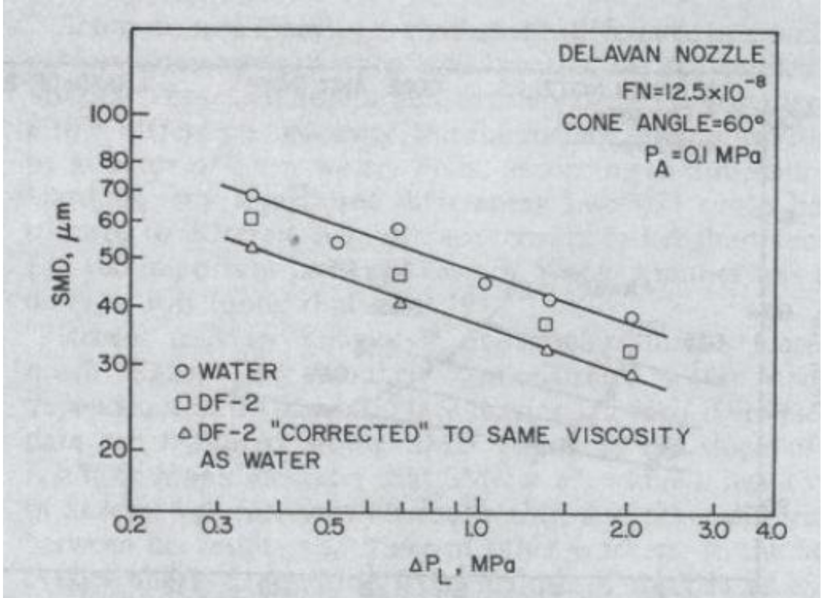


Figure 60 Influence of surface tension on SMD for a 60° cone angle [14]

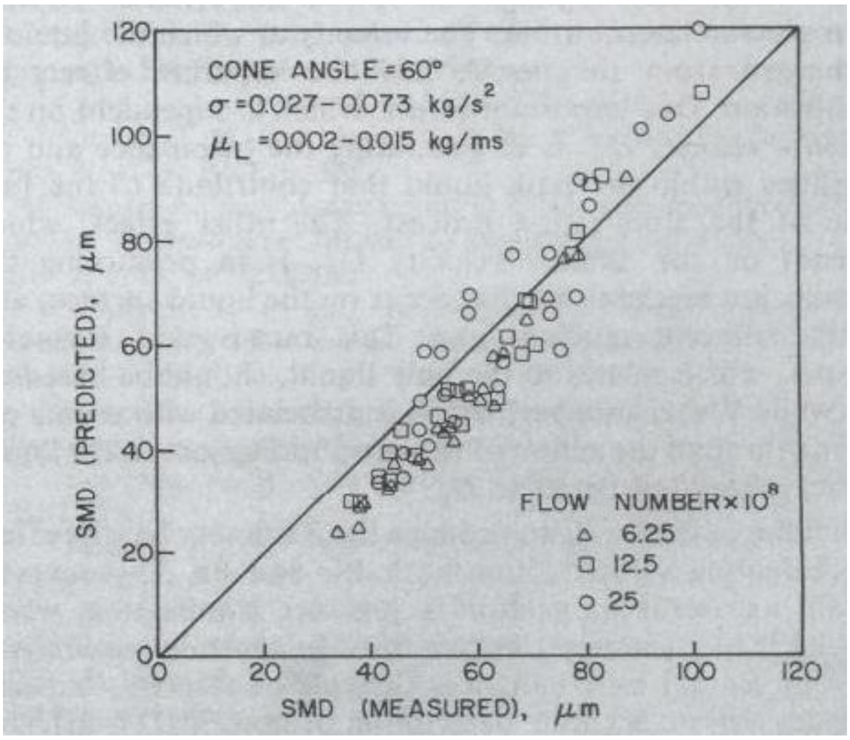


Figure 61 Correlation of experimental data with equation (1) for a 90° cone angle [14]

5.4.2 SMD for twin-fluid atomizers

From the experiments conducted half a century ago by Nukiyama and Tanasawa [15] on a plain-jet airblast atomizer, it was found:

$$SMD = 0.585(\sigma/\rho_L U_R^2)^{0.5} + 53(\mu_L^2/\sigma\rho_L)^{0.225}(Q_L/Q_A)^{1.5}$$

This equation is not dimensionally correct, and so it needs the introduction of a characteristic length L_c raised to the power 0.5, that could be the diameter of the liquid discharge orifice, or of the air nozzle at exit, but it was found that this length has no effect on the drop size.

Another form to derive SMD/L_c is to take in account the effects of ALR (air to liquid ratio), Weber number and Ohnesorge number, in a basic equation like:

$$SMD = SMD_1 + SMD_2$$

This kind of approach led to:

$$SMD/L_c\,(1 + ALR^{-1}) = AWe^{-0.5} + BOh^{0.5}$$

That can also be written as:

$$SMD/L_c = [1 + ALR^{-1}]\,\left\{A\left(\sigma/\rho_A U_A^2 D_p\right)^{-0.5} + B\left(\mu_L^2/\sigma\rho_L D_p\right)^{0.5}\right\}$$

Considering different twin-fluid atomizers, their different design features and internal flow effects led to some changes in the equation, e.g. Rizk and Lefebvre found for a plain-jet atomizer [13]:

$$\begin{aligned} SMD = 0.48d_0\left[\sigma/\rho_A U_A^2 D_p\right]^{0.4}[1 + ALR^{-1}]^{0.4} \\ + 0.15d_0\left[\mu_L^2/\sigma\rho_L D_p\right]^{0.5}[1 + ALR^{-1}] \end{aligned}$$

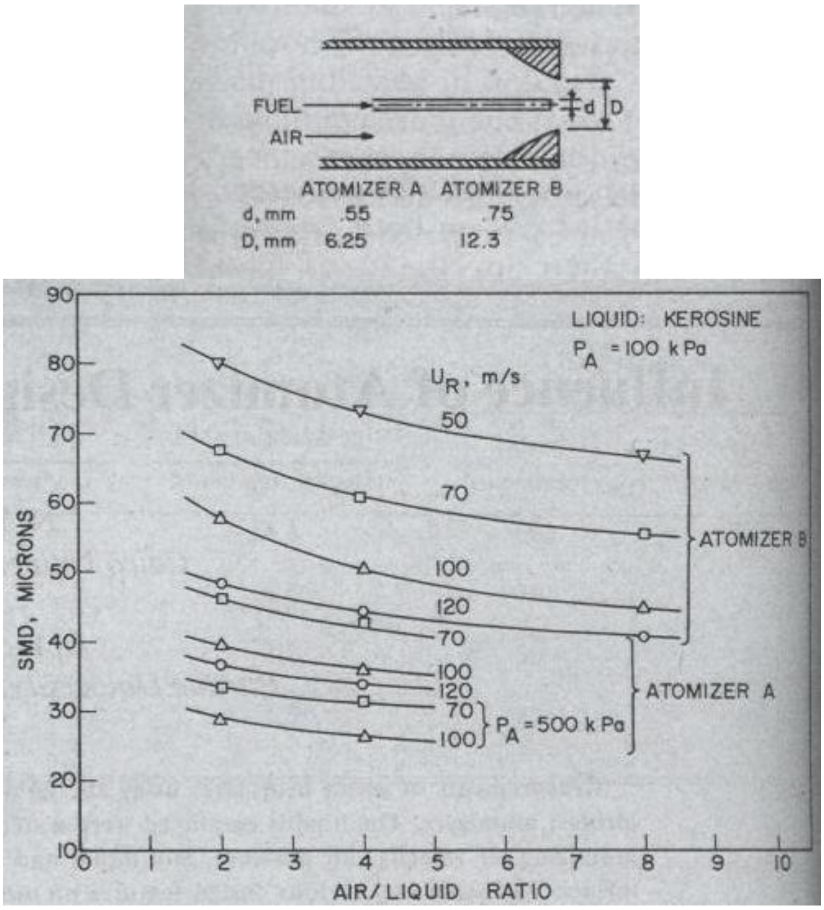


Figure 62 Typical results obtained with 2 different plain-jet atomizers, whose dimensions are represented in the apparatus above [13]

While for prefilming airblast atomizer, Lorenzetto and Lefebvre found [16]:

$$SMD/D_h = [1 + ALR^{-1}]\left[0.33\left(\sigma/\rho_A U_A^2 D_p\right)^{0.6}(\rho_A/\rho_L)^{0.1} + 0.068\left(\mu_L^2/\sigma\rho_L D_p\right)^{0.5}\right]$$

With D_h hydraulic diameter of the air exit duct, and D_p prefilimer diameter.

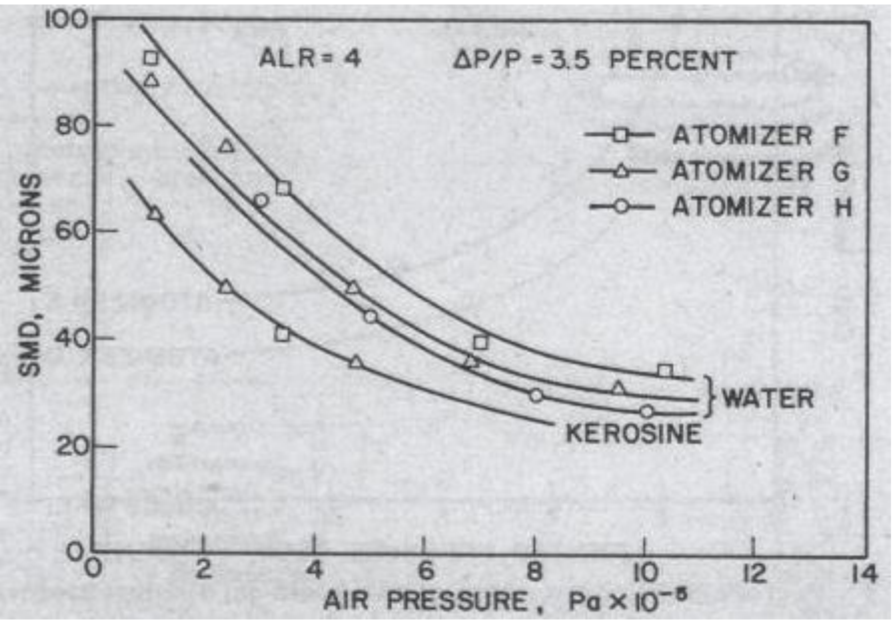


Figure 63 Performance comparison of plain-jet (F) prefilming (G) and "flat sheet" airblast (H) atomizers [13]

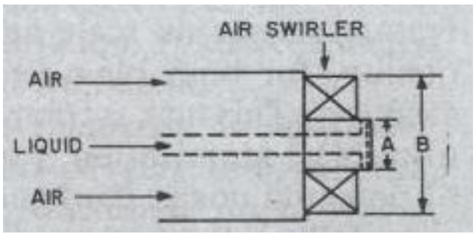


Figure 64 Atomizer F [13]

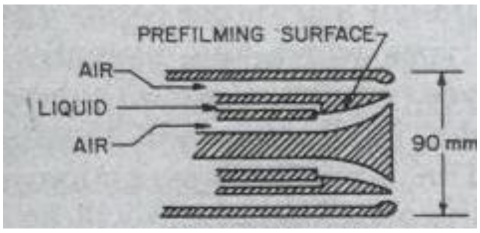


Figure 65 Atomizer G [13]

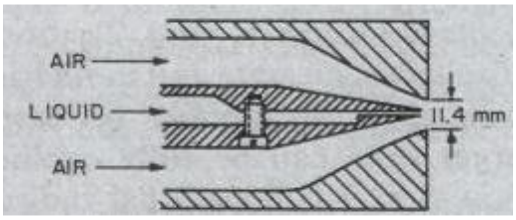


Figure 66 Atomizer H [13]

Both the last two equations show that SMD increases with an increase in the liquid viscosity.

6. Evaporation process

6.1 Phenomenon’s description

It is possible to divide evaporation into two distinguishing phases, the heat-up and the steady-state periods.

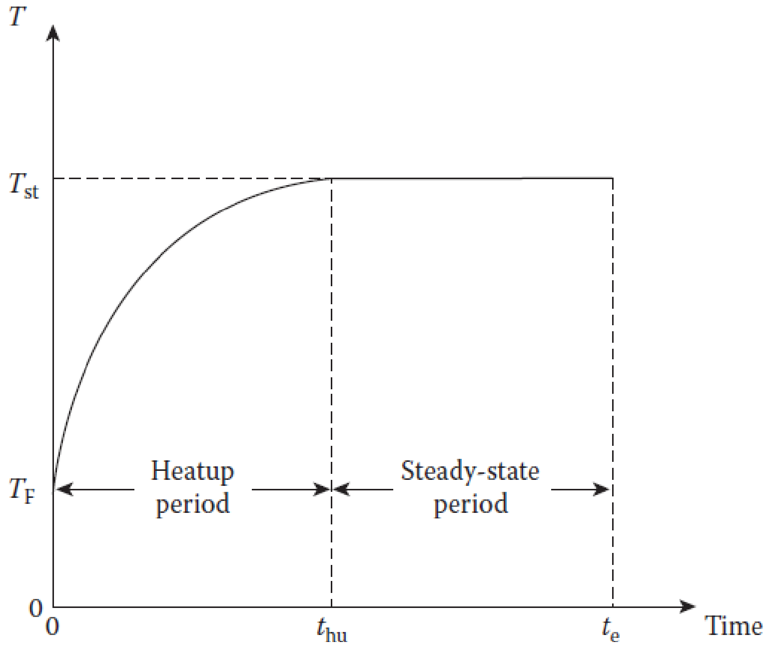


Figure 67 Fuel temperature variation during evaporation [1]

If a single-component fuel drop is immersed in a hot gas flow, it starts warming up, and almost all the heat supplied to the drop is used to make the drop pass from its initial temperature value T_F, to the achievement of the steady-state temperature T_{ST}. Once achieved, this value remains constant, since all the heat supplied will be used only to make the evaporation complete. Note that in case of multi-component fuel drop the evaporated fraction will differ in amount and composition.

In order to make a proper description of the process it is important to note that, in spray combustion computations, it is typical to assume that the overall spray behaviour can be obtained as the sum of the behaviours of all the single droplets, everyone surrounded by a gas phase. Therefore this chapter is characterized by the description of different models for the evaporation of a single droplet.

d^2 *law model*

One of the most important work about the basic droplet vaporization model is the d^2 *law model*, developed by Godsave, and it is characterized by the following assumptions:

- It uses a quasisteady spherically symmetric model for both gas and liquid phases
- Droplet and its wet-bulb temperature are assumed uniform and constant.
- It is assumed that the fuel vapor mass fraction at the gas-liquid interface is a function of the surface temperature.
- This model neglects liquid-phase heat and mass transfer in the droplet.

Because of all these assumptions, this model leads to a simple estimate of the droplet vaporization rate.

Godsave derived the rate of evaporation for a single drop:

$$m_F = (\pi/4)\rho_F \lambda D$$

With λ, that could be assumed constant (figure 2), defined as:

$$\lambda = d(D)^2/dt$$

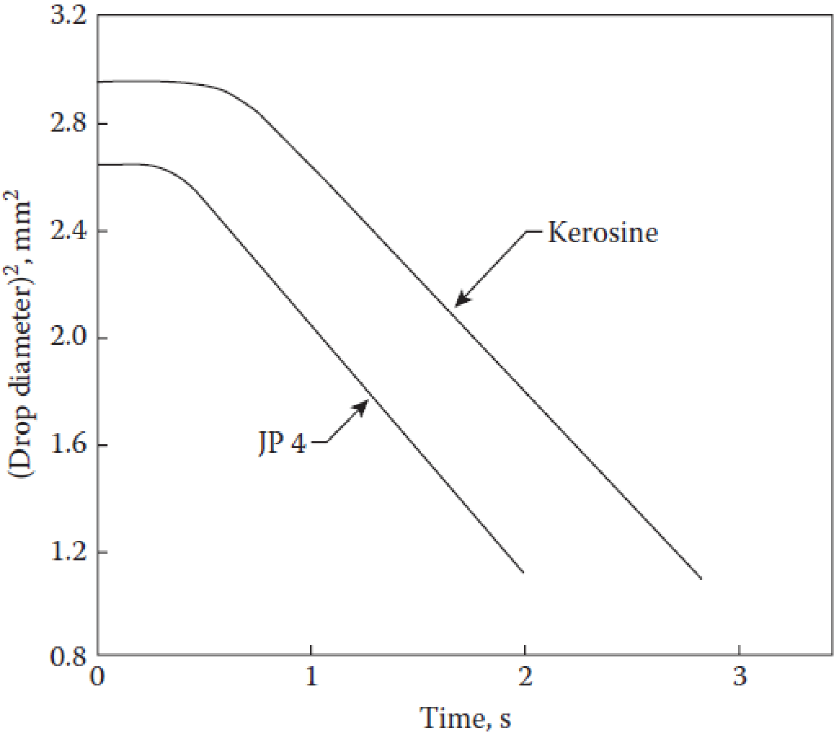


Figure 68 Evaporaton rate curves for JP4 and Kerosine[1]

It is also possible to define the average rate of evaporation as :

$$\dot{m}_F = (\pi/6)\rho_F \lambda D_o$$

And the drop lifetime t_e:

$$t_e = D_o^2/\lambda$$

With D_o initial drop diameter.

It is possible to introduce the mass number B, defined as:

$$B = \frac{c_{pg}(T_g - T_s)}{L} = \frac{Y_{fs}}{1 - Y_{fs}}$$

With L latent heat of fuel and Y_{fs} the fuel vapor mass fraction at the interference.

It is now possible to write the evaporation rate in terms of B:

$$\dot{m}_F = 2\pi D(k/c_p)_g \ln(1+B)$$

To take in account forced convection when relative motion exists between the droplets and the surrounding gas, it is enough to multiply $\dot{m}_F$ by the correction factor

$$1+0.22 Re_D^{0.5}$$

Where the drop Reynolds number Re_D is typically about 5. [1][2]

Infinite Conductivity Model

Another way that could be used to describe the evaporation process is the *Infinite Conductivity Model* developed by Law. He assumes that the droplet is characterized by a rapid internal mixing, where droplet temperature is spatially uniform but varying with time. This model is basically the same of the d^2 *law model*, but the liquid-phase temperature is assumed uniform and varying with time inside the droplet instead of constant, while the gas-phase model is always spherically symmetric and quasisteady. This model was in part affected by Sirignano's study. He showed that the uniform temperature limit comes from the infinite conductivity limit, rather than from rapid mixing limit.

Equations that describe this model are the same of the d^2 *law model*,but the latent heat of fuel is replaced by:

$$L + \frac{1}{m}\left(\frac{4}{3}\pi r^3 \rho_l c_{pl}\right)\frac{dT_l}{dt}$$

The additional term accounts the transient liquid droplet heating.[2]

Conduction Limit Model

A more complicated model is the *Conduction Limit Model.* It is used when the internal liquid motion is neglectable, and the phenomenon is led just by thermal diffusion. In this case equations of diffusion are used, with initial and boundary conditions. The difficulty of that model consists in considering a moving boundary layer during the droplet vaporization. The equations are always the same of the d^2 *law model* with L replaced by:

$$L + \frac{1}{m}(4\pi r^2 k_l \frac{\partial T_l}{\partial t}|_{rs})$$

With the additional terms that accounts the liquid-phase heat flux at the surface.[2]

Convective effects in droplet evaporation

With regards to the evaporation process, it is important to note that very often droplets vaporize in a convective gas field, and so convective effects have to be taken in account. Convection affects evaporation, since first of all it leads to the increase of gasification rate and heat-transfer rate between the phases, and also because it provokes liquid circulation inside droplets, increasing the liquid-transfer rate.

Ranz-Marshall Model

A solution to approach this phenomenon is to correct the fuel mass vaporization rate with a term that accounts fir the convective effects:

$$m_{convection} = m_{spherical} f(Re, Pr)$$

The study of Ranz and Marshall [3] led to this correction factor [3]:

$$f(Re, Pr) = 1 - 0.3Re^{1/2}Pr^{1/3}$$

This correlation is quite simple but is supported by very little theoretical justification. [2]

Prakash and Sirignano's Axysimmetric Model[2]

Prakash and Sirignano developed a complicated model to study evaporation process. First of all they studied liquid internal circulation and droplet heating, and then they developed an analysis on gas-phase boundary layer, coupling it to the previous study.

They used a two-dimensional axysimmetric model, characterized by the division of the problem in different physical regions:

- outer inviscid gas flow: treated as steady potential flow around a sphere
- gas-phase and liquid-phase boundary layer: treated as quasisteady for both momentum and energy transfer
- and inviscid liquid core: treated as quasisteady for momentum while the energy transfer was considered transient.

In this kind of analysis there is also a thin thermal boundary layer near the droplet surface, coupled to the thermal core.

The results of this difficult model led to the conclusion that the quasisteadinesss assumption for thermal layer is not valid, since the thermal inertia is very important, and also that the thin thermal boundary layer could be replaced by considering the thermal core solution up to the droplet surface.
The study of Prakash and Sirignano showed that the *Infinite Conductivity Model* is never realized, and that also *Ranz-Marshall Model* cannot predict the vaporization rate satisfactorily, because it overpredicts the vaporization rate as compared to that given by the axisymmetric model (Figure 70). [2]

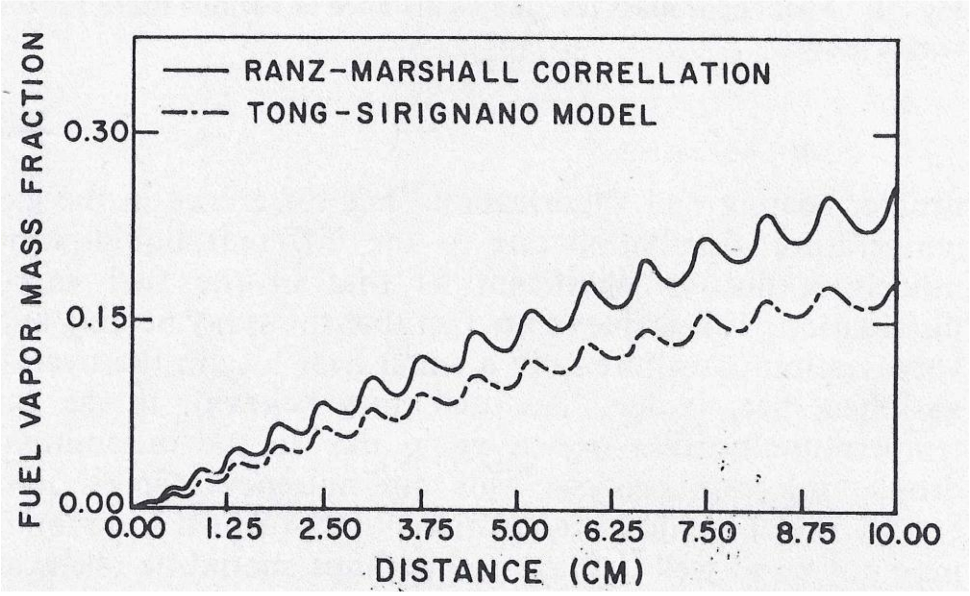


Figure 69 Comparison between Ranz-Marshall and Tong-Sirignano Models

Tong and Sirignano's Axysimmetric Model

In this study a simplification of the process was conducted. Tong and Sirignano developed a one-dimensional gas-phase model, simplifying the convective analysis and coupling it with a simplification of the liquid-phase model. The results showed a good agreement with what found in the Prakash and Sirignano's previous model. [2]

Conclusion

After analyzing the described models, it is possible to say that for spherically symmetric vaporization (no relative gas-droplet motion), the only reliable study is the *Conduction Limit* one, while when a relative gas-droplet motion exists, the model of Tong and Sirignano is reliable, in particular when droplet Reynolds number is about 1. For a more detailed description, the model of Prakash and Sirignano is recommended.

An analysis about the overall spray vaporization was conducted as well, with a one-dimensional transient flow of air and fuel droplets in an open tube, where the injection of fuel droplets was intermittent. This study is based on the equations that describe the gas-phase and the liquid-phase, with two different approaches, the Ranz-Marshall's and the Tong-Sirigano's ones. The system of equations is solved using a hybrid Eulerian-Lagrangian numerical scheme. The results indicated that the model of Tong and Sirignano is valid only when Reynolds number, based on relative velocity and defined as

$$Re_k = \frac{2}{t_r L_r} \frac{r_k \rho}{\mu} |V - V_k|$$

is large compared to the unit, while the model of Ranz-Marshall, as written before, overpredicts the vaporization rate as compared to the axysimmetric model. The results also showed an inherent unsteadiness, due to the intermittent character of the spray.[2]

7. Ignition Process

7.1 Process Description

The ignition process is described by several important phases.

The first phase is based on the formation of a flame kernel, characterized by sufficient size and temperature, in order to support the flame propagation. This phase is dominated by the fuel-air ratio, which should be close to the stoichiometric value, and by the temperature and size of the flame kernel, that depend on the kind of the ignition system used.

Also the ambient conditions are very important. A variation of temperature or pressure can affect the ignition, in particular at high altitude where temperature is not high and therefore it is more difficult to heat properly both air and fuel and to achieve the minimum ignition energy.

In particular, in the case of spark ignition, the spark passage brings about or creates the formation of a kernel, i.e. of a volume of air at high temperature with liquid fuel drops inside. The high temperature is provided partially by the spark energy and partially by the combustion of evaporated fuel drops. The ignition is considered successful, and the flame can propagate, if combustion of the fuel vapor produces a quantity of heat bigger than the heat loss due to the contact with the outside surface (fresh mixture) and the remaining fuel drops undergoing evaporation in the kernel. This is possible only if there is a sufficient amount of fuel drops in the ignition zone. In this case the minimum ignition energy $E_{min}$is achieved and the ignition of the remaining fuel:air mixture can start.

Another important parameter is the quenching distance d_q, defined as the minimum dimension that the inflamed volume must attain to propagate unaided, while the mentioned E_{min} is the minimum amount of energy required from an external source to attain this critical size. Ballal & Lefebvre proposed a model of ignition that assumes chemical reaction rate and mixing time as infinitely fast, in order to consider the fuel vapor created by evaporation as instantly transformed in combustion products. In this model a spark provokes the creation of a spherical volume whose temperature is high enough to start the ignition process. The fuel vapor created, as just written, is instantly transformed in combustion products at stoichiometric flame temperature. If the produced heat exceeds the heat loss, the spark kernel grows enough to fill the whole combustion volume.

Ballal and Lefebvre conducted a number of tests about the ignition process and in particular studied the influence of flow parameters and spark discharge characteristics on quenching distance and minimum ignition energy. For the heterogeneous gas mixture (Isoctane, Kerosine, Gas oil, Diesel oil, Light fuel oil, Heavy fuel oil, in order to have a wide range of volatility) it was found that

$$E_{min} = c_{pa}\rho_a \varDelta T_{ST}\left(\frac{\pi}{6}\right) d_q^3$$

Where:

- For monodisperse spray

$$d_q = \left[\frac{\rho_f D^2}{\rho_A \phi ln(1 + B_{ST})}\right]^{0.5}$$

- For polydisperse spray

$$d_q = \left[\frac{C_3^3 \rho_f D_{32}^2}{C_2 \rho_A \phi ln(1 + B_{ST})}\right]^{0.5}$$

In later studies the chemical effects were considered in this model, leading to a new formula for the quenching distance:

$$d_q = \left[\frac{\rho_f D_{32}^2}{\rho_A \phi ln(1+B_{ST})} + \left(\frac{10\alpha}{S_L}\right)^2\right]^{0.5}$$

Minimum ignition energy is proportional to the value of pressure P. In particular, where evaporative effects are dominant:

$$E_{min} \propto P^{-0.5}$$

While when chemical effects are dominant:

$$E_{min} \propto P^{-2}$$

In general, any change that improve the role of reaction kinetics (for example reduction in P and/or in ϕ that can extend the characteristic time of chemical reactions) tends to increase the dependency of E_{min} on P. [1][5]

In case of gaseous mixture, Ballal and Lefebvre found other expressions for minimum ignition energy and quenching distance:

$$E_{min} = c_p \rho_0 \Delta T_{ad} \left(\frac{\pi}{6}\right) d_q^3$$

- If $u' < 2S_L$

$$d_q = \frac{10K}{c_p \rho_0 (S_L - 0.16u')}$$

- Else ($u' \gg 2S_L$)

$$d_q = \frac{10K}{c_p \rho_0 (S_L - 0.63u')}$$

It’s important to note that the most important difference between homogeneous and heterogeneous mixtures is that for the latter, chemical reaction time is neglectable while for the first it’s dominant.

The second phase is based on the flame propagation, and it could be influenced by the position of the ignition system and by the flame stability. Not a huge number of experiments were carried out on this topic because of many difficulties due to measurement of mean drop-size, drop-size distribution, equivalence ratio, concentration of fuel vapor. Ballal and Lefebvre developed a model for flame propagation, based on a rate of flame propagation, under normal steady-state conditions, through a fuel mist, that is always such that the quench time of the reaction zone is equal to the chemical reactions time added to the evaporation one.

This model brought to an expression for the flame speed S:

$$S = \alpha_g \left[\frac{C_3^3(1-f)\rho_f D_{32}^2}{8C_2\rho_g ln(1+B)} + \frac{\alpha_g^2}{S_L^2}\right]^{-0.5}$$

In this equation S is the sum of two terms, the first characterizes the evaporation rate, while the second the chemical reaction one. In particular when evaporation time domains on the chemical one, flame speed is inversely proportional to mean drop size. This was also demonstrated with other tests conducted by Myers and Lefebvre. This is possible to be noted in the following picture [1]:

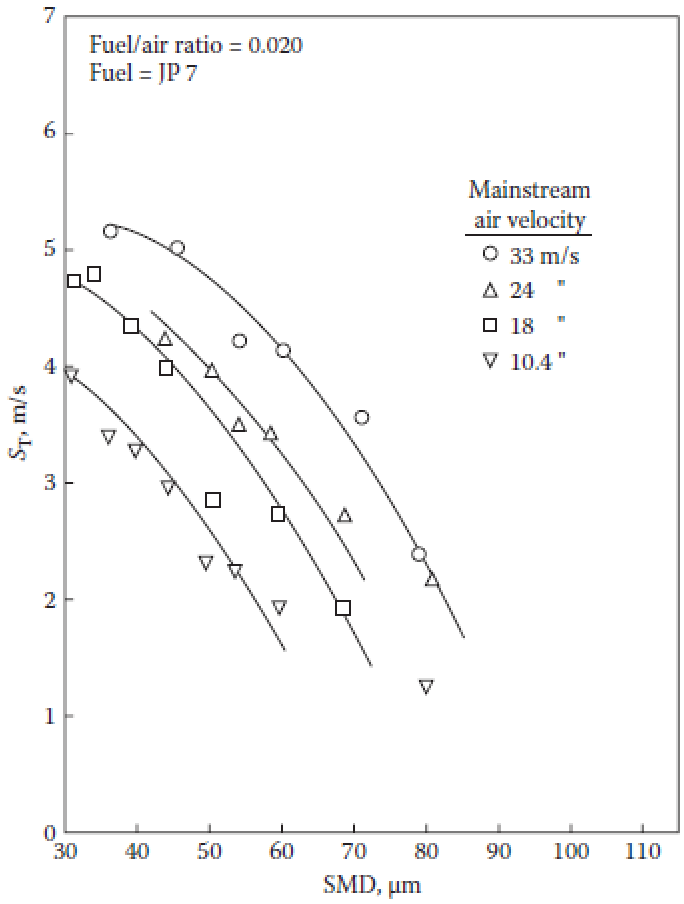


Figure 70 Influence of mainstream velocity and mean drop size on flame speed [1]

The third phase occurs only if there is a tubular or cannular combustion chamber, and it’s based on the diffusion of the flame from a lighted liner to an unlighted liner, and hence is influenced by the location of the interconnector tubes.

As already written, Ballal and Lefebvre carried out some experiments on propane/air mixture on the influence of spark discharge characteristics and flow parameters on minimum ignition energy and quenching distance. What they found was that the optimum spark duration for minimum ignition energy was unaffected by turbulence but decreased with increase in velocity, and that the optimum spark duration was dependent on pressure only up to a certain point. [6]About the influence of flow parameters, it was found that both quenching distance and minimum ignition energy increased with [7]

- reduction in pressure, according to the relation $E_{min} \propto P^{-n}$ (fig.18)

- increase in turbulence intensity, since despite turbulence promotes propagation, it also increases the heat loss by diffusion to the surrounding air, due to the momentum transfer as well as molecular diffusion. (fig. 15, fig.16)

- departures from stoichiometric fuel/air ratio, since the minimum ignition energy was found for stoichiometric fuel/air ratio. (fig.14)

- increase in velocity, probably because the main effect of velocity is in promoting heat loss from the spark kernel during the passage of the spark. (fig.14)

Furthermore E_{min} may increase or decrease with an increase in turbulence scale but it depends on the level of turbulence intensity. Transition zone was found around $u' \cong S_L$ and $u' \cong 4S_L$, where E_{min} is independent from the turbulence scale.(fig.17)

Quenching distance follows the same general trends of E_{min}.

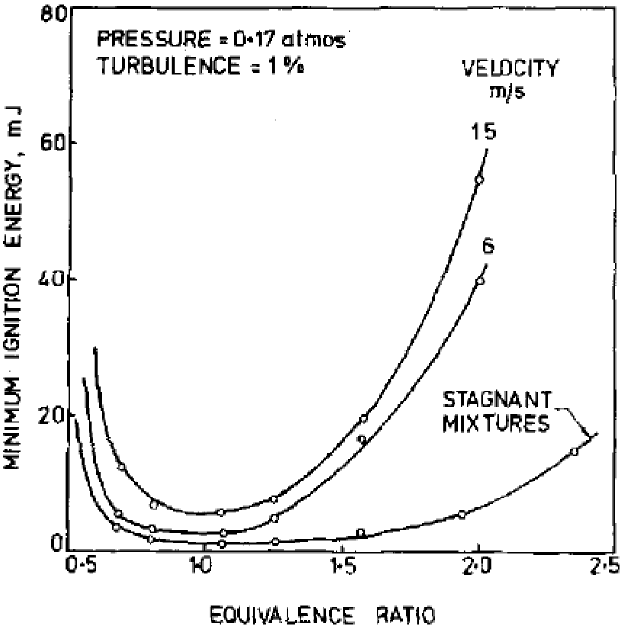


Figure 71 Adverse effect on ignition of increase in mainstream velocity [7]

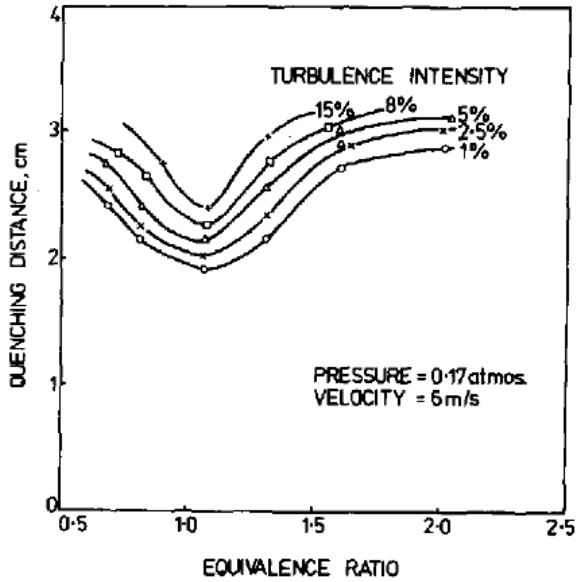


Figure 72 Effect of turbulence intensity on quenching distance[7]

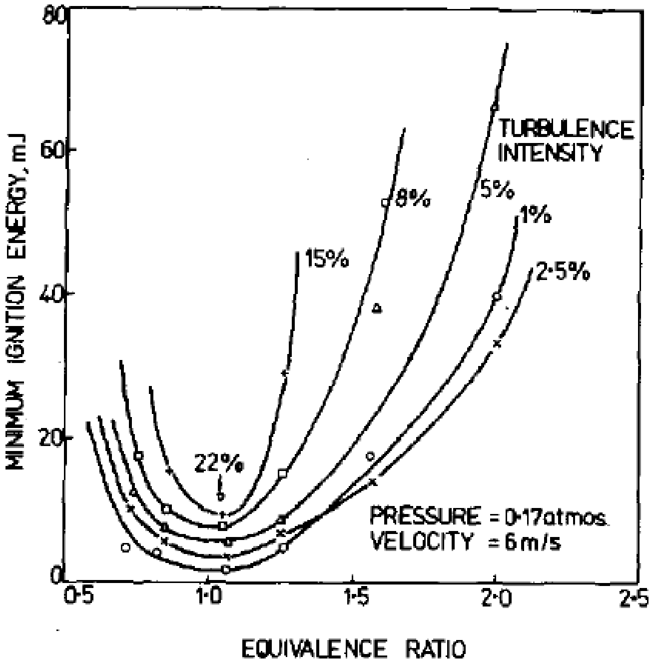


Figure 73 Effect of turbulence intensity on minimum ignition energy[7]

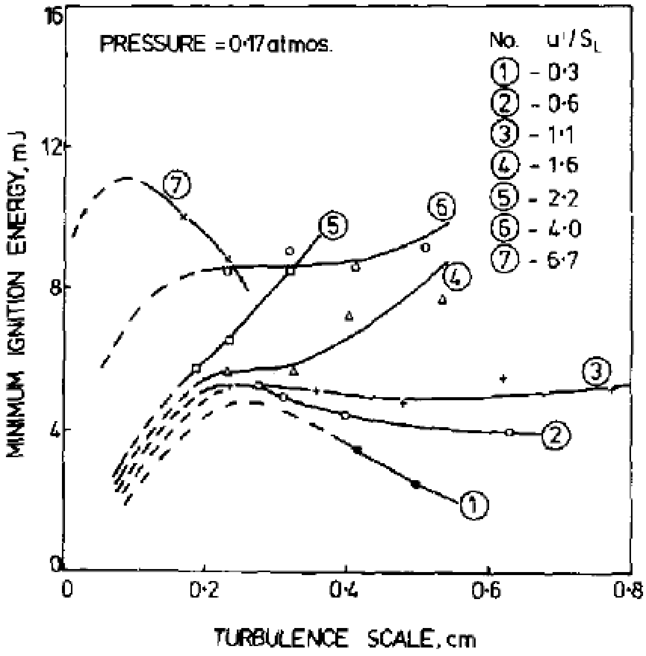


Figure 74 Influence of turbulence scale on minimum ignition energy[7]

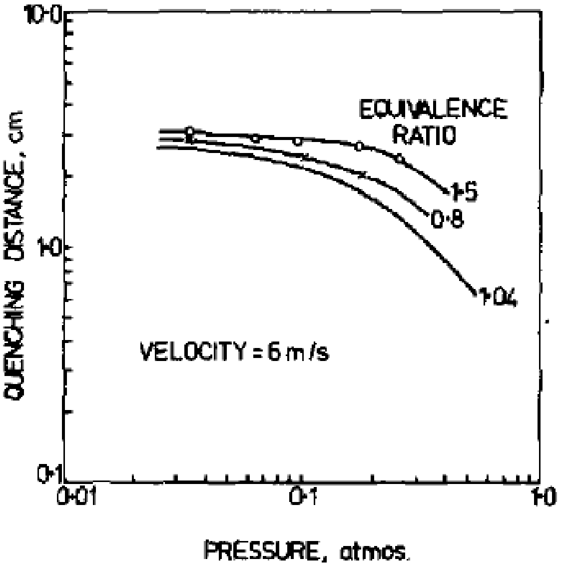


Figure 75 Effect of pressure on quenching distance[7]

Some experiments were conducted also on the ignition of liquid fuel sprays at subatmospheric pressures [8], where it was found that:

- in general, the breakdown voltage requirements in a spark ignition system for liquid fuel sprays is appreciably higher than for gaseous mixture, due to energy used for evaporation, and also to the deposition of liquid fuel on the electrodes which inevitably occurs with liquid fuels..
- There is a strong influence of fuel drop size on minimum ignition energy as also demonstrated at atmospheric pressure, in particular the smaller are the drops, the smaller is the minimum ignition energy. This brings to the important conclusion that even small improvements in atomization quality could benefit the high altitude relighting performance of gas turbine engines.
- Reduction in ambient pressure brings to an increase of the amount of spark energy required to affect ignition, since the minimum ignition energy is higher at that conditions.
- As at atmospheric conditions, minimum ignition energy increases with an increase in mainstream velocity, and decreases with increase in air temperature and in fuel/air ratio toward stoichiometric value

- For well-atomized kerosene-air mixtures there is an extension of the weak ignition limits to lower equivalence ratios, and E_{min} is lower than for corresponding propane-air mixtures.

T. Lee, V. Jain, S. Kozola conducted some tests about measurements of E_{min} using laser sparks for hydrocarbon fuels in air like propane, dodecane and Jet-A fuel [9]. They found some interesting results, that here are reported, since Jet-A-Fuel is one of the most common fuel for aircraft:

- E_{min} obtained with laser sparks was larger than that obtained with electrical spark for air/propane at 1 atm

- a progressively larger optimum equivalence ratio at minimum ignition energy , away from stoichiometric conditions, was found for heavier hydrocarbons

- for Jet-A Fuel, a decrease in fuel loading (the amount of liquid fuel per total chamber volume) brings to an increase in minimum ignition energy. Maybe this is because of a depletion of light-end hydrocarbon species at low fuel loadings. (Fig. 14)

- the pressure dependence on E_{min}becomes less important when fuel is varied from propane, dodecane to jet-A fuel.

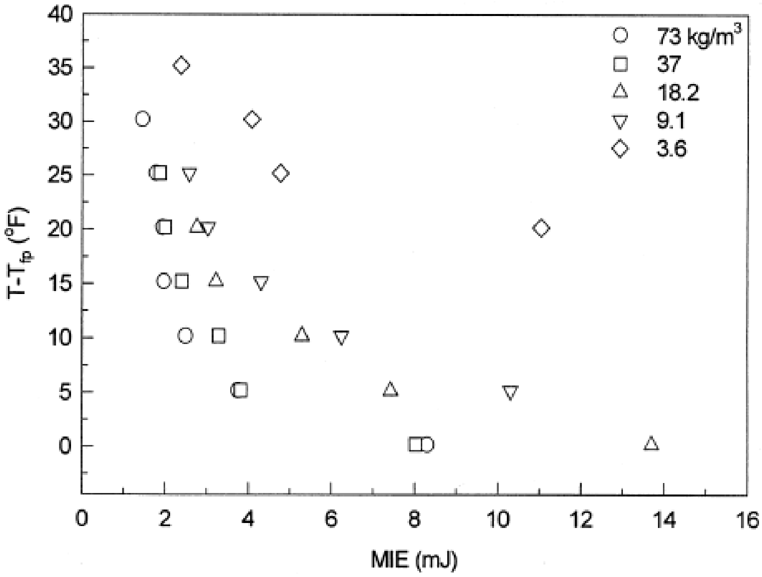


Figure 76 The fuel loading effect on the minimum ignition energy [9]

8. Ignition systems

Combustors need an ignition system to start the combustion process. In aircraft engine combustors, the igniter is typically mounted in a recess on the wall of the combustor, near the primary zone. It is difficult to make the igniter protrude down in the primary zone, since can be destroyed by the high temperature or the high turbulence can lead to the quenching of the intensity of the spark. one solution could be the use of a torch igniter, a plasma jet or a laser igniter.

Therefore there are different kinds of ignition systems, all characterized by energy, duration and frequency of the spark discharge. All these features are dependent on the ignition unit design, igniter design and storage condenser size.

A simple ignition system is composed by a voltage generator, lead and igniter plug, and it has the task to draw power from an electrical supply in order to give energy to the igniter plug and hence to give the start to the combustion process. In gas turbine engines field, the ignition system most used is the spark one, since it’s the most convenient and satisfactory, but, in general, there are different types of igniters:

Spark Igniter

This device is composed by an induction coil that charges, thanks to an electromechanical vibrator or to a transistorized charging unit , a condenser until the condenser voltage reaches the breakdown value of charge of the sealed discharge gap, that’s about 2 kV. The condenser then discharges a choke through the surface discharge plug, in order to control the spark duration. The surface discharge plug is composed by a central and an outer grounded electrode, separated by a ceramic insulator that ends in a thin layer of semiconductor material, which facilitates ionization of the spark. There are two types of this plug, in the first type, called flush fire, the semiconductor is flush with the electrodes, while in the second one, called sunken fire, the semiconductor is recessed.
In this kind of igniter the storage of energy in the condenser is

ensured by a safety resistor.
Since lots of energy is dissipated in sound and radiation waves and also by conduction to the plug face, only a quarter of the developed energy reaches the plug tip.

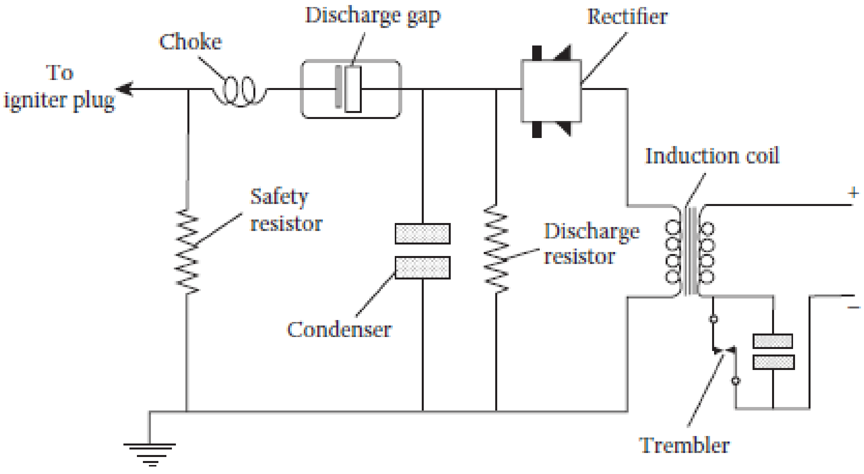


Figure 77 Spark ignition system [1]

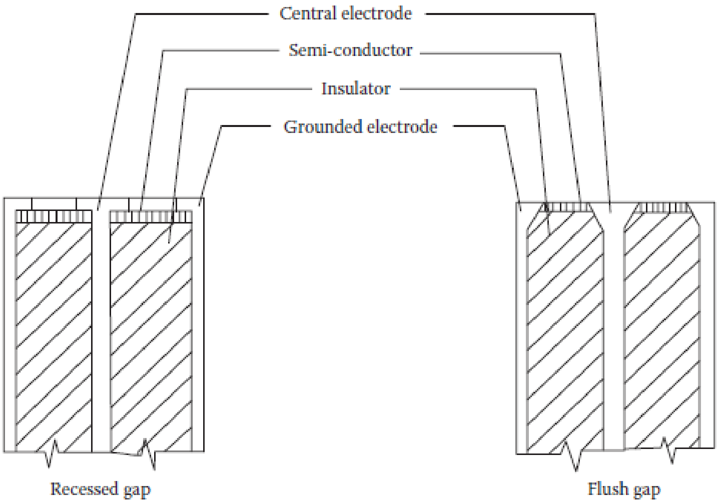


Figure 78 Surface discharge plug: flush fire and sunken fire [1]

With regards to this important kind of igniter, it should be considered that some of its parameters are dependent on the operative conditions. Breakdown voltage e.g. depends on different variables like gap width, air pressure, temperature and velocity, air-fuel ratio, mean drop size and drop-size distribution. Some of these dependences are shown in the following pictures:

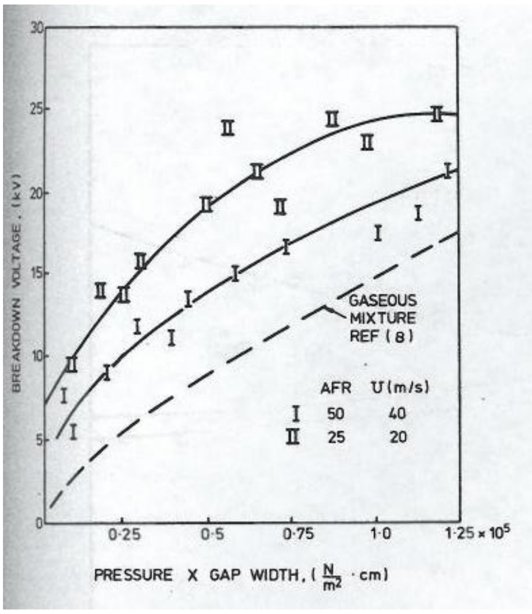


Figure 79 Breakdown potential as a function of pressure and gap width [2]

About the energy released, it was found that it increases with an increase of velocity, pressure and gap width:

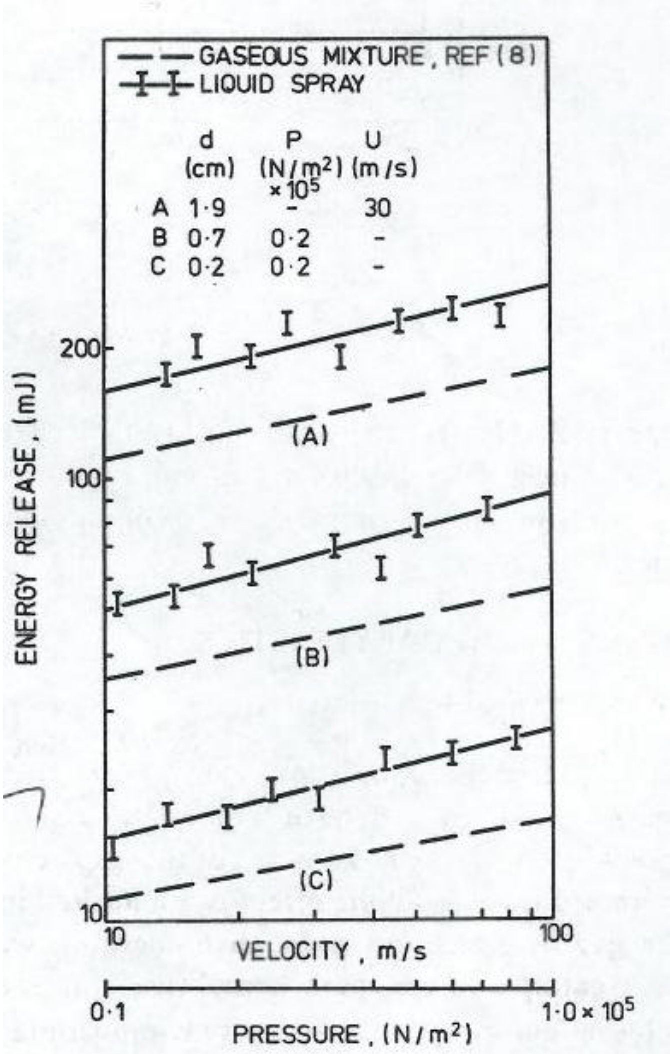


Figure 80 Influence of air pressure and velocity on spark energy [2]

Also the spark time has to be considered, since if it is short, a large part of energy is dissipated in shock waves, but on the other end, if it is too long, the energy is wasted, since it is added to the mixture after the initiated ignition process.

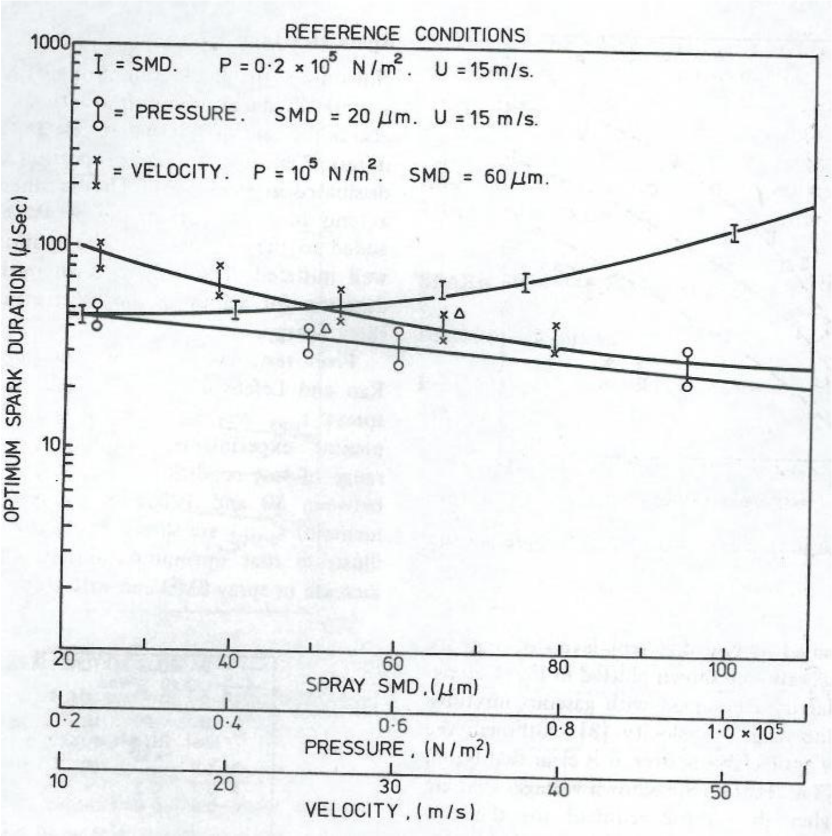


Figure 81 Influence of pressure, velocity and SMD on optimum spark duration [2]

The last parameter that is considered is the spark gap width. It was found that an increase in the gap width leads to the decrease of the quenching effect, but if the gap is too wide, the energy is wasted in creating a larger spark kernel that needs to achieve ignition. The gap width is a function of the mean drop size, in terms of SMD, and of pressure, as it is shown by the following pictures:

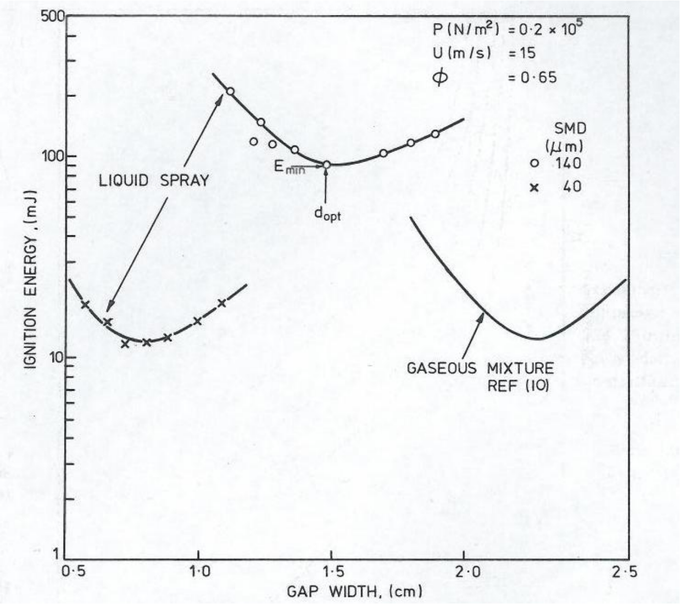


Figure 82 Gap width variation with SMD [2]

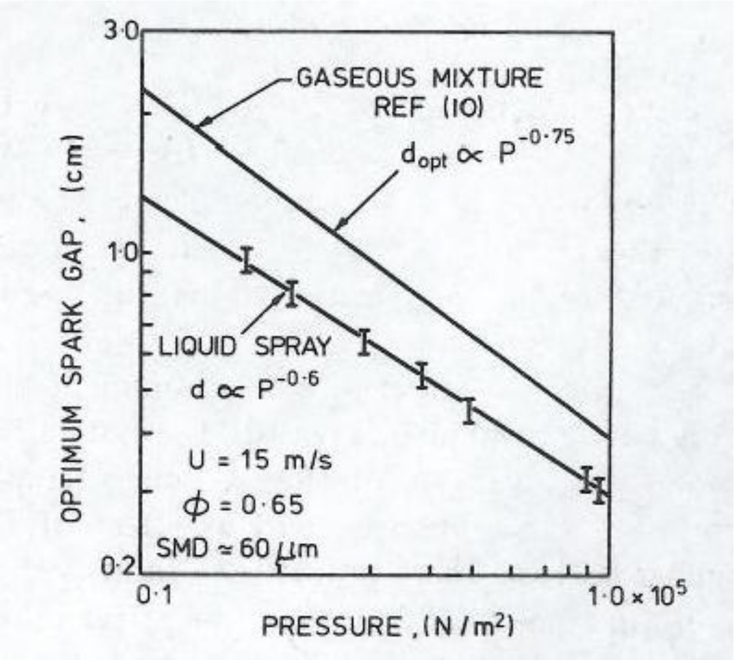


Figure 83 Gap width variation with pressure [2]

Torch Igniter

This kind of igniter was used in many aircraft combustors. It consists of a spark plug with an auxiliary fuel jet, used to generate a “torch” of burning droplets that starts the ignition of the main fuel and hence the combustion process. This device is obligatory for the vaporizer combustor. The problem of the torch igniter is the fuel cracking and gumming when the atomizer is inoperative, while its performance is quite insensitive to its location, so making the torch igniter good for difficult conditions, for example at high altitude.

Glow plug

Glow plug is used for a rapid reignition, when a temporary fuel absence or ingestion of ice or water can cause the extinction of the flame. It is fitted on the liner wall, with a part protruding in the primary zone. The main disadvantage can occur if a part of the plug detaches, damaging in this way the turbine. For this reason this kind of device found few applications, in particular with helicopters engines, for which apparently they seem ideally suited.

Hot-surface ignition

This kind of ignition is based on the increase of the temperature of a hot surface where fuel can evaporate and, with air, can reach the ignition temperature. This technique is not used in gas turbine engines since the huge amount of heat that this system need to complete the process described.

Plasma jet

This system of ignition was developed by Weinberg. In the first period it was based on an electrical discharge that occurs in a small cavity, supplied with a plasma jet via a small cavity.
Afterwards, Weinber and Warris developed another kind of plasma jet ignition, by using a lukewarm gas characterized by some hot parts of highly dissociated species. This system brought good results in ignition and also stability, but later they also developed the pulsed plasma jet ignition, that ensured lighter electrical equipment, since large currents are required transiently.

Laser ignition

This system is based on the phenomena of a focused output of an enough powerful laser beam, that is able to cause electrical breakdown of gases. This kind of ignition could be used with combustible mixtures and would be characterized by some advantages like the absence of heat losses. Also in this system, like in the spark one, it is very important the duration of the energy pulse. Some disadvantages of using e.g. ultraviolet laser energy is that it will make the combustion products highly absorptive of ultraviolet radiation. Furthermore the wavelength of the laser energy needs to be fine tuned, and the presence of some additives and inhibitors in the fuels can change the fuel absorption characteristics, making the wavelength not tuned as expected and so changing the time of the ignition or bringing to the redesign of the laser system.[3]

Chemical ignition

This system exploits the characteristics of some substances that are able to ignite when they get in touch with air. An example is the trimethly aluminum. These substances are called pyrophoric fuels.

Gas addition and Oxygen injection

It’s been demonstrated that gas addition on ignition limits can bring good advantages. Also the addition of oxygen can improve the performance of the ignition as well as of the combustion process.

9. Simplified analysis on ignition and flame stabilization for a simple turbojet

In this chapter three main themes will be taken in account with a simplified analysis:

- Mixture strength analysis in the main vortex created in the primary zone to stabilize the flame.

- Implementation of minimum ignition energy equation based on the equivalence ratio values found with the first point, and a comparison with some experimental results.

- A simplified analysis about flame stabilization in the primary zone.

9.1 Mixture strength analysis

This paragraph deals with what happens in the primary zone during the ignition process.

As explained in the paragraph 1.3.3 and represented in figure 6, in order to optimize the flame stabilization there are different solutions. The one chosen for this kind of analysis is the one represented in figure 6 c, that uses a mix of swirl and opposite jets. This mix causes the birth of vortexes in the primary zone. Since this is a simplified analysis, it will take in account just one main vortex with a diameter of about the same dimension of half the length of the primary zone.

As second hypothesis, in order not to complicate the problem, it is assumed that the maximum air velocity at the edge of the vortex is about the half the velocity of the air coming in from the liner, that can be calculated with some simple assumptions.

To start the analysis it is useful to have a look to the following figures, where every section is defined by a number or letter.

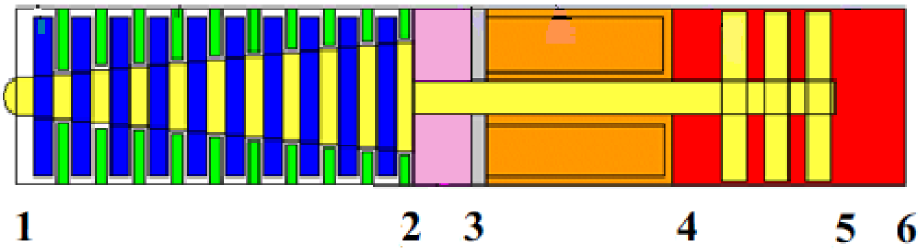


Figure 84 Section of a simple gas turbine engine

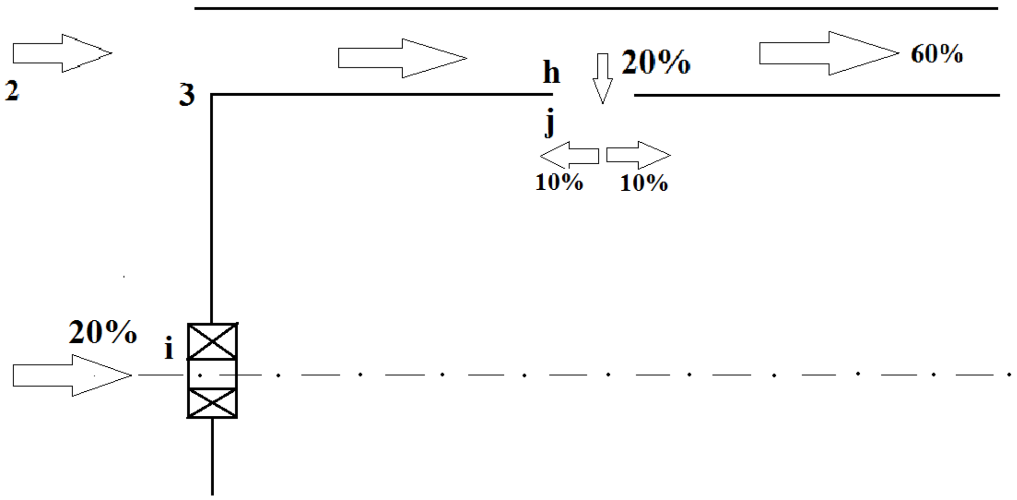


Figure 85 Section of the primary zone of an annular combustion chamber

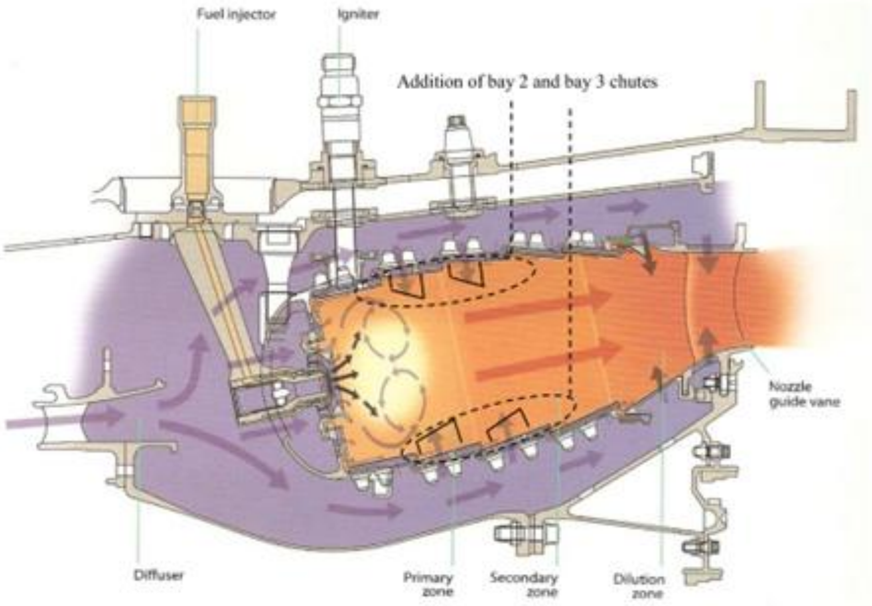


Figure 86 Rolls-Royce Phase 5 typical combustor with schematic of bay 2 and bay 3

9.1.1 Valuation of air velocity at the edge of the vortex

The first value that has to be calculated is the air velocity in the h section, v_h, that can be found by equalizing the mass flow in the h section, defined in two different ways:

$$\dot{m}_h = \rho_h A_h v_h = C_d A_h [2\rho_h \, (P_{th} - p_j \,)\,]^{0.5} \tag{1}$$

Where C_d is the discharge coefficient depending on the kind if hole; its typical value is between 0.6 and 0.8. For a simple hole, considered in this case, 0.6 is used.
In order to simplify the current analysis, some assumptions must be made, due to the low velocities and temperatures that characterize the problem of the engine restart:

$$\rho_h \cong \rho_3 \cong \rho_2$$

$$P_{th} \cong P_{t3} \cong P_{t2}$$

One important parameter is the pressure drop between h and j section, called *cold loss*. The combustor cold loss is due to the dump of air being injected through the wall. Good designs would have a value of between 2 and 4 % of total pressure at the design point, depending upon geometric constraints

$$0.02 \leq \frac{P_{th} - p_j}{P_{th}} \leq 0.04$$

So, called *n* the value chosen for the dimensionless pressure drop, it is now possible to express the term $P_{th} - p_j$ as nP_{th}, and so as nP_{t2}.
Once made these assumptions, it is now possible to determine v_h from the equation (1):

$$v_h = C_d \left[\frac{2nP_{t2}}{\rho_2}\right]^{0.5}$$

So the air velocity at the vortex edge, v_v, is:

$$v_v = \frac{1}{2} v_h = C_d \left[\frac{nP_{t2}}{2\rho_2}\right]^{0.5}$$

Where P_{t2} , assumed having the same value of P_2, is known once known the compressor pressure ratio:

$$P_{t2} = PR * P_1$$

and ρ_2 is calculated as:

$$\rho_2 = \frac{P_{t2}}{RT_2}$$

with T_2 defined as:

$$T_2 = \frac{T_1}{\eta_c}\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

where η_c is the compressor efficiency.

Data used:

- PR = 1.5; a very low value since this analysis is dealing with the engine restart, where the engine can also be in windmilling conditions.
- Altitude = 11000 m;
- P_1 = 25000 MPa;
- T_1 = 243 K;
- η_c = 0.84;

- n = 0.03;
- C_d = 0.6;
- R = 287 m^3/KgK;
- γ = 1.4;

These data yield to a v_v value of 23.15 m/s.

9.1.2 Vortex Structure

The vortex structure is described using the Rankine model, where the tangential velocity is represented in the following picture:

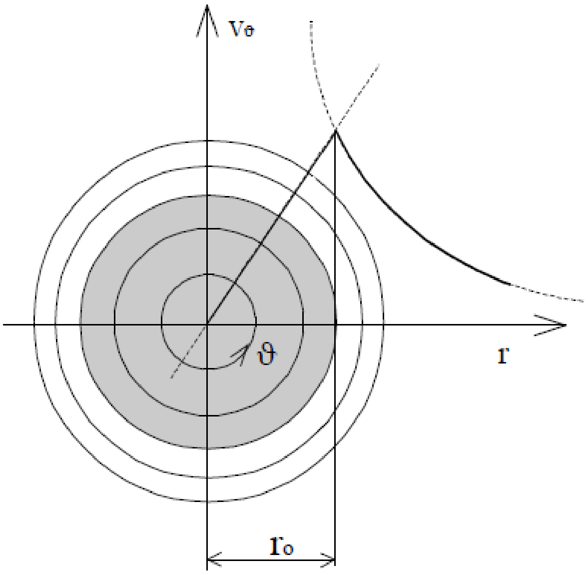


Figure 87 Tangential velocity distribution in the Rankine model of a vortex.[3]

With r_0 radius of the vortex.

As shown in the previous figure, the maximum air velocity is at the edge of the vortex.

These considerations make possible to consider the vortex divided in concentric circles, everyone characterized by a different velocity that rises linearly with the vortex radius:

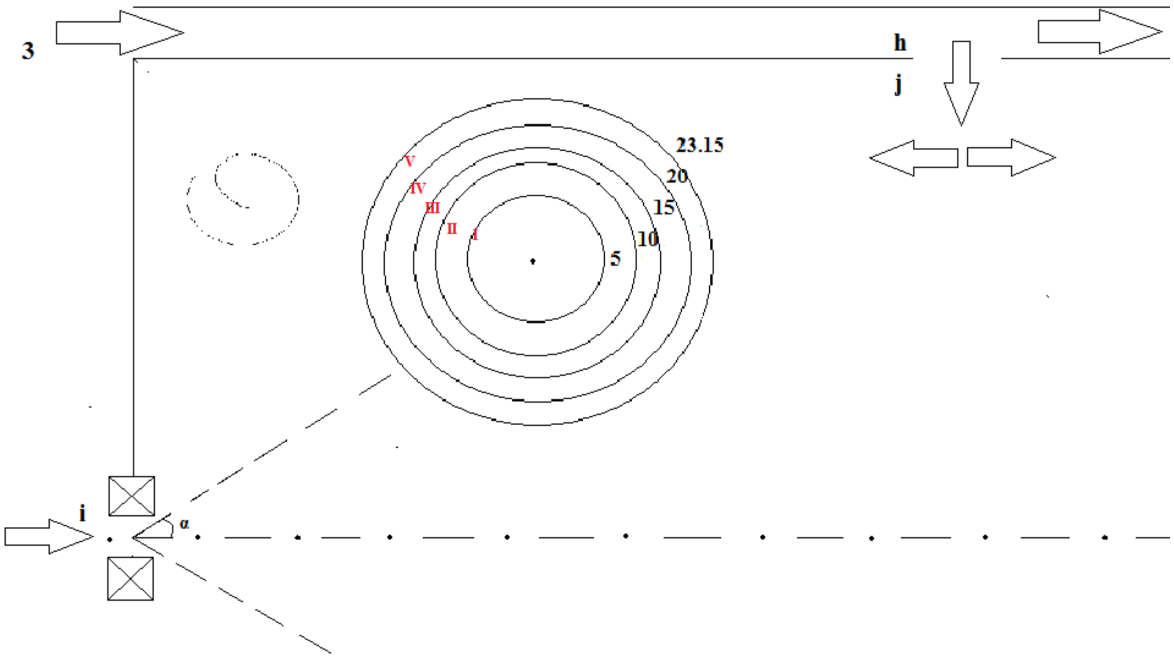


Figure 88 Primary zone section with concentric circles scheme of the main vortex

Where the air velocity is distributed on five circles, numbered from I to V, and varies from 5 to 23.15 m/s as explained in Figure 88.
With the exception of I, all the other geometries are annuli, and these annular areas will be used to calculate the air mass flow per zone.
Furthermore this is assumed being a 2-dimensional problem, since it better fits an annular combustor here considered.

9.1.3 Air Mass flow distribution in the vortex

In order to estimate the air/fuel ratio in the vortex, the first step regards the valuation of the air mass flow in the five circles in which the vortex is divided.

The first hypothesis is that the air density is the same for every circle. This leads to assume that the air mass flow varies just with surface and velocity. In particular it is possible to express the total air mass flow coming in the primary zone as a multiple of the air mass flow in the first circle.

Total mass flow is:

$$\dot{m}_{tot} = \frac{1}{2}\dot{m}_i + \frac{1}{2}\dot{m}_h = \dot{m}_I + \dot{m}_{II} + \dot{m}_{III} + \dot{m}_{IV} + \dot{m}_V$$

Where:

- $\dot{m}_{II} = \frac{A_{II}}{A_I}\frac{v_{II}}{v_I}\dot{m}_I$
- $\dot{m}_{III} = \frac{A_{III}}{A_I}\frac{v_{III}}{v_I}\dot{m}_I$
- $\dot{m}_{IV} = \frac{A_{IV}}{A_I}\frac{v_{IV}}{v_I}\dot{m}_I$
- $\dot{m}_V = \frac{A_V}{A_I}\frac{v_V}{v_I}\dot{m}_I$

With:

$$A_i = \pi(r_i^2 - r_{i-1}^2) \text{ for i = 2 : 5}$$

And

$$A_I = \pi(r_I^2)$$

From the linear profile assumed for air velocity with radius, it can be found:

- $\frac{r_{II}}{r_I} = 2 \rightarrow \frac{A_{II}}{A_I} = \frac{\pi(r_{II}^2 - r_I^2)}{\pi r_I^2} = 3$

- $\frac{r_{III}}{r_I} = 3 \rightarrow \frac{A_{III}}{A_I} = \frac{\pi(r_{III}{}^2 - r_{II}{}^2)}{\pi r_I{}^2} = 5$
- $\frac{r_{IV}}{r_I} = 2 \rightarrow \frac{A_{IV}}{A_I} = \frac{\pi(r_{IV}{}^2 - r_{III}{}^2)}{\pi r_I{}^2} = 7$
- $\frac{r_V}{r_I} = 2 \rightarrow \frac{A_V}{A_I} = \frac{\pi(r_V{}^2 - r_{IV}{}^2)}{\pi r_I{}^2} = 9$

So this distribution leads to:

$$\dot{m}_{tot} = (1 + 2 * 3 + 3 * 5 + 4 * 7 + 4.63 * 9)\dot{m}_I = 91.67\dot{m}_I \tag{2}$$

Where both $\dot{m}_i$ and $\dot{m}_h$ are splitted into two zone, the first in the two region of the primary zone, the second in the primary and secondary zone, as shown in Figure 87.
Figure 85 also shows how the total air mass flow is divided into the main entrance of the combustion chamber and the liner, with also the percentage of air coming in through the hole in the primary zone from the liner.
So, once known the total air mass flow coming from the compressor $\dot{m}_0$, it is possible to calculate $\dot{m}_i$ and $\dot{m}_h$ as:

$$\dot{m}_i = \dot{m}_h = 0.2\dot{m}_0$$

And then $\dot{m}_I$ as:

$$\dot{m}_I = \frac{\dot{m}_{tot}}{91.67} = \frac{0.1\dot{m}_0 + 0.1\dot{m}_0}{91.67} = 0.0022\dot{m}_0$$

Therefore, choosing a typical value for the total air mass flow of 7.5 kg/s, used for example for some tests on a Rolls-Royce Viper turbojet [7], the five velocities result:

- $\dot{m}_I = 0.0164$ kg/s
- $\dot{m}_{II} = 0.0982$ kg/s
- $\dot{m}_{III} = 0.2454$ kg/s
- $\dot{m}_{IV} = 0.4582$ kg/s
- $\dot{m}_V = 0.6818$ kg/s

9.1.4 Fuel mass flow distribution in the vortex

In order to provide the fuel mass flow distribution in the vortex, a different approach is used. Instead of an analysis of the different velocities that fuel particles can have per circle, an analysis about fuel particles dimension is developed, starting from a modified Rosin-Rammler distribution of drop diameters for an airblast atomizer, that is used in this case.

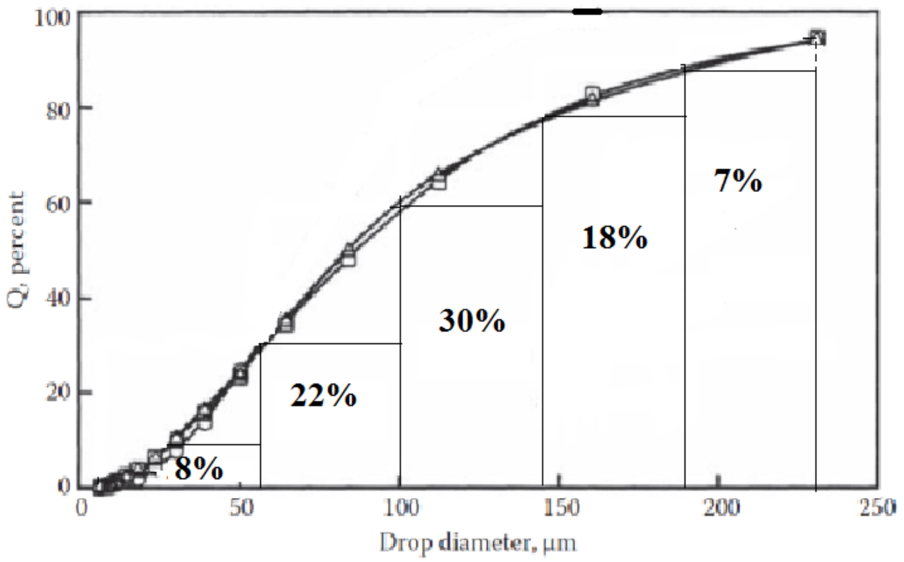


Figure 89 Modified Rosin-Rammler curve for an airblast atomizer [1]

Figure 88 also shows the different percentage of drop particles with different diameter.

The main hypothesis of this part of analysis is that the heaviest particles (last column) penetrate the vortex till the last circle since they are characterized by a bigger inertia, then the fourth column penetrates the vortex till the fourth circle, and the first three columns of particles penetrate respectively the first three circles.

A typical value of total fuel mass flow injected is 7% of the air mass flow coming in the main entrance of the primary zone $\dot{m}_i$ and so:

$$\dot{m}_f = 0.07\dot{m}_i = 0.0525 \text{ kg/s}$$

Starting from the percentage represented in Figure 88, it is possible to estimate the fuel mass flow per circle:

- $\dot{m}_{fI} = 0.16\dot{m}_f$ = 0.0084 kg/s
- $\dot{m}_{fII} = 0.2\dot{m}_f$ = 0.0105 kg/s
- $\dot{m}_{fIII} = 0.32\dot{m}_f$ = 0.0168 kg/s
- $\dot{m}_{fIV} = 0.22\dot{m}_f$ = 0.0116 kg/s
- $\dot{m}_{fV} = 0.1\dot{m}_f$ = 0.0053 kg/s

9.1.4.1 Effect of combustor geometry and pressure on performance of airblast atomizer

.

The analysis treated so far is simplified by some assumptions, and the effect of combustor geometry and pressure on performance of the airblast atomizer is not described. This does not mean that this effect is not important, but just that in this preliminary work is not considered. So in this paragraph a small digression about airblast atomizer is presented.

In a work of Grech, Mehdi, Zachos, Pachidis and Sing [8], an interesting CFD analysis of a typical airblast atomizer is developed, simulated at different sub-idle operating conditions. Two different geometry for the combustor are used, one simple linear-only combustor, and the other one with a more detailed geometry. These CFD models were run at three different pressure of 101 kPa, 41kPa and 31kPa, and interesting conclusions can be made.

First of all the following figures show how SMD increases significantly with decrease in chamber pressure, for both the detailed and simple models:

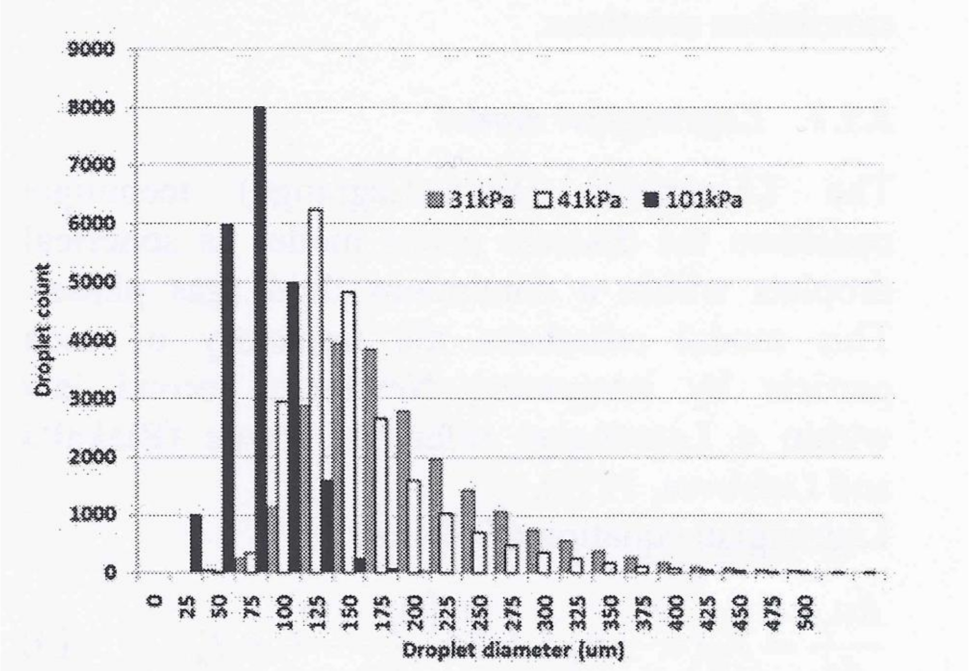


Figure 90 Fuel droplet distribution for detailed model of combustor

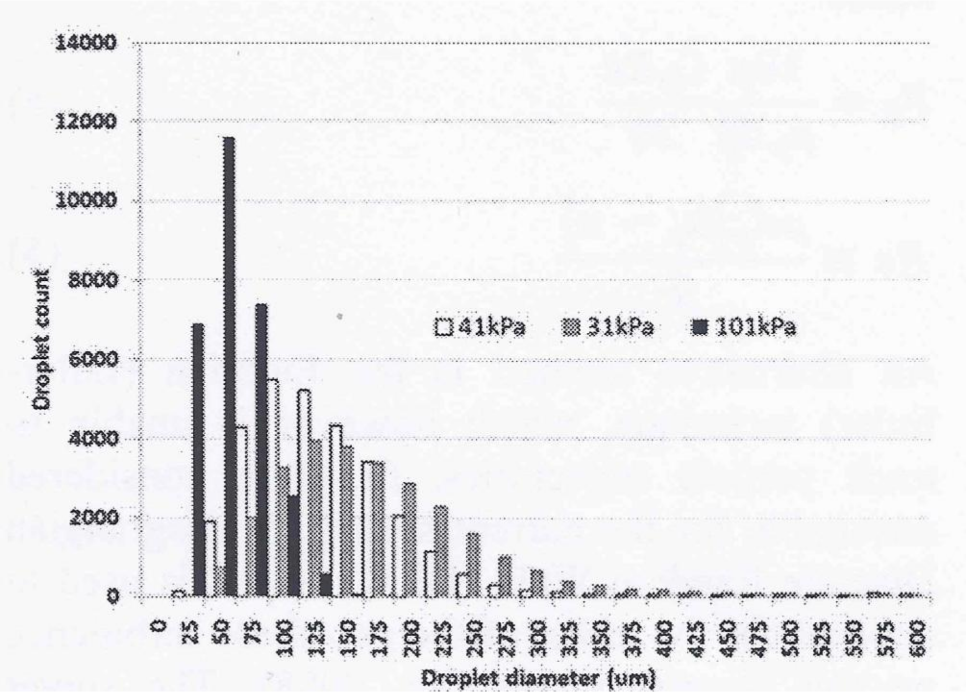


Figure 91 Fuel droplet distribution for simple model of combustor

A second important parameter is the fuel droplets distribution, that is highly dependent on the chamber pressure as well, as shown by the following figures, where data from the analysis of Kozaily et al.(2009) are also represented:

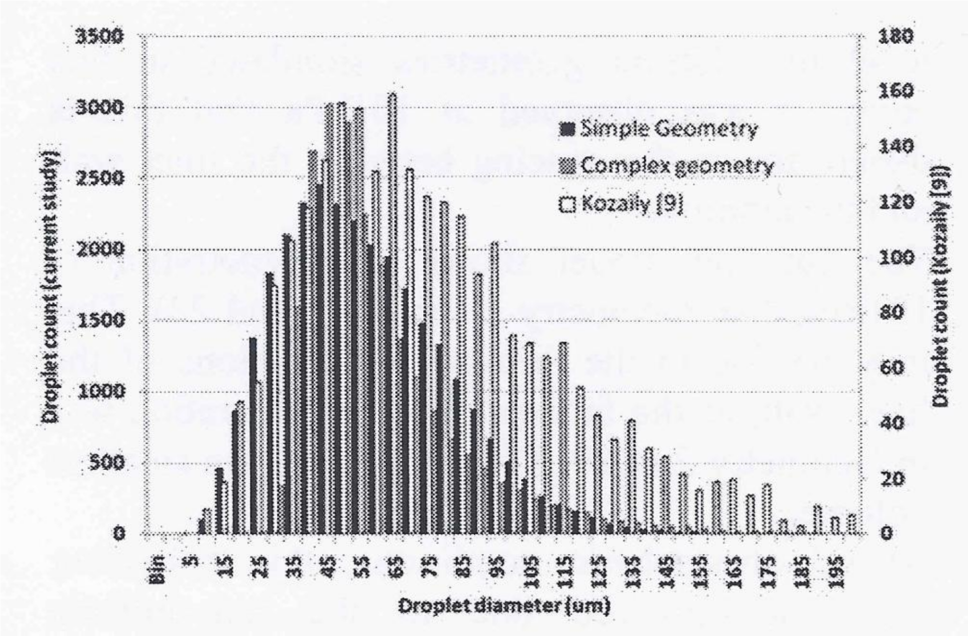


Figure 92 Fuel droplet distribution at 101 kPa

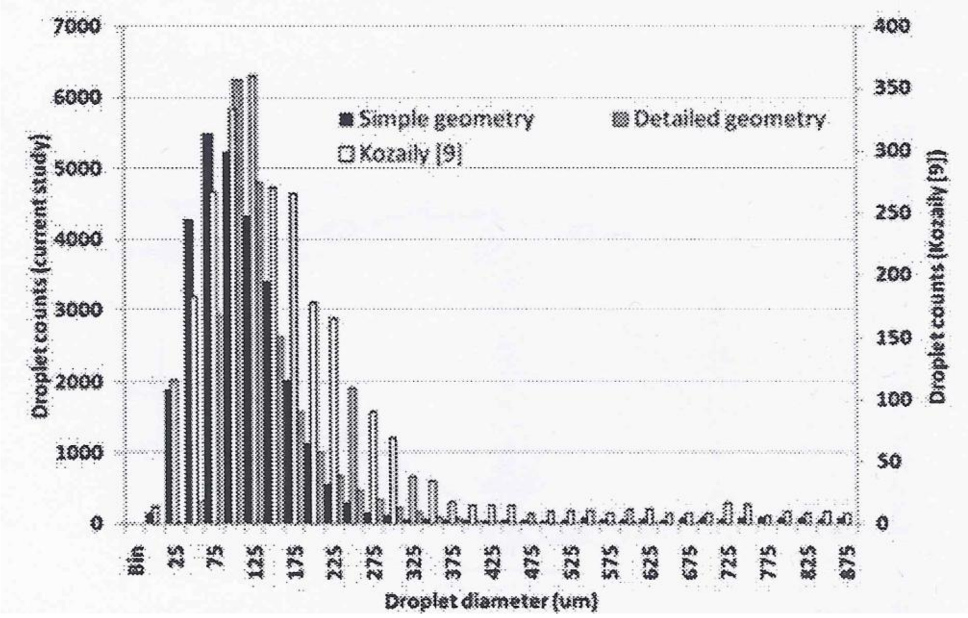


Figure 93 Fuel droplet distribution at 41 kPa

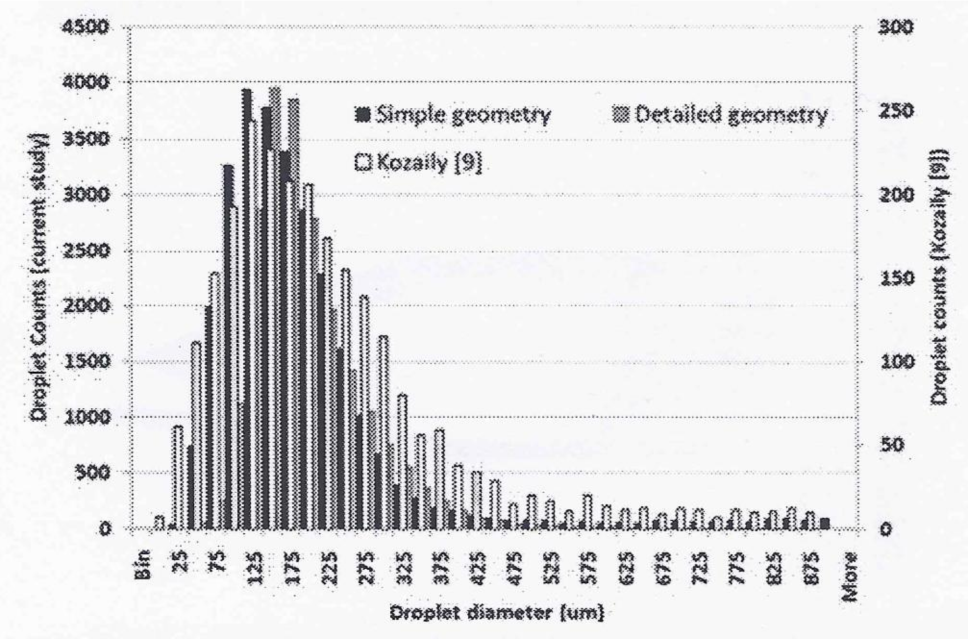


Figure 94 Fuel droplet distribution at 31 kPa

From the previous figures it can be noted how the droplets distribution change with chamber pressure.

Other interesting conclusions are about combustion chamber geometry, where no significant change were observed in SMD dimension and distribution, while droplet penetration seems to be dependent on the liner wall geometry only at atmospheric conditions, but irrelevant at sub-idle conditions.

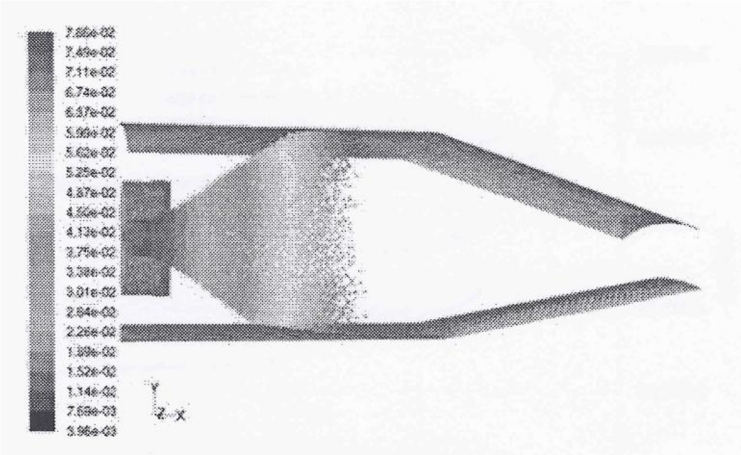


Figure 95 Baseline model: Fuel penetration(m) at 101kPa

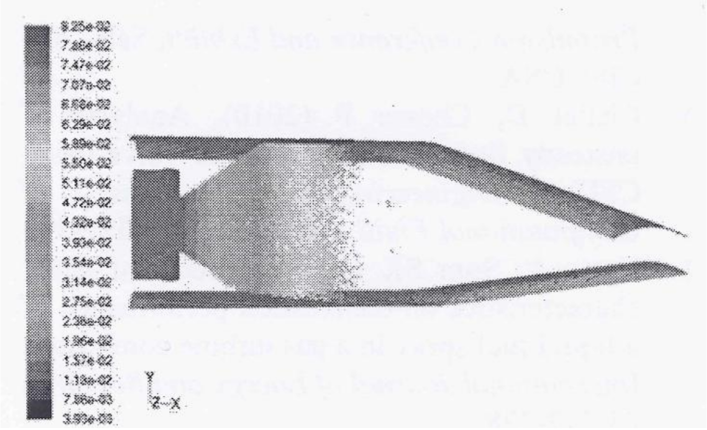


Figure 96 Second geometry: Fuel penetration (m) at 101 kPa

From this paragraph it should be noted that there are other parameters that have to be taken in account, since they can affect atomization and then ignition process.

9.1.5 Air/Fuel Ratio and Equivalence Ratio

Once valued air and fuel mass flow distribution per circle in the main vortex, it is possible to calculate the air/fuel ratio:

- $AFR_I = \frac{\dot{m}_I}{\dot{m}_{fI}}$ = 1.9480
- $AFR_{II} = \frac{\dot{m}_{II}}{\dot{m}_{fII}}$ = 9.3503
- $AFR_{III} = \frac{\dot{m}_{III}}{\dot{m}_{fIII}}$ = 14.6099
- $AFR_{IV} = \frac{\dot{m}_{IV}}{\dot{m}_{fIV}}$ = 39.668
- $AFR_V = \frac{\dot{m}_V}{\dot{m}_{fV}}$ = 129.8758

In order to calculate the equivalence ratio a fuel has to be chosen.

In this case propane C_3H_8, is used for two main reason:,

- it is easier to find experimental results about propane, that are used to compare the results of this analysis;
- propane can be compared to other fuel used in aeronautical field, since its calorific value and flame speed are quite similar to the calorific value (see Table 1) and flame speed (Figure 90) of other hydrocarbons;

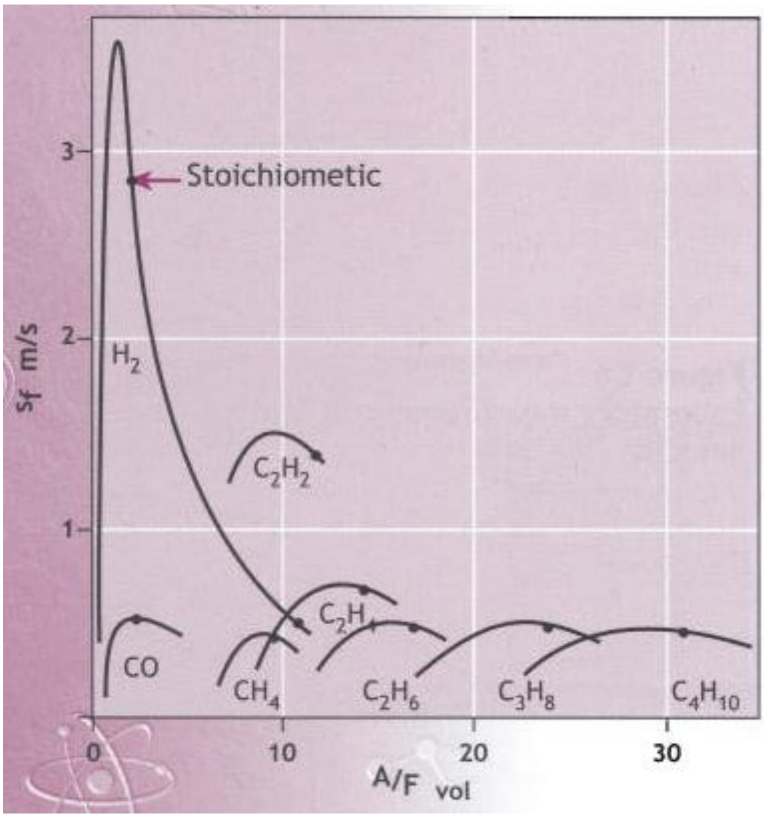


Figure 97 Laminar flame speed for different hydrocarbons at different A/F ratios [2]

The equivalence ratio ϕ is defined as the ratio between the air/fuel ratio and the stoichiometric air/fuel ratio that is now calculated for propane.
The first step is to balance the chemical reaction of propane with air:

$$aC_3H_8 + b(O_2 + 3.76N_2) \rightarrow cCO_2 + dH_2O + eN_2$$

Once assumed a=1, it easy to find that:

- b = 5;
- c = 3;
- d = 4;
- e = 18.8

Since the oxygen molecular mass is 16, the nitrogen one is 14, the carbon one 12 and the hydrogen one 1, the stoichiometric air/fuel ratio can be find as:

$$AFR_{st} = \frac{b * (2 * 16 + 3.76 * 2 * 14)}{a * (3 * 12 + 8 * 1)} = 15.6$$

It is now possible to calculate the equivalence ratio per circle:

- $\phi_I = \frac{AFR_I}{AFR_{st}}$ = 0.1249
- $\phi_{II} = \frac{AFR_{II}}{AFR_{st}}$ = 0.5994
- $\phi_{III} = \frac{AFR_{III}}{AFR_{st}}$ = 0.9365
- $\phi_{IV} = \frac{AFR_{IV}}{AFR_{st}}$ = 2.5428
- $\phi_V = \frac{AFR_V}{AFR_{st}}$ = 8.3254

All the results found in this paragraph are summarized in the next table:

Cicle labelled	Air mass flow per circle [kg/s]	Fuel mass flow per circle [kg/s]	Air/fuel ratio per circle	Equivalence ratio per circle
I	0.0164	0.008	1.95	0.12
II	0.0982	0.01	9.35	0.60
III	0.2454	0.017	14.61	0.94
IV	0.4582	0.012	78.59	2.54
V	0.6818	0.005	351.47	8.33

Table 2 Results of the mixture strength analysis

In the previous table the red values are the only ones included in propane flammability limits, 27 – 6 a/f ratio, as shown in Table 2 , in Chapter 4.

In the next paragraph these results will be analyzed, in order to provide the best zone where the minimum ignition energy is the lowest, and so where it is better to start the ignition.

9.2 Minimum ignition energy analysis

In this paragraph the results of the previous analysis are used to calculate the minimum ignition energy for a mixture of propane-air, and the results are then compared to an experimental graph.
As shown in Chapter 7, the equation that describes the minimum ignition energy is :

$$E_{min} = c_{pa} \rho_a \Delta T_{ST} \left(\frac{\pi}{6} \right) d_q^3$$

Figure 91 provides the quenching distance d_q data, that are used for the minimum ignition energy calculation. In particular four points are used, two are the minimum value and the last value of the curve, the other two are the second and third values found in the previous paragraph. The first and the last two values found with the previous analysis are not considered, since they exceed the flammability limits for propane/air mixture.

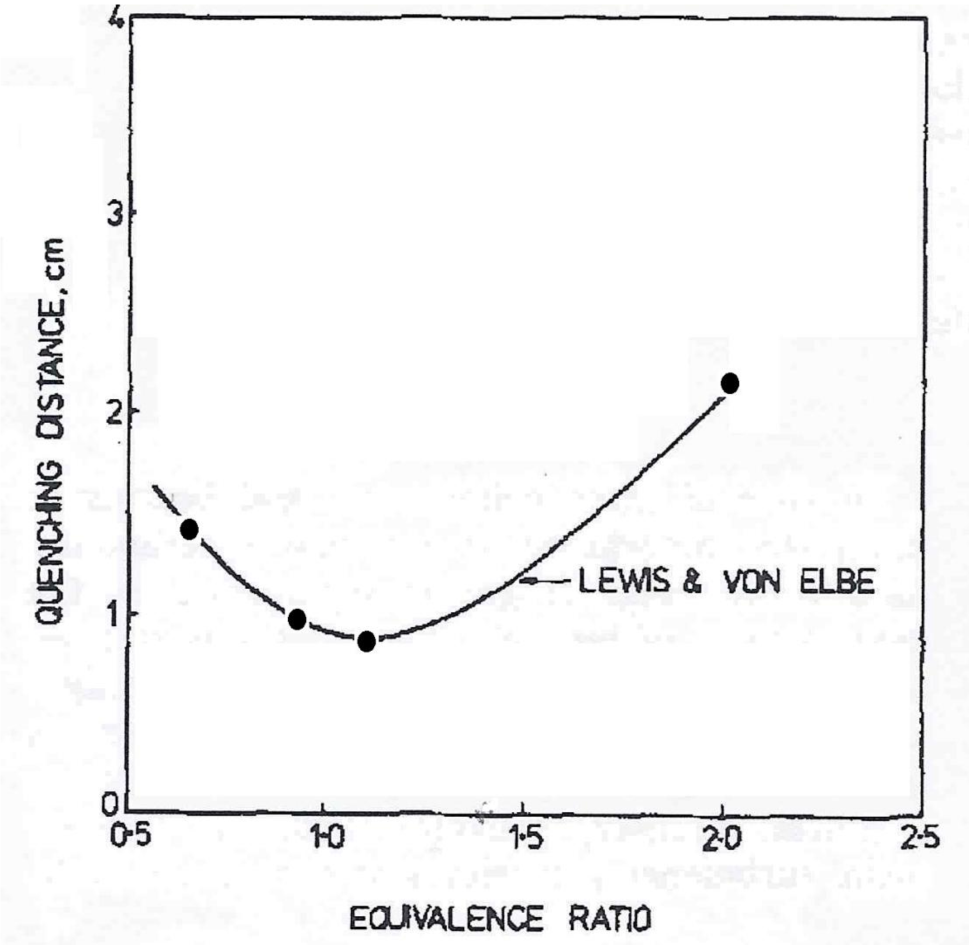


Figure 98 Quenching distance for a propane/air mixture at subatmospheric conditions [4]

As shown in Figure 91, the four values of quenching distance are:

- 1.5 cm
- 1.0 cm
- 0.9 cm
- 2.0 cm

Quenching distance and the consequent Minimum ignition energy derived with these data is represented in the following figures:

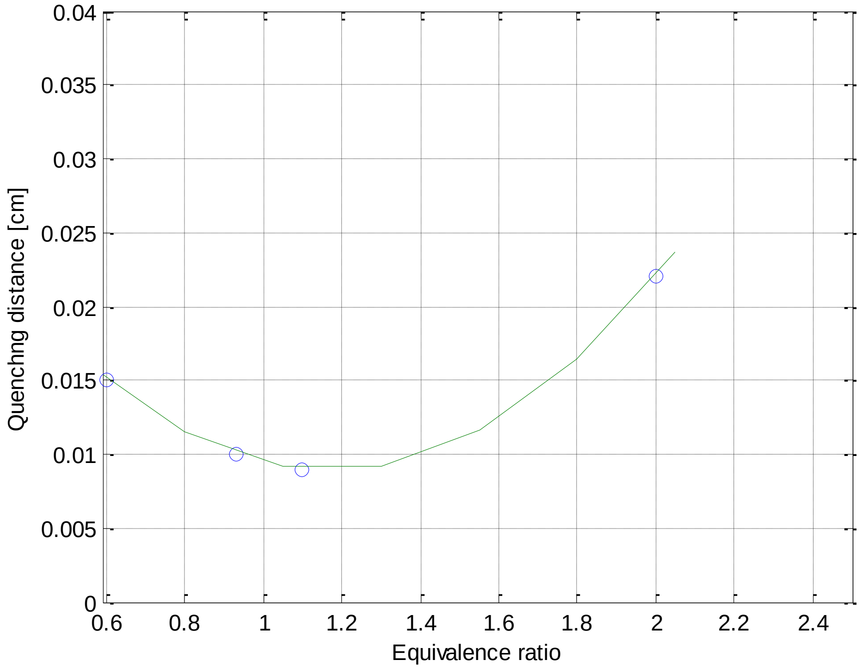


Figure 99 Quenching distance variation with equivalence ratio for a propane/air mixture

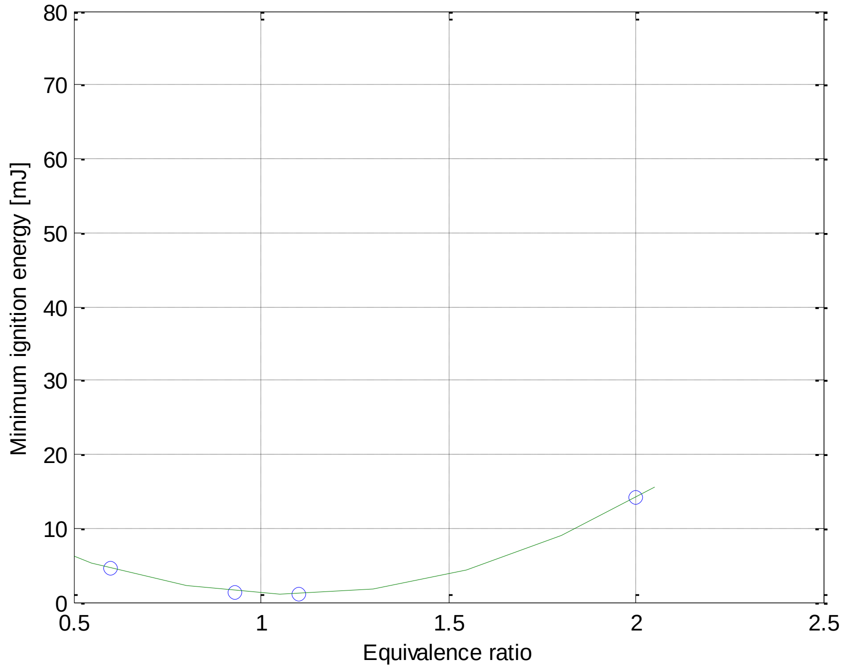


Figure 100 Minimum ignition energy variation with equivalence ratio for a propane/air mixture

Figure 92 shows how minimum ignition energy varies with equivalence ratio. The curve represented can be compared to the following figure, that represents the result of an experiment conducted in 1975 by Ballal and Lefebvre [4]:

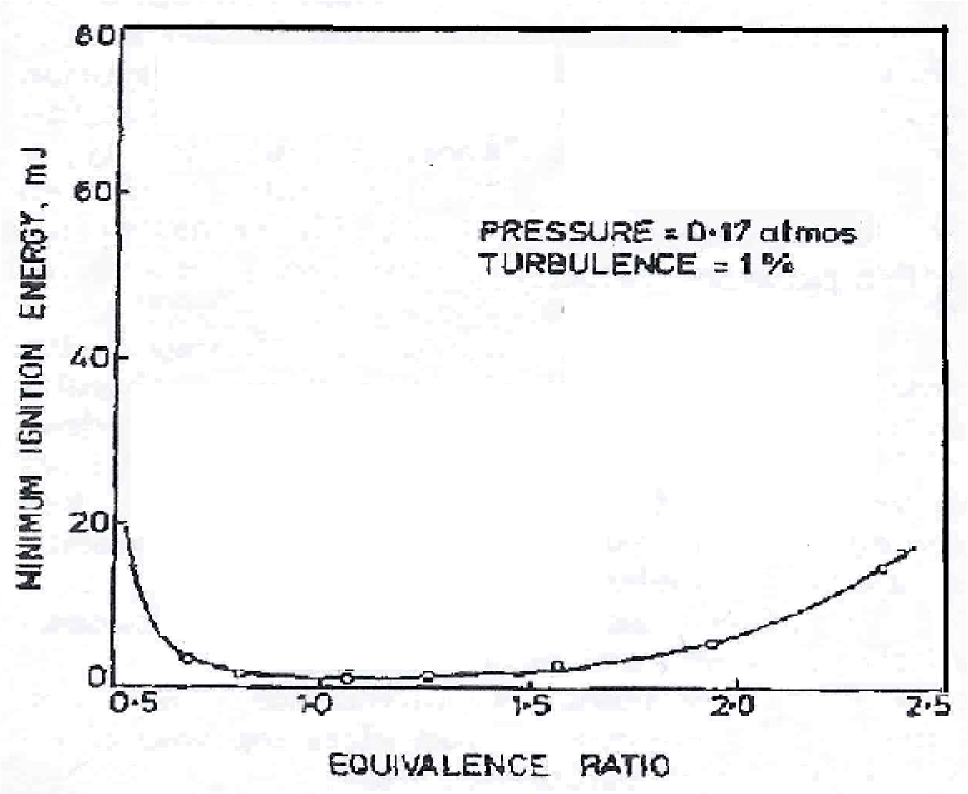


Figure 101 Variation of minimum ignition energy with equivalence ratio for a propane/air mixture found by Ballal and Lefebvre (1975) [4]

9.3 Simplified analysis of flame stabilization in the primary zone

Once ignited the fuel-air mixture, it is fundamental to guarantee the flame stabilization in order to allow the combustion to spread in all the primary zone without undesired phenomenon like blow-off or flash-back.

The main condition that has to be respected to stabilize the flame is the same order of magnitude of the mean air velocity throughout a section of the primary zone and the flame speed.

In order to compare these two values it is necessary to remind that the mean Mach number in the primary zone must be between 0.02

and 0.05 to provide a proper fuel-air mix and a region of slow velocity where the flame can be stabilized [1]. Taking in account that this work has to deal with the ignition of an engine at high altitude, with adverse pressure and temperature conditions, the minimum value of 0.02 for the Mach number has been chosen. Once known the Mach number, it is necessary to calculate the speed of sound, in order to have the mean air velocity in the primary zone. The speed of sound can be defined as:

$$a = \sqrt{\gamma R T_3}$$

With :

- $\gamma = 1.2$
- R = 260 Pa m^3/kg K

While T_3 is assumed the same of the temperature at the stage 2, that can be calculated as :

$$T_2 = \frac{T_1}{\eta_c}(PR)^{\frac{\gamma-1}{\gamma}}$$

With

- T_1 temperature value at ambient conditions
- η_c compressor efficiency
- PR pressure ratio guaranteed by the compressor

These data are taken at an altitude of 11000 m, so an ambient temperature of 243 K and an ambient pressure of 25000 Pa. Dealing with an engine that has to be restarted or in windmilling conditions, a PR of 1.5 can be used.

With these data it has been found:

$T_2 =$ 324.81 K

a = 318.3406 m/s

and a mean air velocity value of:

$$v_{air_{mean}} = M * a = 6.37 \text{ m/s}$$

Now it is important to analyze the typical laminar flame speed, that for the large part of hydrocarbons is quite similar (figure [84]), about 0.5-0.6 m/s.

A complex phenomenon like combustion is often characterized by turbulence. So for this simplified analysis a turbulent flame speed has to be chosen.

As it can be noted from the following figure, the turbulent flame speed is about 10 times the laminar flame speed, so about 5-6 m/s, that has the same order of magnitude of the mean air velocity found before. This means that if the ignition is successful, the flame generated could be stabile with these conditions of the primary zone.

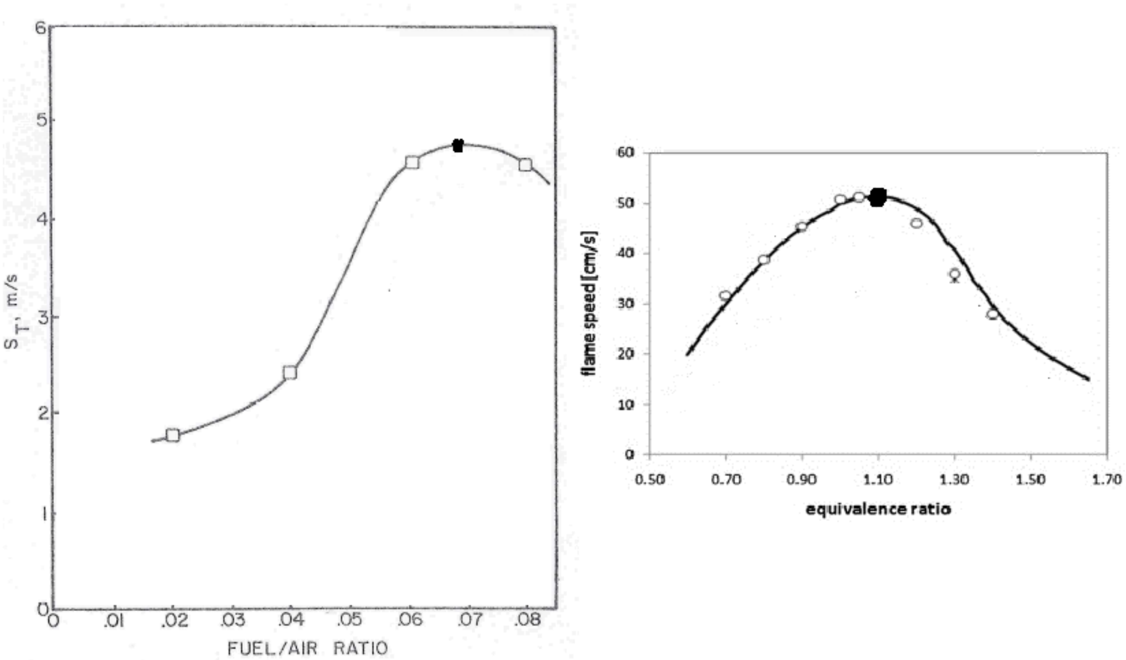


Figure 102 Comparison between laminar and turbulent flame speed for propane[5][6]

10. Conclusions

As written in the abstract, one of the most important requirements for a gas turbine engine is its relight capability, and restarting at high altitude is more difficult due to adverse ambient conditions.

This work has had the purpose to give a complete vision of what affects the ignition process, and after all some interesting conclusions can be made.

Ignition process is driven in particular by fuel atomization and evaporation. Evaporation process is as better as smaller are the fuel particles, so the choice of the right atomizer is fundamental in order to optimize ignition and particles combustion. Different kind of atomizers are presented, but since this would be a very general work it is not possible to say which is the best. It depends on the kind of engine and on its dimension, but, in general, for small engines a rotary atomizer could be the best choice because of its small dimension, low cost, ease of maintenance and also because of an easy design. On the other hand, for big engines a piloted airblast atomizer could be the best choice, because it is protected from overheating, it has a better fuel/air mixing and using a simplex pressure-swirl nozzle makes the device prevented from a poor atomization quality at startup.

Other conclusions can be made on the basis of the previous chapter. The analysis presented is preliminary and simplified by some approximations but it covers some of the main phenomena found in a practical case.

The results found show that the value of equivalence ratio that minimizes minimum ignition energy is 1.1, so the perfect mixture strength in the vortex is between the third and the fourth circle, that represents the perfect zone to ignite the fuel/air mixture.

This is where we would like to put the igniter too. Unfortunately, this is difficult on aero engines because it is then necessary to retract the igniter out of the flow and put it flush with the wall to preserve it. However devices like the torch igniter may be applied to bring the ignition source closer to the optimum position.

This master thesis wanted to be the first step of a complicated and long road that should bring to the construction of a box of conditions within the engine restart is possible. These conditions vary with altitude, but knowing them it could be possible to design a gas turbine engine that is able to restart also at high altitude, with adverse pressure and temperature conditions.

11. Future Goals

Starting from the analysis presented in the 9th chapter, these are the main future goals that have to be achieved, in order to build the box of ideal conditions in which a gas turbine engines can restart:

- Conducting experimental tests, recreating high altitude conditions.
- A different criteria has to be chosen to analyze the fuel particles in the vortex. Stokes number can be an idea, but an analysis with a CFD code is the best choice.
- CFD can be very useful also to have a better description of the vortex and air velocity in different parts of the primary zone.
- Different atomizers have to be used, at different pressure and temperature conditions, in order to have an idea on which could be the best choice, since their performance vary very much with environment conditions, as shown in Figures [90-94] .
- In order to verify that atomization properties don’t vary with combustion chamber geometry at sub-idle conditions, other tests on different combustion chamber at these conditions have to developed.
- It could be useful to test different kind of fuels, since their properties vary with pressure and temperature conditions, as shown in the 4th chapter.

- Different kind of igniters can also be tested in order to bring improvements to the ignition process.

This work wanted to make the first move in a wide and difficult area as the ignition of gas turbine engines, and so many things have to be made in order to achieve the main objective of the engine restart at high altitude.

Appendix A

Different Applications for Gas Turbine Engines

1. Power Generation Applications

G.T. engines are used in Power generation applications like

- the grid system, for the distribution of electrical power. In this case the engine is characterized by the constant synchronous speed of the shaft power system.
- Supplying for grid system, divided in three categories: Peak lopping engines, Base load power plant and Mid merit power plant.
- Standby generators, for emergency use. This kind of application is characterized by low unit cost, low unit weight and volume, fast start time. In this case the diesel engine competition is very strong.
- CHP (combined heat and power), for industrial processes.
- Closed cycle

2. Industrial Mechanical Drive Applications

In this kind of environment the purpose of the G.T. engine is to drive a pump or compressor, like in the case of gas and oil pipeline system. In these applications the gas is pumped from a well head to industrial and domestic consumers. The power required is about 6-10 MW, 15 MW, and 25-30 MW, that are beyond the practical size for a Diesel engine.

3. Automotive Applications

The first G.T. engine that propelled an automotive vehicle was produced in the UK IN 1950, but however the diesel and petrol engines have continued to dominate, and so the G.T. engine is used only in some specialist applications. An explanation of the problems of G.T. engine in this field resides in three reasons:

- Poor part load thermal efficiency
- Long acceleration time from idle condition to full load
- Huge capital investment required to improve G.T. engine performance in this field and to reduce unit's cost.

Unfortunately these disadvantages are heavier than the importance of some advantages like better part speed torque capability, lower weight and volume per unit power or lower emissions. In the end, the G.T. engine is used only in the hybrid electric vehicle and in the main battle tank.

4. Marine Applications

The first time of a G.T. engine in a marine application was in 1947, in UK. In this field this kind of engine is able to compete with diesel engine and also with nuclear power plant, but sometimes a combination of different engines is used. There are different types of combination, like:

- CODAG: Combination of Diesel engine, for propulsive power at low speed, and G.T. engine, for propulsive power at high speed
- CODOG: Combination of Diesel and G.T. engine, where only one of them can drive the propeller or water jet .
- COGAG and COGOG: Combination of G.T. engines for low and high speed.
- CODLAG : Combination Of Diesel engine, Electric engine and G.T. engine
- IED or FEP: Combination of Electric and G.T. engine, where G.T. engine drives a generator to provide electrical power for propulsion.

Other examples of a G.T. engine in marine applications are the Hovercraft (typical pressure ratio between 5:1 and 10:1), the Fast Ferry (that uses a CODOG, pressure ratio between 15:1 and 25:1) and large merchant container ships, while CODOG, COGAG and CODLAG are used for frigate, destroyer and light aircraft carrier.

Appendix B

Matching procedure for a turbojet configuration

The typical matching procedure for a turbojet configuration is summarized in the following pictures:

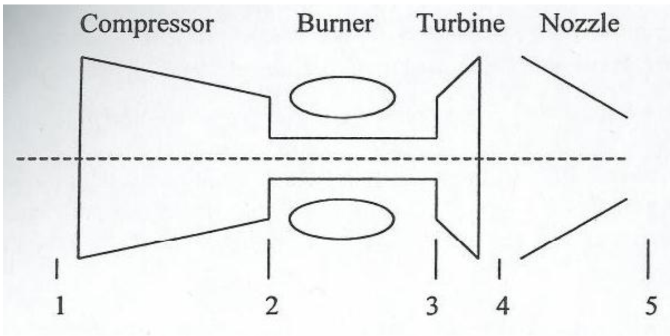
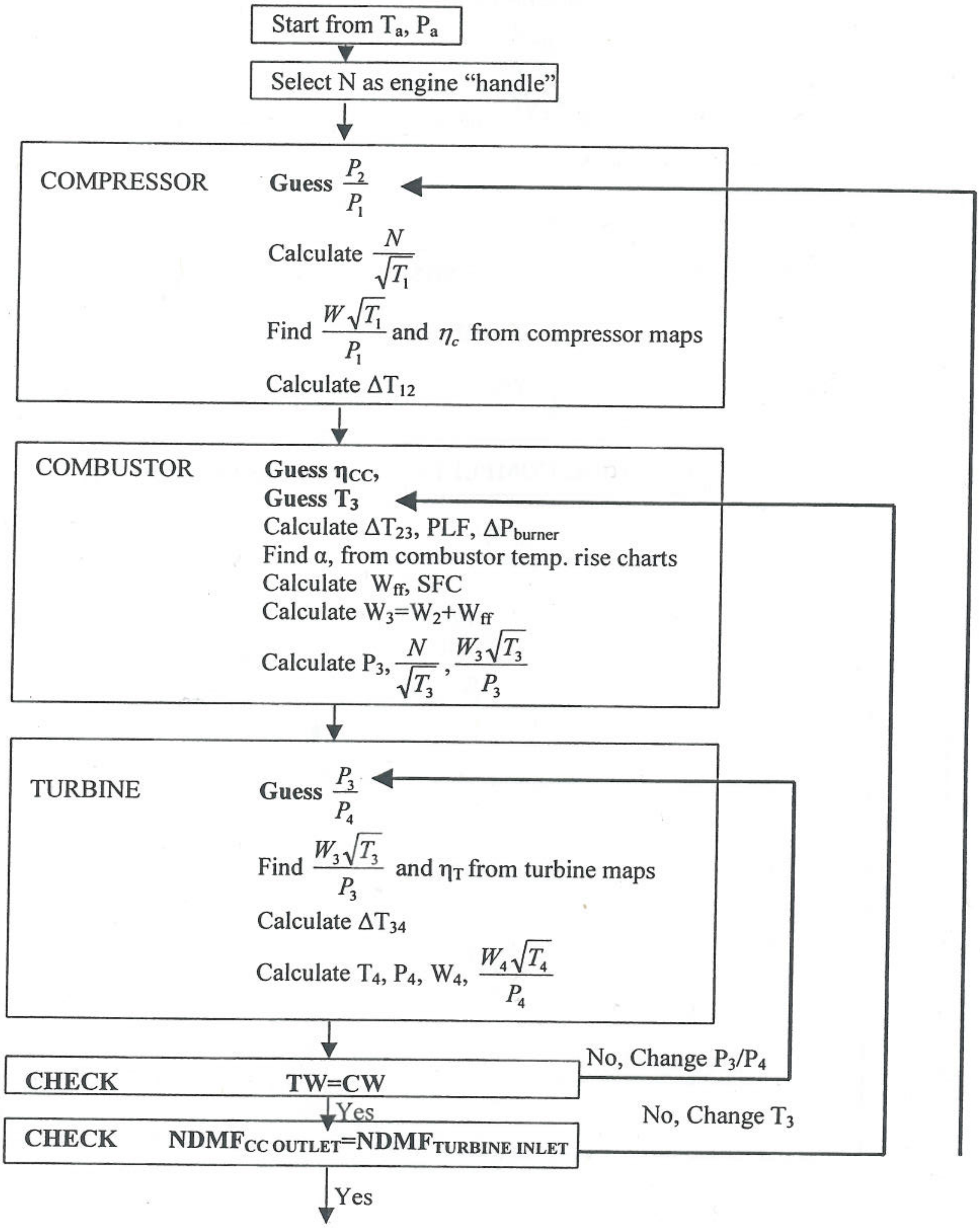


Figure 103 Turbojet scheme

Gas generator with nozzle (Multiple-curve turbine characteristic)



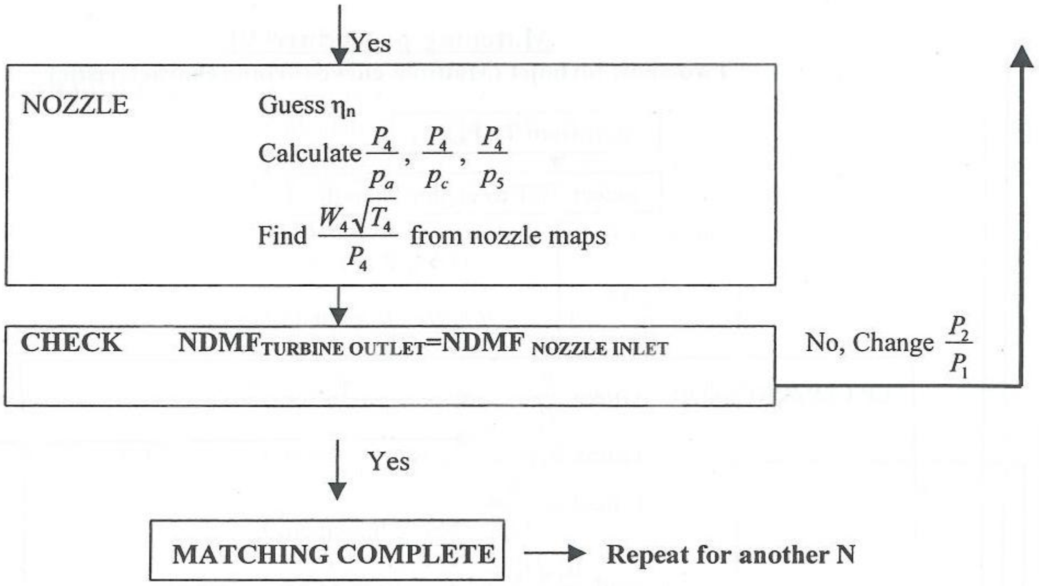


Figure 104 Matching procedure

Nomenclature

1st chapter

υ_i', υ_i'' = stoichiometric coefficients for the species i,

M_i = *i-th* chemical species

ω = reaction velocity [mol/(cm^{3}s)]

$\dot{\omega}_1$ = variation velocity of the *species 1* concentration [mol/(cm^{3}s)]

k = proportionality's factor

c_i = concentration of the i-th species

A = collision frequency [1/s]

E_a = activation energy [J]

n = global reaction order

k_f = forward constant

k_b. = backward constant

k_c = linking constant

We = Weber number

ρ_A = air density [kg/m^3]

σ/D = Droplet tension force [N/m^2]

C_D = drag coefficient of the droplet

Oh = Ohnesorge number

Re = Reynolds number

μ_L = dynamic viscosity [kg/m s]

SOT = Stator Outlet Temperature [K]

4th chapter

ρ = density [kg/m^3]

$d_{T1/T2}$ = relative density

μ = dynamic viscosity [Pa·s]

υ = kinematic viscosity [m^2/s]

τ = shear stress [Pa]

D = drop diameter [cm]

d_q = quenching distance [cm]

S_L = laminar flame speed [cm/s]

α = thermal diffusivity [m^2/s]

f = fraction of total fuel in vapor form

D_{32}= mean volume diameter [cm]

B = mass-transfer number

U = velocity [m/s]

Subscripts

a = air

f = fuel

R = relative

5th Chapter

We = Weber number

P = air density [kg/m^3]

σ/D = Droplet tension force [N/m^2]

C_D = drag coefficient of the droplet

Oh = Ohnesorge number

Re = Reynolds number

μ = dynamic viscosity [kg/m s]

U = velocity [m/s]

λ = wave length

E_{min} = minimum ignition energy [mJ]

c_p = specific heat at constant pressure [J/(kgK)]

ΔT = temperature rise due to combustion [°C]

d_q= quenching distance [cm]

k = thermal conductivity [W/(mK)]

S_L = laminar flame speed [cm/s]

u' = rms value of fluctuating velocity in x direction [cm/s]

α = thermal diffusivity [m^2/s]

C_3= D_{30}/D_{32}

S = flame speed [cm/s]

f = fraction of total fuel in vapor form

D_{32}= mean volume diameter [cm]

D_{30} = mean surface diameter [cm]

B = mass-transfer number

MMD = Mass median diameter [cm]

Subscripts

a = air

f = fuel

g = gas

l = liquid

R = air relative to liquid

Crit = critic

6th Chapter

m_F = rate of evaporation for a single drop

ρ = density [kg/m^3]

λ = evaporation constant [cm^2/s]

D = droplet diameter [cm]

$\dot{m}_F$ = average rate of evaporation for a single drop

D_o= initial drop diameter [cm]

t_e= drop lifetime [s]

T = Temperature [K]

Y_{fs}= fuel vapor mass fraction

L = latent heat of fuel

k = thermal conductivity [W/(mK)]

c_p = specific heat at constant pressure [cal/kgK]

Re_D= droplet Reynolds number

Pr = Prandtl number

Subscripts

f = fuel

l = liquid

g = gas

7th Chapter

We = Weber number

P = air density [kg/m^3]

σ/D = Droplet tension force [N/m^2]

C_D = drag coefficient of the droplet

Oh = Ohnesorge number

Re = Reynolds number

μ = dynamic viscosity [kg/m s]

U = velocity [m/s]

λ = wave length

E_{min} = minimum ignition energy [mJ]

c_p = specific heat at constant pressure [J/(kgK)]

ΔT = temperature rise due to combustion [°C]

d_q= quenching distance [cm]

k = thermal conductivity [W/(mK)]

S_L = laminar flame speed [cm/s]

u' = rms value of fluctuating velocity in x direction [cm/s]

α = thermal diffusivity [m^2/s]

C_3= D_{30}/D_{32}

S = flame speed [cm/s]

f = fraction of total fuel in vapor form

D_{32}= mean volume diameter [cm]

D_{30} = mean surface diameter [cm]

B = mass-transfer number

MMD = Mass median diameter [cm]

Subscripts

a = air

f = fuel

g = gas

l = liquid

R = air relative to liquid

Crit = critic

9^{th} Chapter

$\dot{m}$ = air mass flow [kg/s]

$\dot{m}_f$ = fuel mass flow [kg/s]

p = pressure [Pa]

P = total pressure [Pa]

T = temperature [K]

ρ = density [kg/m^3]

Φ = equivalence ratio

γ = specific heats ratio

η_c= compressor efficiency

AFR = air/fuel ratio

S_l = laminar flame speed [m/s]

S_t = turbulent flame speed [m/s]

d_q= quenching distance [cm]

E_{min}= minimum ignition energy [mJ]

c_p = specific heat at constant pressure

R = air constant $\left[\frac{Pa\ m^3}{Kg\ K}\right]$

References

1st Chapter

[1] P. P. Walsh, P. Fletcher (2004), *Gas Turbine Performance,* Second edition ed, Blackwell Science, Malden, USA.

[2] Arthur H. Lefebvre and Dilip R. Ballal (2010), *GAS Turbine Combustion Alternative Fuels and Emissions,* Third Edition ed, CRC Press Taylor&Francis Group, USA.

[3] Rolls-Royce, (1986), *The Jet Engine*

[4] Eric M. Goodger (2000), *TRANSPORT FUELS TECHNOLOGY MOBILITY for the MILLENNIUM,* LANDFALL PRESS, England.

[5] Jack D. Mattingly, David T. Pratt, William H. Heiser, (2002), *Aircraft Engine Design,* Second Edition, AIAA Education Series

2nd Chapter

[1] Braig, W., Schulte, H. and Riegler, C. (1999), "Comparative Analysis of the Windmilling Performance of Turbojet and Turbofan Engines", *Journal of Propulsion and Power,* vol. 15, no. 2, pp. 326-333.

[2] Michel Franchet, G. H. (Jan. 6, 2004), "EMERGENCY DEVICE FOR RELIGHTING A WINDMILLING TURBOJET", *United States Patent No 6,672,049 B2,* .

[3] P. P. Walsh, P. Fletcher (2004), *Gas Turbine Performance,* Second edition ed, Blackwell Science, Malden, USA.

[4] Shou, Z. Q. (1981), "Calculation of windmilling characteristics of turbojet engines.", *TRANS' ASME J.ENGNG.POWER,* vol. 103, no. 1 , Jan. 1981, pp. 1-12Y.

3rd Chapter

[1] Arthur H. Lefebvre and Dilip R. Ballal (2010), *GAS Turbine Combustion Alternative Fuels and Emissions*, Third Edition ed, CRC Press Taylor&Francis Group, USA.

[2] Professor Luciano Galfetti, (2009),Combustion in the propulsive systems, Politecnico di Milano

4th Chapter

[1] Eric M. Goodger (2000), *TRANSPORT FUELS TECHNOLOGY MOBILITY for the MILLENNIUM*, LANDFALL PRESS, England.

[2] J. Odjers, D. K. (1986), *GAS TURBINE FUELS and THEIR INFLUENCE ON COMBUSTION*, ABACUS PRESS.

[3] Atkins, D. L. and Ervin, J. S. (2001), "Freezing of Jet fuel within a buoyancy-driven flow in a rectangular optical cell", *Energy and Fuels,* vol. 15, no. 5, pp. 1233-1240.

[4] Eric M. Goodger, Stephen O. T. Ogaji, (2011), *Fuels & Combustion in Heat Engines*, Cranfield University Press, Cranfield University, Bedfordshire, MK43 0AL, England.

[5] Myers, G. D. and Lefebvre, A. H. (1984), "FLAME PROPAGATION IN HETEROGENEOUS MIXTURES OF FUEL DROPS AND AIR.", *Proceedings - Society of Automotive Engineers,* pp. 349.

[6] Xuesong Wu, Qianqian Li, Jin Fu, Chenglong Tang, Zuohua Huang, Ritchie Daniel, Guohong Tian, Hongming Xu (2011), “Laminar burning characteristics of 2,5-dimethylfuran iso-octane blend at elevated temperatures and pressures”, *Fuel 95* (2012), pp 234-240

5th Chapter

[1] Arthur H. Lefebvre and Dilip R. Ballal (2010), *GAS Turbine Combustion Alternative Fuels and Emissions,* Third Edition ed, CRC Press Taylor&Francis Group, USA.

[2] Kim, W. T., Mitra, S. K., Li, X., Prociw, L. A. and Hu, T. C. J. (2003), "A predictive model for the initial droplet size and velocity distributions in sprays and comparison with experiments", *Particle and Particle Systems Characterization,* vol. 20, no. 2, pp. 135-149.

[3] Sharma, N. Y., Datta, A. and Som, S. K. (2001), "Influences of spray and operating parameters on penetration of vaporizing fuel droplets in a gas turbine combustor", *Applied Thermal Engineering,* vol. 21, no. 17, pp. 1755-1768.

[4] Lee, D., You, G., Choi, S. and Huh, H. (2011), "Analysis of formation and breakup mechanisms in rotary atomization through spray visualization", *Journal of Visualization,* vol. 14, no. 3, pp. 273-283.

[5] Ballal, D. R. and Lefebvre, A. H. (1979), "Ignition and flame quenching of flowing heterogeneous fuel-air mixtures", *Combustion and Flame,* vol. 35, no. C, pp. 155-168.

[6] Ballal, D. R. and Lefebvre, A. H. (1975), "The influence of spark discharge characteristics on minimum ignition energy in flowing gases", *Combustion and Flame,* vol. 24, no. C, pp. 99-108.

[7] Ballal, D. R. and Lefebvre, A. H. (1975), "The influence of flow parameters on minimum ignition energy and quenching distance", *Symposium (International) on Combustion,* vol. 15, no. 1, pp. 1473-1481.

[8] Ballal, D. R. and Lefebvre, A. H. (1978), "Ignition of liquid fuel sprays at subatmospheric pressures", *Combustion and Flame,* vol. 31, no. C, pp. 115-126.

[9] Lee, T. -., Jain, V. and Kozola, S. (2001), "Measurements of minimum ignition energy by using laser sparks for hydrocarbon fuels in air: propane, dodecane, and jet-A fuel", *Combustion and Flame,* vol. 125, no. 4, pp. 1320-1328.

[10] Frederick D. M. Williams (Feb. 13, 1951), "MULTIPLE FUEL JET BURNER AND TORCH IGNITER UNIT WITH FUEL VAPORIZING TUBES", *United States Patent No 2,541,900,* .

[11] Ralph J. Sneeden (Oct. 6, 1970), "FUEL VAPORIZER FOR GAS TURBINE ENGINES", *United States Patent No 3,531,937,* .

[12] Sovani, S. D., Sojka, P. E. and Lefebvre, A. H. (2001), "Effervescent atomization", *Progress in Energy and Combustion Science,* vol. 27, no. 4, pp. 483-521.

[13] Rizk, N. K. and Lefebvre, A. H. (1983), "INFLUENCE OF ATOMIZER DESIGN FEATURES ON MEAN DROP SIZE.", *AIAA Journal,* vol. 21, no. 8, pp. 1139-1142.

[14] Wang, X. F. and Lefebvre, A. H. (1987), "MEAN DROP SIZES FROM PRESSURE-SWIRL NOZZLES.", *Journal of Propulsion and Power,* vol. 3, no. 1, pp. 11-18.

[15] Nukiyama, S., and Tanasawa, Y., “Experiments on the Atomization of Liquids in an airstream,” *Transactions of the Society of Mechanical Engineers, Japan,* Vol. 5,pp. 68–75, 1939.

[16] Lorenzetto, G. E. and Lefebvre, A. H. (1977), "MEASUREMENTS OF DROP SIZE ON A PLAIN-JET AIRBLAST ATOMIZER.", , pp. 1006-1010.

6th Chapter

[1] Arthur H. Lefebvre and Dilip R. Ballal (2010), *GAS Turbine Combustion Alternative Fuels and Emissions,* Third Edition ed, CRC Press Taylor&Francis Group, USA.

[2] Aggarwal, S. K., Tong, A. Y. and Sirigano, W. A. (1984), "COMPARISON OF VAPORIZATION MODELS IN SPRAY CALCULATIONS.", *AIAA Journal,* vol. 22, no. 10, pp. 1448-1457.

[3] Ranz , W.E. ; Marshall , W.R. , Jr. Evaporation from drops, part2 . *Chemical Engineering Progress*1952 , 48 (4), 173 – 180 .

7th Chapter

[1] Arthur H. Lefebvre and Dilip R. Ballal (2010), *GAS Turbine Combustion Alternative Fuels and Emissions,* Third Edition ed, CRC Press Taylor&Francis Group, USA.

[2] Kim, W. T., Mitra, S. K., Li, X., Prociw, L. A. and Hu, T. C. J. (2003), "A predictive model for the initial droplet size and velocity distributions in sprays and comparison with experiments", *Particle and Particle Systems Characterization,* vol. 20, no. 2, pp. 135-149.

[3] Sharma, N. Y., Datta, A. and Som, S. K. (2001), "Influences of spray and operating parameters on penetration of vaporizing fuel droplets in a gas turbine combustor", *Applied Thermal Engineering,* vol. 21, no. 17, pp. 1755-1768.

[4] Lee, D., You, G., Choi, S. and Huh, H. (2011), "Analysis of formation and breakup mechanisms in rotary atomization through spray visualization", *Journal of Visualization,* vol. 14, no. 3, pp. 273-283.

[5] Ballal, D. R. and Lefebvre, A. H. (1979), "Ignition and flame quenching of flowing heterogeneous fuel-air mixtures", *Combustion and Flame,* vol. 35, no. C, pp. 155-168.

[6] Ballal, D. R. and Lefebvre, A. H. (1975), "The influence of spark discharge characteristics on minimum ignition energy in flowing gases", *Combustion and Flame,* vol. 24, no. C, pp. 99-108.

[7] Ballal, D. R. and Lefebvre, A. H. (1975), "The influence of flow parameters on minimum ignition energy and quenching distance", *Symposium (International) on Combustion,* vol. 15, no. 1, pp. 1473-1481.

[8] Ballal, D. R. and Lefebvre, A. H. (1978), "Ignition of liquid fuel sprays at subatmospheric pressures", *Combustion and Flame,* vol. 31, no. C, pp. 115-126.

[9] Lee, T. -., Jain, V. and Kozola, S. (2001), "Measurements of minimum ignition energy by using laser sparks for hydrocarbon fuels

in air: propane, dodecane, and jet-A fuel", *Combustion and Flame,* vol. 125, no. 4, pp. 1320-1328.

[10] Frederick D. M. Williams (Feb. 13, 1951), "MULTIPLE FUEL JET BURNER AND TORCH IGNITER UNIT WITH FUEL VAPORIZING TUBES", *United States Patent No 2,541,900,* .

[11] Ralph J. Sneeden (Oct. 6, 1970), "FUEL VAPORIZER FOR GAS TURBINE ENGINES", *United States Patent No 3,531,937,* .

[12] Sovani, S. D., Sojka, P. E. and Lefebvre, A. H. (2001), "Effervescent atomization", *Progress in Energy and Combustion Science,* vol. 27, no. 4, pp. 483-521.

[13] Rizk, N. K. and Lefebvre, A. H. (1983), "INFLUENCE OF ATOMIZER DESIGN FEATURES ON MEAN DROP SIZE.", *AIAA Journal,* vol. 21, no. 8, pp. 1139-1142.

[14] Wang, X. F. and Lefebvre, A. H. (1987), "MEAN DROP SIZES FROM PRESSURE-SWIRL NOZZLES.", *Journal of Propulsion and Power,* vol. 3, no. 1, pp. 11-18.

[15] Nukiyama, S., and Tanasawa, Y., “Experiments on the Atomization of Liquids in an airstream,” *Transactions of the Society of Mechanical Engineers, Japan*, Vol. 5,pp. 68–75, 1939.

[16] Lorenzetto, G. E. and Lefebvre, A. H. (1977), "MEASUREMENTS OF DROP SIZE ON A PLAIN-JET AIRBLAST ATOMIZER.", , pp. 1006-1010.

8th Chapter

[1] Arthur H. Lefebvre and Dilip R. Ballal (2010), *GAS Turbine Combustion Alternative Fuels and Emissions,* Third Edition ed, CRC Press Taylor&Francis Group, USA.

[2] Ballal, D. R. and Lefebvre, A. H. (1978), "Ignition of liquid fuel sprays at subatmospheric pressures", *Combustion and Flame,* vol. 31, no. C, pp. 115-126.

[3] Dennis M. DeFreitas. (Nov. 29, 1994), "LASER IGNITION METHODS AND APPARATUS FOR COMBUSTORS", *United States Patent No 5,367,869,* . Oxford, N.Y.

9th Chapter

[1] P. P. Walsh, P. Fletcher (2004), *Gas Turbine Performance,* Second edition ed, Blackwell Science, Malden, USA.

[2] Eric M. Goodger (2000), *TRANSPORT FUELS TECHNOLOGY MOBILITY for the MILLENNIUM*, LANDFALL PRESS, England.

[3] Professor Arturo Baron, (04/2010),Combustion Note sui vortici piani, Politecnico di Milano

[4] Ballal, D. R. and Lefebvre, A. H. (1975), "The Influence of flow parameters on minimum ignition energy and quenching distance", *Combustion and Flame,* vol. 35, no. A, pp. 155-168.

[5] Arthur H. Lefebvre and Dilip R. Ballal (2010), *GAS Turbine Combustion Alternative Fuels and Emissions,* Third Edition ed, CRC Press Taylor&Francis Group, USA.

[6] E. Ranzia, A. Frassoldati, R. Grana, A. Cuoci, T. Faravelli, A.P. Kelley, C.K. Law, “Hierarchical and comparative kinetic modeling of laminar flame speeds of hydrocarbon and oxygenated fuels”, Combustion and Flame, Vol. 38, Issue 4, pp. 468-501.

[7] C. Freeman, A. G. Wilson, I. J. Day, M. A. Swinbamks (1998), “Experiments in Active Control of Stall on an Aeroengine gas Turbine”, Journal Of Turbomachinery, Vol. 120, pp. 637-647.

[8] N. Grech, A. Mehdi, P. K. Zachos, V. Pachidis, R. Sing, “EFFECT OF COMBUSTOR GEOMETRY ON PERFORMANCE OF AIRBLAST ATOMIZER UNDER SUB-ATMOSPHERIC CONDITIONS”, Engineering Applications of Computational Fluid Mehanics, Vol.6, No. 2, pp. 203-213, (2012)