DESIGN AND EXPERIMENTAL CHARACTERIZATION OF AN AIR-ASSISTED, IMPINGING-JETS ATOMIZER FOR AERONAUTICAL APPLICATIONS WITH BIOFUEL

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2 Introduction

2.1 Motivation

The commercial aviation sector counts a fleet of over 15'750 aircrafts, which operates on a single fossil fuel product, and contributes to the 2÷3% of the global carbon emissions [1].

The increasing concerns around the environmental impact of the sector, along with its future rate of growth (which is estimated, on fleet basis, around 4.7% year on year), raised the interest around the reduction of the greenhouse gases emissions.

The reduction of the emissions can be achieved either through the technological development of the engine components, as a more efficient engine burns lesser fuel, or through the development of innovative and more ecologic fuels, as the use of renewable feedstock results in a more neutral carbon cycle.

The technological development of the engine components allows a reduction of the emissions, as a more efficient engine burns lesser fuel, and therefore results in lesser specific emissions [g/kWh].

![Figure 2.1 - Fuel consumption reduction over the last 60 years [32]. The values are referred to the De Havilland Comet, the first civil jet airliner.](image)

Among the engine components, the atomizer affects in a great extent the combustion promptness, cleanness, and efficiency. The technological development of the component aims to achieve the best atomization - in terms of evaporation
rate and penetration - with a reduced power consumption for the pressurization of the fuel and, if present, the assisting gas.

The development of alternative fuel, however, allows a faster benefit, as it is not constrained to the industrial assets of the aeronautical sector, in which the high investment costs slow the renovation of the production [2]. Moreover, the use of alternative fuels presents further advantages over the use of conventional jet fuel, as a reduced cost fluctuation, a worldwide homogeneous distribution of the feedstock and, depending on the alternative fuel production, better fuel properties [3]. For these reasons, the contribution of alternative jet fuel is expected to grow up to 30% within 2030 [4].


2.2 Literature review

2.2.1 Atomization

Atomization is the process through which a volume of liquid is disintegrated into a fine spray of droplets. Its main objective is to increase the specific surface area of the liquid, which is of fundamental importance in order to achieve high evaporation rates.

The main technologies in use for aeronautical applications are the pressure and pneumatic atomizations. The pressure atomization consists of a simple injection of pressurized fuel through a nozzle. The pneumatic atomization allows to reach a similar performance with lower liquid pressures, but requires the presence of a pressurized air stream assisting the process.

The multiple impinging jets atomization is one of the main adopted configurations for the liquid propellant rocket engines, as along with the high evaporation rate it provides a good mixing of the liquid oxidiser and propellant [5]. It consists of the use of two or more fuel nozzles, each producing an isolated liquid column directed towards a common impingement point. The jet impingement allows, if compared with the injection of the single jet, a good atomisation for smaller liquid pressures.
**Pressure atomization**

The atomisation of a single and isolated jet emerging from a nozzle has been the subject of a large number of theoretical and experimental studies, based on the fundamental work of Rayleigh and Weber.

In 1878, Rayleigh investigated the atomisation of non-viscous fluids at low jet velocities [6], refining the previous studies of Plateau. In 1931, Weber extended the studies to viscous fluids [7]. In the following decades, several authors extended the investigation to different velocities and fluid properties, leading to the identification of four regimes of breakup with increasing jet velocities [8]:

I. Rayleigh-Plateau breakup

   The liquid is ejected from the nozzle in the shape of a liquid column. The surface tension on the column external surface causes oscillations on its shape, referred as capillary instabilities, and results in droplet sizes greater than the nozzle diameter.

II. First wind-induced breakup

   The gradual increase of the surrounding air friction provides a further amplification to the oscillations of the liquid column. For low jet velocities, the oscillations manifest at a certain distance from the nozzle, as in the upstream region the surface tension succeeds to oppose the surrounding air action and to keep the liquid column in its shape. In these conditions the regimen is referred as first wind-induced breakup, and the resulting droplet size is comparable with the orifice diameter.

III. Second wind-induced breakup

   For higher jet velocities, the breakup extends upstream, up to the orifice region. This regimen is referred as second wind-induced breakup, and results in a smaller resulting droplet size.

IV. Prompt atomisation

   For liquid velocities over ~100 m/s, the presence of intense flow turbulence and cavitation bubbles within the nozzle result in an instantaneous atomisation on the nozzle exit, with droplet sizes much smaller than the orifice diameter [4].
The atomisation regimen is identified through the jet Reynolds number:

$$Re = \frac{\text{INERTIAL FORCE}}{\text{VISCOUS FORCE}} = \frac{\rho_F \cdot v_j \cdot d_F}{\mu}$$

The interaction with the surrounding air affects the atomisation just in conditions of wind-induced breakup, as in regimen I the friction forces are negligible and in regimen IV the whole atomisation occurs on the orifice exit. The effect of the surrounding air on the atomisation process is represented and quantified through the Weber number:

$$We = \frac{\text{DISRUPTIVE AERODYNAMIC FORCE}}{\text{CONSOLIDATING SURFACE TENSION}} = \frac{\rho_F \cdot u_r^2 \cdot d_F}{\sigma}$$

The fundamental studies on the disintegration of the single jet have been crucial for the identification of the variables - expressed as adimensional groups - leading the breakup phenomenon. Lefebvre [5] identified the values of Re and We as representative of both the nature and the grade of the atomisation process, even for more refined atomisation strategies than the single jet.
Pneumatic atomization

The pneumatic atomisation, also referred as twin fluid atomisation, consists of the use of an atomising air flow, which is aimed to increase the relative velocities over the external surface of the liquid phase, and therefore its disintegration. The technique is referred as air assisted atomisation if it involves relative small quantities of air on high velocities, as air blasted atomisation otherwise [6].

The main established and studied technologies, as reviewed in [7], consist either of the use of several air jets, which increase the liquid atomisation shaping it as a liquid sheet (air blasted, external mixing atomisation), or of an internal mixing resulting in the injection of the two fluids from the same nozzle (air assisted, internal mixing atomisation).

As observed for the atomisation of an isolated jet in regimen of wind-induced breakup, the effectiveness of the technique is represented through the Weber number, which presents a proportionality with the square of the relative speed between the two fluids: \( \text{We} \propto u_R^2 \)

In practice, the influence of the relative speed on the droplet size also depends on the atomiser configuration, in the form of \( \text{SMD} \propto u_R^A \), with the \( A \) value on the exponent spanning - in extent to the previous studies reviewed in [8] - between 0.4 and 1.33. The Air-to-Fuel Ratio (AFR) - the dimensionless ratio between the air and fuel flow rates - is also an important variable for the atomisation, as the effectiveness of the atomising air flow results defined between the threshold values \( \text{AFR}_{\text{MIN}} \) and \( \text{AFR}_{\text{MAX}} \). For values below \( \text{AFR}_{\text{MIN}} \), the effect of the air flow is negligible as the flow is insufficient to overcome the viscous and surface tensions opposing the disintegration of the liquid phase. Instead, the extension over \( \text{AFR}_{\text{MAX}} \) provides a limited improvement on the atomisation, as the additional air does not participate to the breakup process. The threshold values also depend on the atomiser configuration.

Both the air assisted and the sir blasted methods require a large amount of air to achieve a good atomisation. Previous experiments operated with air blasted water achieved a SMD of 75 \( \mu \text{m} \) with an AFR of the order of \( \sim 1 \) [9]. Experimental studies on swirl air blasted atomisers showed that an SMD of the order 50 \( \mu \text{m} \) can be achieved at a AFR of \( \sim 8 \) [10].
**Multiple impinging jets atomization**

The multiple jet impingement consists of the use of two or more fuel nozzles, each producing an isolated jet directed towards the geometrical impingement point. The impingement mechanisms - and therefore the resulting jet shape and droplet size - depends on the number of jets, as well as on the fuel properties and involved momentums, expressed as Re and We, [11] and [12].

The main previous investigations on the multiple jet impingement are focused on the collision of two jets, which results in three distinct regimens/regiminia [13] of atomisation, depending on both Re and We.

In these conditions, the impingement angle has a negligible effect on the development of the atomisation mechanism [14], but affects the resulting shape of the atomising jet, which still is of great interest as it is related with the spray penetration of the combustion chamber [15].

![Figure 2.2 - Liquid sheet development. Closed rim regimen.](image)

The Ohnesorge number, defined as the dimensionless parameter expressing the ratio between the viscous forces and the inertial and surface tension forces, allows a further classification within each regimen [11]:

\[
Oh = \frac{\text{VISCOS FORCE}}{\sqrt{\text{SURFACE TENSION - INERTIA}}} = \frac{\sqrt{We}}{Re} = \frac{\mu}{\sqrt{\rho_F \cdot \sigma \cdot d_F}}
\]

As the value is calculated over the nozzle diameter \(d_F = 0.5\) mm, it does not depend on the motion conditions, and it’s therefore representative, for a given atomiser configuration, of the liquid properties.
I. Closed rim

For small jet velocities and for high viscosities and surface tensions (for small Re and We), the impingement of the liquid jets results in the formation of a thin liquid sheet, presenting a distinct bounding rim, which collects the major portion of the liquid flow.

For high Oh numbers (\(>10^{-1}\)), the viscous forces succeed to oppose the lateral development of the liquid sheet, as the impinging jets present little inertia. The impact results in fact in the coalescence of the liquid columns into a larger single vertical column, and therefore undergoes Rayleigh-Plateau breakup.

For lower Oh (\(10^{-2} \div 10^{-1}\)), the curvature force associated with the surface tension limits the lateral extent of the liquid sheet, and shapes the bounding rim as distinct and closed. The same force causes the rim to retract and close on the sheet lower portion. As its two halves collide on each other on the apex, it gives rise to a second liquid sheet, perpendicular to the first one. The process repeats, reducing the resulting liquid chain to a liquid column in some cases, to a fishbone structure in others.

For further lower Oh (\(10^{-3} \div 10^{-2}\)), the liquid sheet undergoes the periodic and symmetrical formation of ligaments separating from the inferior region of the rim in a shape referred as fishbone structure. The atomisation is caused by the Rayleigh-Plateau instabilities within the bounding rim, which are transmitted from the impingement point through a variation of the sheet thickness.

For further inferior values of Oh (\(<10^{-3}\)), the same instabilities do not result in detaching ligaments, but instead in an atomisation widespread over the whole rim.

II. Open rim

For higher Re and We, the viscous and surface tensions fail to sustain the liquid sheet shape, whose rim opens in the inferior part. Kelvin-Helmholtz instabilities separate the two halves of the bounding rim, and cause the separation of ligaments and droplets from the liquid sheet.

The conditions of open rim with lower Re and higher We (and therefore higher Oh), are referred as conditions of aerodynamic instabilities. The instabilities result in an asymmetrical sinusoidal wave through the sheet centre, which imposes a flapping motion to the inferior portion of the sheet.

Instead, at higher Re, the increased fuel inertia expands the lower opening towards the superior portion of the sheet. As the rim loses its distinct definition, the
development is referred as rimless separation, and results as a transition stage between the spread open rim and the flapping ligaments main regimens.

III. Flapping ligaments

The impact results in the formation of a perforated liquid sheet, which atomises as separated liquid ligaments shaped as concentrical arcs over the crests of the impact wave. The wavelength tends to assume a constant wavelength for increasing Weber numbers.

For high Oh (high We and low Re), the liquid sheet keeps a smooth surface and develops the flapping motion on its external region. The progressive reduction of Oh extends the oscillation towards the inner region of the sheet, which develops as a ruffled surface.

IV. Developed atomisation

In conditions of high Re and We, the jet impingement does not result in the formation of a liquid sheet, as the impact results in the direct formation of the single droplets. As for the regimen III, the flow assumes the shape of the impact wave, and results in a series of arc-shaped clouds of particles.

The impingement of three and four jets also results in a liquid chain behaviour for small flows and high viscosities and surface tensions, but assumes more complex and ruffled shapes for increasing velocities [14]. In these conditions, the development appears to be more sensitive on both the propagation of the instabilities and the impingement angle. The main droplet source is still the bounding rim, but some droplet also appears above the impingement point and on the lower part of the resulting jet, as distinct detached ligaments.

Previous experiments operated with impinging jets of water show that jet velocities of the order of 12.5 m/s are required to obtain an SMD in the range of 300 µm [17], while velocities of 40 m/s result in a SMD of 50 µm [18].
**Combined technique**

The main contribution for the design of the present work injector is an experimental investigation over the atomising technique of interest [18], limited to the use of two liquid nozzles, as represented in Figure 2.3.

The authors investigated the performance of the atomiser through backlit and particle/droplet optical imaging techniques. The experiments have been led with different liquid properties (through the use of different liquids) and involved quantities (expressed as AFR), along with the effect of the impingement angle between the two liquid nozzles.

![Figure 2.3 - The atomizer configuration adopted in the referred previous contribution [18]. The impingement angle $\alpha$ has been set on the values of 30°, 45° and 60°.](image-url)
The experimental activities led to the following main conclusions:

- It is possible to define two distinct modes of atomisation, depending on the involved flow rates:

  The atomisation mode is referred as classical if the liquid columns (two in this case) collide on each other on the impingement point. The vertical air flow affects the atomisation as the jets approach to the centre, but the liquid phase still preserves the shape of a column until the impingement. After the jet collision, the air stream amplifies the oscillations on the resulting jet (shaped as a liquid sheet in this case), and therefore increases its atomisation.

  The atomisation mode is instead referred as prompt if the vertical air flow has enough momentum to move the impingement point to a lower position (in reference to the geometrical impingement point). For even higher momentum, the impingement point disappears, as the liquid column is disintegrated before reaching the injector axis. In these conditions, the jets still undergoes the collision, but as atomising droplets instead of liquid columns. The transaction from classical to prompt atomisation can be identified through a critical dimensionless parameter, such as the AFR or the flows momentum ratio.

- As for the airless multiple jet configuration, the impingement angle between the liquid nozzles does not affect the atomisation mode, and therefore just affects the shape of the resulting spray, which is wider for higher angles and vice versa.

- The liquid viscosity appears to affect the atomisation more than its surface tension, which affects the width of the liquid sheet in the absence of the air stream, but results negligible towards the atomisation process in its presence. High liquid viscosities reduce the atomisation, as the viscous forces better oppose to the inertial forces.

- The authors also identified a critical value of AFR after which the fuel properties do not affect the atomisation. An atomising technique presenting the same performances over different liquid properties is of special interest in the applications where flexible fuels are required, as in the present work.
2.2.2 Alternative Jet Fuel

While, for other applications, the use of alternative fuels with different properties or phase is allowed through a small and justified engine upgrade (as, for example, the reciprocating engine in the automotive sector), aviation presents far greater restrictions on alternative fuels, for two main reasons. First, the extreme conditions of combustion require specific fuel properties, which reduces the range of suitable candidate fuels to a restricted group of liquid hydrocarbon blends. Moreover, the alternative fuel has to be interchangeable with the present jet fuel, and therefore backwards compatible with the existing fleet. If not, airports would have to provide different qualities of fuels, introducing logistic issues, and limiting the movement of the aircrafts towards the destinations where the alternative refueling is available [8]. Because of this second requirement, alternative fuels for aviation are also referred as drop-in fuels.

An alternative fuel is therefore suitable for aviation if it presents similar properties to conventional jet fuel, especially in terms of heating value and cold flow properties [6]. In addition, in order to further guarantee the fuel fitness, the alternative blend is constrained to consist for at least 50%v of conventional jet fuel.

Aviation turbine alternative fuel, or Alternative Jet Fuel (AJF), is defined as a mixture of conventional and synthetic hydrocarbons, referred as conventional and synthetic (or alternative) blending components.

It is important to mark the difference between the alternative jet fuel (the final mixture) and the alternative blending component, as the standard specification for unconventional jet fuels - ASTM D7566 - does not allow the direct use of the second, and sets different requirements for both of them, as illustrated, in part, in Table 2.1.
The conventional blending component is conventional Jet Fuel (JF), while the alternative blending components belong to four distinct classes, classified according to the feedstock nature and the production process. All the classes but the last are referred as Synthetic Paraffinic Kerosines (SPK):

- **HEFA** SPK from Hydroprocessing of Esters and Fatty Acids
- **F-T** Fischer-Tropsch Hydroprocessed SPK
- **AtJ** Alcohol-to-Jet SPK
- **SIP** Synthesized Iso Paraffins from Hydroprocessed Fermented Sugars

The main common trait between the four classes is in the composition: almost all the composing compounds are paraffins, along with a smaller amount of naphthenes (15%w) and traces of aromatics (5‰w, against the 20%w of conventional JF).

The processes are engineered in order to maximize the production of paraffins, as their structure presents a high H/C ratio and therefore increases the blend heating value. Among the paraffins, the branched isoparaffins induce a higher resistance to oxidation (and therefore a higher blend octane number) along with a reduction of its freeze and flash points, both critical parameters for aviation [3]. Naphthenes also reduce the hydrocarbon blend freezing temperature [4], while a minimal aromatic content has to be present in order to prevent sealing damage.

All these production technologies convert biomass, and can therefore be referred as Biomass-to-Liquid (BtL) conversions, even though in common usage the term refers to the Fischer-Tropsch production.
Jet Fuel

Aviation turbine fuel, commonly known as Jet Fuel (JF), is a distillate of the kerosine type, refined from conventional petroleum sources.

As gasoline and diesel fuel, JF is mainly composed of paraffins, naphthenes and aromatics, along with small amounts of olefins and other compounds. It is enriched with several additives, aimed to inhibit the hazard of static charges, reduce the oxidizing and corrosive potentials, increase the lubricity and improve the cold flow properties. The presence of additives, even though in parts per million, marks the main difference between jet fuel and kerosine.

In extent to aviation, the composition presents intermediate values for both vapor pressure and octane number, which result as the best values for the stable combustion under the extreme conditions of the turbine engine. Moreover, the high flash point reduces the explosion hazard, while the low freeze and wax points allow the high altitude flight.

The main jet fuel grades for civil aviation applications are Jet A and Jet A-1. Jet A is only supplied for domestic flights in USA, while Jet A-1 is adopted in the rest of the world. The two grades present similar properties, and mainly differ in the freezing temperature: -40 and -47 °C respectively for A and A-1 grades.

The American standard specification ASTM D1655 defines both A and A-1 grades, while the European standard specification DEF STAN 91-91 only defines the A-1 grade, with slight and more stringent exceptions.
HEFA

Synthetic paraffinic kerosine from Hydroprocessing of Esters and Fatty Acids (HEFA) is also referred as Hydroprocessed Renewable Jet fuel (HRJ) and, whenever animal biomass is not involved, as Hydroprocessed Vegetable Oil (HVO).

The suitable feedstock for HEFA production is fat biomass, rich of glycerides (especially triglycerides), free fatty acids and fatty esters. The existing production plants mainly convert camelina oil, jatropha oil and algae as energy crops, cooking oil and animal fat as side products of other industrial chains [1].

After a first pretreatment, aimed to remove impurities from the feedstock, the biomass is refined through three main hydroprocessing stages:

I. Hydrotreatment

The main purpose of this stage is to convert the biomass into paraffins. Oxygen is removed in presence of excess hydrogen via hydrodeoxygenation and decarboxylation processes, along with nitrogen, sulphur and residual metals.

II. Selective hydrocracking

Selective hydrocracking is necessary to reduce the paraffins carbon number to a suitable value for aeronautical applications, namely $C_8 \div C_{16}$. The presence of this stage marks the difference between the production processes of hydroprocessed jet fuel and diesel fuel, which is referred in this case as green diesel.

III. Isomerization

The paraffins are then converted into more compact isoparaffins, reducing the hydrocarbon blend freeze and flash points. These reactions are empowered by multifunctional catalysts.

The whole production process can easily be integrated in a conventional oil refinery, avoiding the development cost of a dedicated plant [5].
**F-T**

The production of Fischer-Tropsch hydroprocessed synthetic paraffinic kerosine, or simply F-T fuel, consists of an indirect conversion.

First, the feedstock is processed into synthesis gas, a gaseous mixture of molecular hydrogen and carbon monoxide, along with small amounts of methane and water. Subsequently, the synthesis gas is converted into the paraffinic blending component through the Fischer-Tropsch synthesis, named after the chemists who developed the catalytic reaction in 1925.

Because the whole production process consists of an indirect conversion, the feedstock nature has a limited influence on the properties of the blending component.

While HEFA needs a specific kind of biomass, F-T fuel can be produced from a wider range of less valuable feedstock, as agricultural residues and municipal solid waste, along with further alternative (even though fossil) sources as coal and natural gas. On the downside, the conversion process is more expansive.

The whole production process consists of four main stages:

I. **Gasification** or **Steam reforming**

Solid feedstock as biomass and coal is converted into synthesis gas through gasification, while gaseous feedstock as natural gas is steam reformed.

II. **Fischer-Tropsch synthesis**

While the F-T synthesis consists of a wider set of reactions, the production of the blending component for aviation focuses on the conversion of synthesis gas into normal paraffins. The reaction is promoted with an iron catalyst and a low reactor temperature [7].

The final conversion of normal paraffins into isoparaffins is operated as in the described production process of HEFA:

III. **Selective hydrocracking**

IV. **Isomerization**
The production of Alcohol-to-Jet synthetic paraffinic kerosine (AtJ) consists of the catalytic conversion of a mixture of monohydric alcohol compounds into a mixture isoparaffins, and is structured as follows:

I. Fermentation

The process feedstock consists of raw biomass, waste gases rich in carbon monoxide and synthesis gas. The feedstock is refined, through fermentation, into a mixture of methanol, ethanol and butanol. The alcohol blend compounds are then converted into longer chain compounds through dehydration and oligomerization.

II. Hydroprocessing

The hydroprocessing stage is structured as the complete production process of HEFA (Hydrotreatment + Selective hydrocracking + Isomerization), and as for the production of HEFA, it results in an isoparaffinic blend, which in this case presents both the gaseous and the liquid phases.

III. Fractionation

The fractionation consists of the separation of the gaseous and liquid portions of the isoparaffins, and is often achieved through distillation.

The standard specification for alternative blending components currently only allows isobuthanol - C₄H₁₀O - for the AtJ production [8]. ASTM is considering to extend the limitation to the C₂÷C₅ alcoholic compounds.
**SIP**

Synthesized Iso Paraffinic aviation fuel (SIP) is an alternative blending component produced from hydroprocessed fermented sugars. The production process consists of three main stages [8]:

I. **Fermentation**

The process feedstock consists of sugar rich biomass, in a great extent maize and sugarcan crops [5], which is converted through fermentation in farnesene (C$_{15}$H$_{24}$), a branched olefin.

II. **Hydroprocessing**

As for the production of AtJ, the stage is structured as the production process of HEFA. In this case, as the process is fed with farnesene (C$_{15}$H$_{24}$), the resulting isoparaffinic blend consists of farnesane (C$_{15}$H$_{32}$).

III. **Fractionation**

As for the AtJ, the gaseous and the liquid portions of the resulting isoparaffinic blend (farnesane in this case) are separated.

While these two last classes (AtJ and SIP) are still in early development, HEFA and F-T fuels have been operated as blending components in several demonstration flights and can count an increasing number of operating production plants. The Finnish company Neste Oil has a HEFA annual production of two millions tons, while the American Solena planned the development of eight plants, for an F-T fuel annual production of one million tons [6].
2.3 Objectives

The present contribution has been elaborated over two main objectives.

First, to evaluate the performances achieved through the innovative fuel atomization technique, based on the combined use of an atomizing air flow and multiple impinging fuel jets, as illustrated in section 1.2.

Because of the absence of a commercial component presenting the required geometrical configuration, an injector prototype has been designed and manufactured for the purpose. The characterization has been operated through the measurement of the resulting droplet size distribution over different conditions of air and fuel flow rates and over different numbers of fuel nozzles.

Second, but not of a lesser importance, the present work is aimed to assess the performances, in extent to the atomization process, of a selected AJF against the conventional JF.

The experimental activities have been operated under several constraints on the injector design, in terms of available production technologies (as illustrated in 3.2), as well as on the air and fuel feedlines, in terms of maximum achievable pressure and maximum measurable flow (4.2). As result, the designed atomiser presents a fuel nozzle diameter up to 10 times larger than the commercial counterparts, and still, coupled with the fuel feedline, generates a mass flow 10 times smaller. Moreover, the atomisation is led into an atmospheric pressure, a value 25÷35 times smaller than the actual value for aeronautic combustors: the process is therefore referred as operated in non-reactive conditions. Nevertheless, the results of the experimental activities are still of interest for the investigation over the actual operating conditions, if in the form of non-dimensional parameters as for example the AFR.
2.4 Thesis structure

The following chapter 2 presents the design of the injector prototype, along with a description of the rest of the experimental set and the experimental activities optical measurement instrument and the whole experimental setup. The chapter also introduces the selected fuel for the present work activities: a 50:50 mixture of green diesel and conventional jet fuel.

In chapter 2, the injector design is presented through its axial cross-section, as it allows to better describe both the air and fuel paths flowing within it, and then through the description of its three-dimensional development around the axis. The chapter also introduces the selected fuel for the present work activities (a 50:50 mixture of green diesel and conventional jet fuel), along with the optical instrument used for the characterization and the rest of the experimental setup. In its end, the chapter presents the experimental approach.

The results of the measurement are presented and discussed in the following chapter 3, in which the atomizer performances are compared in condition of different fuels, flows, geometrical configuration and alignment, with a focus on the conditions presenting the greater combined effect between the two atomizing techniques. The resulting main conclusions are presented in the following thesis closure, along with an overview over the future work.
3 Materials and methods

3.1 Atomizer design

The main objective of the present work is to investigate the performances related to the combined use of the air assisted and multiple jet impingement atomisation strategies, in order to evaluate its fitness with the avionic engine. The technique consists of the introduction of an high speed air stream towards the impingement point of two or more liquid jets, in order to increase the atomisation of the liquid phase as it approaches the centre and collide.

The cross section of the injector design, in extent to the $N_J = 2$ configuration, is illustrated in Figure 2.1. The injector is composed of a superior part, referred as injector tail (A), and an inferior part, referred as injector head (B). The two parts are connected on an horizontal surface, referred as connection surface (C), through the use of six bolted joints (D).

The injector tail is the vertical segment through which the fuel and the air flow from the connections with the respective feedlines (E and F) to the connection with the injector head, which holds the atomiser. The fuel and the air nozzles (G and J) are designed as separated components, connected to the injector head as screws in the respective threaded holes, referred as nozzle blocks (I and K). The use of interchangeable nozzles allow the use of the same injector head for the experimental characterisation of different atomiser configurations, in terms of nozzle diameter and length, as well as in terms of nozzle number, as better illustrated further in this section.
Figure 3.1 - Cross section of the designed injector
The fuel path through the injector is composed of three distinct stages, as the flows assumes a vertical, horizontal and angled motion towards the impingement point H. In the first stage, the fuel flows within the injector tail from the connection with the feedline to the connection with the injector head.

The injector tail consists of two concentric tubes, which define the axial channels of both the air flow (within the internal tube) and the fuel flow (between the internal and external tubes). The width of the fuel axial channel has been set to the value of 2 mm, as this value allows a resulting flow a laminar Re, and therefore limit the pressure drops through the path the nozzle. The injector tail has been designed with a length of 500 mm, in order to ensure the symmetrical development of the flow, and therefore compensate the flow misalignment on the feedline connection.

In the second stage, the fuel path develops from the inner to the external region of the injector head. As the flow reaches the end of the axial channel, it branches into two radial channels (one for each nozzle block), which are carved into the injector head connection surface. As for the axial channel, the width of 2 mm guarantees a correct development of the flow within the section. The fuel leakage through the connection plane, directed towards both the external atmosphere and the internal air path, is avoided through the use of an internal (L) and an external (M) large O-rings.

In the third and final stage, the flow is directed from the external end of the radial channel to the impingement point with a fixed impingement angle of 45°. The fuel flows, in the order, through the smooth section of the nozzle channel (which gentles the fuel acceleration), through the nozzle and through the impingement distance.

The nozzle internal diameter has been set to the value of 0.5 mm, the smallest achievable value in extent to the available conventional technologies for the realisation of the components, as illustrated. The nozzle length has been designed as 46 mm long, in order the secure the full development of the flow as it approaches to the nozzle end. Also in

Figure 3.2 - Detail of the atomizer geometry
this case, the fuel leakage through the nozzle thread is avoided through the use of an O-ring between the nozzle screw head and the injector head (P).

The air path consists of a vertical descent through the injector tail from the feed line connection to the nozzle. The whole channel consists presents a diameter of 10 mm, while the nozzle presents a diameter of 1 mm for a length of 10 mm. On the nozzle end, which is set on an impingement distance of 10 mm, the flow assumes a conical shape, and surrounds the impingement point in a manner that depends on the flow rate of atomising air. As the fuel nozzle, the air nozzle is shaped as a screw, and, as for the fuel line, the air line (which is in pressure) is sealed through the use of an O-Ring between the screw head and the injector head (Q).

The nozzles have been designed as separated components in order to avoid the burden, in terms of costs and time, related to the production of more injector heads (one for each required number of fuel nozzles). The design of the fuel path is extended around the axis to a total of 12 nozzle blocks and radial channels, as illustrated in Figure 2.3. In accordance to the required configuration, each nozzle block is coupled with either a fuel nozzle or a screw of the same size, which in this second case blocks the flow on the corresponding radial channel. The channels are set as 12 in order to allow the use of two, three and four nozzles in conditions of stable and axisymmetric flow.

Even though the permanent connection between the injector head and the injector tail would have simplified the design, the use of the bolted joint have been preferred as it allows the future use of alternative injector heads presenting a different configuration, as, for example, a different impingement angle.
Figure 3.3 - The designed injector head
3.1.1 Manufacture and alignment

The prototype of the designed injector has been manufactured in stainless steel, in order to avoid the corrosion due to the use of fuel. Both the injector head and the injector tail bottom connection - AISI 304 - are shaped through turning. The radial channels and the nozzle blocks are carved in the injector head through further machining processes. The concentric tubes - AISI 316L - are welded with each other and with the feedline connections on top, with the bottom connection on the bottom.

The fuel nozzle consists of a M7 standard screw, with a through hole of 2 mm of diameter along its axis, which is filled and bonded with two concentric capillary tubes, one inside the other. The use of two tubes instead of one covers the gap between the external diameter of the required inner tube (1 mm) and the minimum hole diameter achievable in the screw with the available production technologies (2 mm). The air nozzle consists of a M22 screw, also presenting a through hole along its axis. The through hole presents a diameter of 10 mm within the screw thread, and a smaller diameter of 2 mm within the screw head, which it is bonded with the capillary tube.

The subtractive manufacturing technologies did not allow the perfect alignment of the nozzle blocks. The correct condition of impingement has been achieved with a manual alignment of the assembled nozzles, through a slight plastic bending over the exposed portion of the capillary tube. On the other hand, the inconvenience opened the door over the investigations in conditions of nozzle misalignment, which allow a direct quantification of the effect of the jet impact, as illustrated in chapter 5.
Figure 3.4 - Cross section of the fuel (on top) and air (on bottom) nozzles
3.2 Alternative jet fuel selection

This section introduces the Alternative Jet Fuel - AJF - used within the experimental activities.

The standard specification ASTM D7566 is an extension of D1655 towards alternative fuels. The European DEF STAN 91-91 has no extension, and also refers to D7566 as specification for alternative fuels.

The specification introduces the limitations for the alternative blending components (which depend on their nature), along with further limitations for the AJF (which it has to meet along with the requirements of the conventional D1655). It also defines the maximum blending ratio allowed: 50% for the affirmed HEFA and F-T technologies, 30% for AtJ and 10% for SIP.

The Finnish company Neste Oil provided 200 liters of HEFA, which have been used as alternative blending component for the present work experimental activities. The fuel is known under the commercial name of NEXBTL (Next Generation Biomass-to-Liquid) or just Neste Renewable Diesel.

As the last name suggests, the fuel has not been designed as an aviation blending component, but as a 100% compatible diesel fuel. Its production process is operated as described in 2.2.1, besides missing the selective hydrocracking stage. This fraction of the HEFA production chain is commonly referred as green diesel.

As a matter of fact, the whole global HEFA productive capacity is focused on green diesel, which is able to better compete, in terms of economical margin, with the conventional refined fuel. As consequence, the use of HEFA technologies for the production of aviation blending components shows a reduced interest.

Nevertheless, despite the absence of the cracking stage within its production process, the fuel still presents compatible properties for blending with conventional jet fuel as alternative blending component. The ASTM is in fact evaluating to extend towards it the standard specification for alternative jet fuels [6].

This decision led to several demonstration flights during the last decade: the NEXBTL fuel itself has been tested with success in December 2014 as a 15% blending component on a Boeing 787 flight, within the Boeing ecoDemonstrator program.

For these reasons, NEXBTL has been chosen as alternative blending component for the present work, as a 50% blend with conventional Jet-A fuel. The experimental activities, as described in chapter 5, have been operated also on plain conventional
JF (100\%)}, in order to compare the performances of the conventional fuel with the performance of the innovative blend, which has been set on the maximum blending ratio in order to further emphasize their differences.
The table presents the properties of both the conventional and alternative blending components are presented in table. The knowledge of the properties of the two blending components allows the calculation of just some of the AJF properties. The values of the other properties remain unknown, and have been assumed as the mean
values of the two blending components, in extent, for example, of the calculation of
the fuels Ohnesorge number, as illustrated in chapter 5.

The first two columns on the right present the requirement for both the AJF (D1655
and D7566) and the requirements for the alternative blending component, which in
the case of HVO refers to the second appendix of the alternative fuels standard
specification for alternative fuels: D7566_A2.
3.3 **Droplet size distribution measurements and imaging**

The main aim of the atomization process is to increase the specific surface of the liquid phase, in order to achieve high evaporation rates. In practice, the process results in a range of droplet sizes, spanning from the µm to the mm, depending on the atomizer and on the properties of the liquid phase.

The performances of the designed injector and the selected fuels are investigated through the measurement of the distribution of the droplet size. The characterisation is operated with the Malvern Particle Sizer 2600, a commercial instrument operating an optical technique based on the Fraunhofer diffraction of monochromatic light. The experiments are conducted with different conditions, in terms of injector head configuration and position, and in terms of involved fuel and air flows. The results of the different measurements are compared on their distribution mean value, variance and quantiles.

The atomisation mechanism in the proximities of the impingement point has also been evaluated through photographic imaging, as the development of this region affects the development of the whole atomising jet, included the sample region for the size distribution characterization.

The pictures have been taken with a Phantom V4.2 HSC high speed camera. The optical whatever has been set on the minimum value ($10^{-6}$ s), in order to capture the development of the separating ligaments and droplet in high definition, no matter their speed.
3.3.1 Optical technique

The Malvern Particle Sizer 2600 is composed of an optical measurement unit and a connected computer. The optical measurement unit collects the sample data, and provides it to the computer in the form of 16 averaged values. On these values, the computer develops a mathematical model, which is then used to calculate the statistical parameters of interest for the spray characterisation.

The models of common use for these applications are based on either statistical or empirical consideration. The use of the model allows the experimental approach to produce significant results on a small number of measurements.

Optical measurement unit

The optical measurement unit is composed of a transmitter and a receiver. These two parts are aligned in front of each other on the horizontal axis Z, also referred as beam axis.

The transmitter consists of a low power He-Ne laser emitter and the associated optics. The emitter develops a 10 mW Gaussian beam - TEM$_{00}$ - on a wavelength of 0.6328 µm. The optical lens expands its cross section diameter to 9 mm.

The receiver consists of a detector set and the associated optics. The set is composed of 30 concentric semiannular detectors - here referred as 15 concentric annular detectors for the sake of convenience - and an additional central detector.
The sample is defined as the interception between the beam and the crossed atomising jet, which is set between the aligned transmitter and receiver. The presence of its particles impose a light diffraction on a fraction of the crossing beam, which is deflected over the 15 annular elements of the detector set. The size of the particle defines the diffraction angle, and therefore the coupled detector: small droplets impose wide deflections towards the external rings, large droplets result in narrow angles towards the elements closer to the centre. Instead, the unscattered fraction of the beam couples the central detector, and allows the instrument to estimate the sample concentration, Figure 3.5.

The instrument has a single line of sight over the sample particles, which are therefore assumed as spherical. As the optical technique is based on the Fraunhofer diffraction, the particle optical properties do not affect the measure. The deflection is imposed over the light around the droplet external surface, while the light coupling on the droplet is assumed as absorbed. These assumptions result appropriate for droplet diameters over 2 μm.

The particle position within the sample and its motion also have no influence over the measure, as the convergence of light from the receiver optics to the detector set depends on the droplet imposed diffraction angle - and so just on its size - in almost all the practical cases.

Figure 3.6 - Non-scaled schematic representation of the instrument principle of operation
The particle size range associated to the 15 external rings depends on the focal length of the receiver associated focal lens - or range lens - which operates as an optical Fourier transform. All the present work experiments have been operated with a range lens presenting a focal length of 300 mm, and are therefore referred to a total size range from 5.8 to 564 µm. The 15 size ranges are equispaced on a logarithmic 10 base between these two values, and thus provide to the instrument a higher resolution on the small diameters.

The instrument is not able to detect particles with a diameter outside the total size range, either under or over. As a correct measure requires the detection of the whole sample, the choice of the focal lens requires a trade off between the measurement resolution and full scale. In these terms, the choice of the 300 mm lens has been confirmed as adequate through the first operated characterizations.

In a single measure, and for all of the 15+1 detectors, the instrument collects 1000 detections, or sweeps, for a time of 10 µs each. The averaged values allow the instrument software to develop a mathematical model for the size distribution within an adequate statistical significance.
**Mathematical model and results calculation**

The Malvern associated software collects from the receiver the 15+1 averaged values, still in the form of a discrete distribution of light energy over the detector set elements. The value from the central element is defined as the sample Obscuration:

\[
\text{Obs} = 1 - \frac{\text{UNSCATTERED ENERGY}}{\text{EMITTED ENERGY}} \quad [\%]
\]

The other 15 values - here referred as measured data \(M_1 \div M_{15}\) (FIG. 8 A) - are used to develop a normalized mathematical model of the sample volume distribution, in accordance with the introduced principle of operation of the optical technique. The model is the result of an iterative process set to minimize the Logarithmic Error, or residual difference, between the measured data \(M_1 \div M_{15}\) and the corresponding calculated values \(C_1 \div C_{15}\) (FIG. 8 B):

\[
\text{LE} = \log_{10} \sum_{i=1}^{15} (M_i - C_i)^2
\]

The two main options for the characterization of an atomizing jet are the independent and the Rosin-Rammler models.

The development of the independent model is operated without assumptions over the shape of the distribution. The \(M_1 \div M_{15}\) values are used to define the volume distribution through 15 equation on 15 parameters.

In the development of the Rosin-Rammler model, the volume distribution is constrained to be shaped as a Rosin-Rammler distribution, and is therefore defined through the two parameters - \(X\) and \(N\) - allowing the best fitness to the measured data.

The Rosin-Rammler distribution presents higher LE values than the independent model, as the constraint on the distribution shape affects the model fitness. On the other hand, the reduction to a couple of parameters instead of 15 eases the comparison between the results of different samples, as their distributions result defined with the same shape.

Furthermore, the models on two parameters allows an empirical correction for high Obs values, in order to compensate the influence of multiple scattering on the measure. The phenomenon of multiple scattering occurs when a fraction of the beam undergoes the diffraction of more than a single droplet. It results in a wider
volume distribution and a general underestimation of the droplet size. The whole experimental approach is aimed to avoid high obscuration, as in practice the correction is just required for values over 50%, but within some experimental conditions this has not been possible. The correction model uses the Obs value, along with 12 empirical coefficients, to correct the estimated N and X parameters.

For these reasons, the Rosin-Rammler model has been chosen and used for the present work over its unconstrained counterpart for the calculation of the statistical results. The model fitness has been monitored through the defined LE, considered adequate for values under 5.

The X [µm] and N [ - ] parameters define the normalised volume undersize \( U(D) \) as function of the droplet diameter \( D \) (FIG. 4.2 C):

\[
U(D) = 1 - e^{-\left(\frac{D}{X}\right)^N} \quad \left[ \frac{\mu m^3}{\mu m^3 T} \right]
\]

The calculated distribution, defined for all positive diameters \( D \geq 0 \), is then reduced - and normalized again - to the instrument total size range from 5.80 µm to 564 µm, plus an additional undersize range defined from 1.50 µm to 5.80 µm:

\[
U_R(D) = \frac{e^{-\left(\frac{1.50}{X}\right)^N} - e^{-\left(\frac{D}{X}\right)^N}}{e^{-\left(\frac{1.50}{X}\right)^N} - e^{-\left(\frac{564}{X}\right)^N}} \quad \left[ \frac{\mu m^3}{\mu m^3 T} \right]
\]

The use of the reduced formulation implies the assumption that the total sample volume lies within the extended size range. The extension towards the undersize allows the software to estimate the sample portion of volume between 1.50 µm and 5.80 µm, even though the particles under 5.80 µm are invisible to the instrument optical measurement unit.

The inverse function defines the distribution quantiles, or derived diameters:
The $Q_{50\%}$ quantile is the diameter under which lies half of the sample detected volume. It is, along with $Q_{10\%}$ and $Q_{90\%}$, one of the main statistical parameters for the characterization of the distribution.

In these terms, the $X$ parameter of the Rosin-Rammler distribution can also be considered as a derived diameter, as it corresponds (within the extended size range) to the $Q_{63.66\%}$ quantile:

$$U_R(X) = \frac{e^{-\left(\frac{1.50}{X}\right)^N} - e^{-\left(\frac{X}{X}\right)^N}}{e^{-\left(\frac{1.50}{X}\right)^N} - e^{-\left(\frac{564}{X}\right)^N}} = 63.66\%$$

Among all the possible definitions for the distribution mean value, the Sauter Mean Diameter is the more appropriate for the characterization of an atomizing jet, as its value provides an indication over the sample evaporation process.

The time required for the evaporation of the sample is related to its particles mass and external surface. The total mass - or volume $V_T$ - is proportional to the total required heat, and therefore to the required time. Instead, the total external surface $S_T$ corresponds to the exchange area for the heat transfer, and presents an inverse proportionality to the evaporation time. The Sauter Mean Diameter - SMD - is defined as six times the dimensional ratio between the sample volume and surface, and its value affects the atomization time and therefore the promptness of whole combustion process.

The formulation of the SMD value undergoes the definition of the sample distributions, in terms of volume $V(D)$ and droplet number $Y(D)$:
\[ V(D) = \frac{dU_R(D)}{dD} \]
\[ = N \cdot \frac{D^{N-1}}{X^N} \cdot \frac{e^{-\frac{D}{X}}^N}{e^{-\frac{1.50}{X}}^N - e^{-\frac{564}{X}}^N} \quad \left[ \frac{\mu m^2}{\mu m^3} \right] \]

\[ Y(D) = \frac{6 \cdot V(D)}{\pi \cdot D^3} \quad \left[ \frac{\mu m^{-1}}{\mu m^3} \right] \]

\[ \text{SMD} = 6 \cdot \frac{V_T}{S_T} = 6 \cdot \frac{\int_{1.50}^{564} Y(D) \cdot \frac{\pi \cdot D^3}{6} \cdot dD}{\int_{1.50}^{564} Y(D) \cdot \pi \cdot D^2 \cdot dD} = \frac{\int_{1.50}^{564} V(D) \cdot dD}{\int_{1.50}^{564} V(D) \cdot D \cdot dD} \]

\[ = \frac{1}{\int_{1.50}^{564} \frac{V(D)}{D} \cdot dD} \quad [\mu m] \]

As it is not possible to solve the denominator integral, the SMD calculation requires the conversion of the continuous distribution into discrete.

The extended size range is divided in 32 new size ranges. The first size range is set between \( D_0 = 1.50 \mu m \) and \( D_1 = 5.80 \mu m \), while the other 31 size ranges are equispaced - again on logarithmic 10 basis - between \( D_1 = 5.80 \mu m \) and \( D_{32} = 564 \mu m \). The discrete distribution is defined as the relative volume contents for each of the \( i = 32 \) size ranges (FIG. 8 D):

\[ W_i = \frac{e^{-\frac{(D_{i-1})}{X}}^N - e^{-\frac{(D_i)}{X}}^N}{e^{-\frac{(D_0)}{X}}^N - e^{-\frac{(D_{32})}{X}}^N} \quad \left[ \frac{\mu m^3}{\mu m^3_T} \right] \]
The SMD over the discrete distribution is defined as:

\[
\text{SMD} = \frac{\sum_{i=1}^{32} Wi}{\sum_{i=1}^{32} \frac{Wi}{Gi}} = \frac{1}{\sum_{i=1}^{32} \frac{Wi}{Gi}} \quad [\mu\text{m}]
\]

Where \( Gi \) is the geometrical mean diameter of the size band, equal to the square root of the product of the size boundaries:

\[
Gi = \sqrt[2]{Di_{i-1} \cdot Di} \quad [\mu\text{m}]
\]

The sample variance - \( \sigma^2 \) - around the mean value is defined as:

\[
\sigma^2 = \frac{\sum_{i=1}^{32} (Gi - \text{SMD})^2 \cdot \frac{Wi}{Gi}}{\sum_{i=1}^{32} Wi} = \sum_{i=1}^{32} (Gi - \text{SMD})^2 \cdot \frac{Wi}{Gi} \quad [\mu\text{m}^2]
\]
Figure 3.7 A - Discrete distribution of the normalised measured data [%] over the 15 detector rings

Figure 2.6 B - Discrete undersize cumulative of the normalised measured data [%] over the 15 detector rings and relative size ranges [µm]

The Rosin-Rammler distribution presenting the minimum residual difference with the measured data, reduced from 5.80 to 564 µm
Figure 2.6 C - The Rosin-Rammler distribution presenting the minimum residual difference with the measured data, reduced from 1.50 to 564 µm
Discrete undersize volume cumulative of the calculated values [%] over the 32 size ranges defined from 1.50 to 564 µm

Figure 2.4 D - Discrete distribution of the calculated relative volume contents [%] over the 32 size ranges, defined from 1.50 to 564 µm
3.4 Experimental setup

The injector is constrained to the vertical position, with the injector head - air (A) and fuel (B) nozzles - on the bottom and the connections to the air (C) and fuel (D) feedlines on the top.

The air feedline is defined from the pressurized air line (E) to the connection on the injector end (C). The atomizing air is collected from the air line at 7.5 bar. A pressure regulator (F) reduces the pressure to a lower value of 2.5 bar, which is the maximum value the following rotameter (G) can stand. In these conditions, the line develops a flow through the air orifice (A) up to 0.6 g/s.

The fuel feedline is defined from the pressure vessel (I) to the connection on the injector end (B). The fuel is loaded in the vessel on atmospheric pressure. The vessel is then pressurised through the connection with a high pressure bottle of gaseous nitrogen (J). A pressure regulator (K) set between the two reduces the pressure from the bottle value of 200 bar to the vessel value of 3.2 bar. The fuel flow rate is controlled with a rotameter (L) set between the vessel and in the end of the feedline, where an additional ball valve (M) allows a prompt closure and therefore reduces the fuel consumption.
The vessel pressure has been set to 3.2 bar, as this value, coupled with injector head configuration presenting the higher losses ($N_J = 2$), allows the fuel flow rate to reach the rotameter full scale, or the maximum measurable value, of 5.90 g/s.

Figure 3.8 - Experimental setup
The injector is not constrained to a fixed position towards the optical measurement unit. Its axis is constrained as vertical, and is therefore orthogonal, either coplanar or not, to the horizontal beam axis. In these conditions, the injector position is identified with the position of the geometrical impingement point H, plus the misalignment of the fuel nozzles with the beam axis.

The origin (O) of the coordinate system is set on the centre of the receiver focal lens. The vertical axis is defined as X. The beam axis is defined as Z. The other horizontal axis, orthogonal to both X and Z, is defined as Y.

As the detector line of sight is limited to the X-Y plane, the position of the injector on the beam axis - HZ - does not affect the measurement. On a practical point of view, the sample has to be placed far enough from the origin in order to avoid contact with the focal lens, but still within HZ = 400 mm, in order to avoid optical vignetting error. The HZ value has been set to 300 mm for all the experimental activities.

The T angle between the fuel nozzles and the beam axis is defined on the Y-Z plane. As NJ nozzles are set on the injector head, T is defined as the minimum of the angles, and can therefore span from 0° to 180°/NJ.

The sample position (HX, HY and T), along with the configuration of the injector head (NJ) and the fuel and air mass flows (m_F and m_A) define the conditions of the experiments.

The performances of the designed injector and the selected fuels are investigated through three sets of experiments on these seven degrees of freedom, as described more in detail in the next chapter.

Figure 10 - The four spatial coordinates (HX, HY, HZ and T) define the relative position between H and O.
3.5 Procedures

The experimental activities have been operated over two main sets of experiments.

The aim of the first set of experiments is to locate the injector coordinates (HX, HY and T) presenting the lowest value of SMD, as the prompt atomization of this region affects in a greater extent the whole combustion process. In this first set, the experiments are led with the AJF only, and involve constant values of fuel and air flows.

The second set of experiments, instead, is operated on fixed injector coordinates (the coordinates identified in the previous set), and allows the investigation of the process over different values of fuel and air flows (\(\dot{m}_A\) and \(\dot{m}_F\)). The aim of the set is to recognize the atomisation mechanisms and locate the range of conditions providing either the best atomisation or the most efficient conversion of the air flow momentum. As in the first set, the experiments are led for the three different atomizer configurations NJ. Within the second set, the experimental conditions are also investigated for the JF, and, for both fuels, in conditions of misaligned fuel nozzles, in order to evaluate through their comparison the effect of the alignment on the atomization.
3.5.1 Spatial assessment

The whole experimental set has been operated on the same atomizing air flow rate, $\dot{m}_A = 0.3630$ g/s, while the flow rates have been settled as:

- $\dot{m}_F = 1.54$ g/s for $NJ = 2$.
- $\dot{m}_F = 2.47$ g/s for $NJ = 3$
- $\dot{m}_F = 3.40$ g/s for $NJ = 4$

The fuel flow rates have been set as the maximum values operated in the subsequent second experimental set. Even though the aim of the first experimental set is to locate the injector coordinates presenting the best atomisation, it also is important to monitor the sample obscuration, as it results in multiple scatter error on its higher values. For this reason, the first experimental set has been operated on the maximum flow values of the second experimental set, as on these values the obscuration is highest. In these conditions, the choice of injector coordinates with an acceptable obscuration guarantees the significance of the measurements for the subsequent experimental activities.

The $T$ value has been set on either $0^\circ$, $45^\circ$ or $90^\circ$ for $NJ = 2$, $0^\circ$ or $45^\circ$ for $NJ = 3$ and $NJ = 4$.

The $HX$ value has been set on six different values: $[+5; +20; +40; +60; +80; +100]$ mm.

The $HY$ value has been set on up to seven different values: $[-15; -10; -5; 0; +5; +10; +15]$ mm, depending on the $HX$ value.

The measurements identified $T=0^\circ$ for $NJ = 2$ and $T=45^\circ$ for $NJ = 3$ and $4$ as the $T$ values resulting in the clearer measurement, in accordance to the development of the liquid sheet structures observed in airless conditions and the resulting non-axisymmetric liquid concentration. The second set of experimental activities has therefore been operated on these values.

All the measurements identified the axial region as the region presenting the smaller SMD values. On a greater radial distance from the axis, the measured SMD presents higher values, which increase in different manner depending on both $NJ$, $T$ and $HX$. The coordinate has been constrained to the identified value $HY = 0$ for the entire subsequent experimental set.
On the axial coordinate, instead, the SMD results in high values of SMD for HX = 5, as over this small distance the spray is still in its initial stage of development. The smallest values of SMD are reached on HX = 20 in all conditions.

For further increased values of HX, the atomization results worsen, as a the smaller particles present in the sample evaporate (and are therefore not counted), and as the small droplets are more suitable to coalescence in droplets of greater size. The random nature of the process allows some exceptions, as for example for the good grade of atomisation achieved for HX = 100 in NJ = 2.

Even though the HX = 20 mm value presented a general better atomisation, the final choice for the subsequent experimental set has been directed to the HX = 100 mm value, in order to guarantee the significance of the measurement in NJ = 4 configuration, which would otherwise present high obscuration values.
Table 3.2: Spatial assessment.

For each atomizer configuration NJ, the selected coordinates for the second set of experiments are underlined.
3.5.2 Characterization

The characterization of the spray has been operated for both fuels, for the three atomiser configurations and in conditions of both aligned and misaligned nozzles.

In conditions of nozzle misalignment, the direction of the liquid columns is translated on the horizontal plane, in order to avoid their impingement. The applied misalignment is the minimal required for avoid the impact, in the attempt to isolate the effects of the collision with the smallest modification of the geometrical configuration. The interaction between the different liquid columns is present also in misaligned conditions, as further explained in the next chapter.

Each injector head configuration have been investigated on three different values of fuel flow rate MF, and on six different values of air flow rate MA, as described in Table and Table.

Table 3 - The used total mass flow operated for each of the atomizer configurations, along with the mass flow through the single nozzle MF

<table>
<thead>
<tr>
<th>N_i</th>
<th>( \dot{m}_f )</th>
<th>( \dot{m}_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.29 0.61 0.92</td>
<td>0.1788 0.2340 0.2750</td>
</tr>
<tr>
<td>3</td>
<td>0.15 0.20 0.46</td>
<td>0.3180 0.3630 0.4099</td>
</tr>
<tr>
<td>4</td>
<td>0.23 0.38 0.82</td>
<td>0.4357</td>
</tr>
</tbody>
</table>

Table 4 - The range of mass flows for both fuels and the resulting AFR

<table>
<thead>
<tr>
<th>AFR</th>
<th>( \dot{m}_f )</th>
<th>( \dot{m}_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>0.30 0.20 1.54</td>
<td>0.05 0.07 0.08</td>
</tr>
<tr>
<td>0.61</td>
<td>0.39 0.26 0.12</td>
<td>0.07 0.09 0.08</td>
</tr>
<tr>
<td>0.92</td>
<td>0.45 0.30 0.18</td>
<td>0.11 0.11 0.11</td>
</tr>
<tr>
<td>1.23</td>
<td>0.53 0.35 0.21</td>
<td>0.13 0.13 0.13</td>
</tr>
<tr>
<td>1.39</td>
<td>0.60 0.40 0.24</td>
<td>0.15 0.15 0.15</td>
</tr>
<tr>
<td>1.48</td>
<td>0.68 0.45 0.27</td>
<td>0.17 0.17 0.17</td>
</tr>
<tr>
<td>0.72</td>
<td>0.48 0.28 0.28</td>
<td>0.20 0.20 0.20</td>
</tr>
<tr>
<td>0.85</td>
<td>0.72 0.48 0.28</td>
<td>0.18 0.18 0.18</td>
</tr>
</tbody>
</table>
The conditions of lower MA have not been investigated in misaligned conditions in order to avoid the soiling of the receiver optics, as the defect of air results in an uncomplete fragmentation of the liquid columns, which proceed undisturbed on their misaligned direction. In these cases the characterisation has been extended to MA = 1.48 g/s, in order to keep a sufficient data size for the description of the behaviour in the specific conditions.

For the three values of MA = 0.18 ; 0.28 and 0.36 g/s,
4 Results and discussion

4.1 Misaligned conditions

As the fuel nozzles are misaligned, the liquid columns are not directed towards the geometrical impingement point.

The investigation over the conditions of fuel nozzles misalignment allows to evaluate, through the comparison with the aligned configuration, the effect of the direct impact of the liquid columns in conditions of excess of fuel and the importance of the alignment precision in conditions of excess of air. The misalignment does not erase the interaction between the liquid columns, as, in presence of the atomizing air streams the columns collide in the form of separating ligaments and droplets.

The atomisation presents a pneumatic behaviour, identified with the presence of two distinct regions in the $\dot{m}_A$-SMD diagram, figure 3.1. Within the inclined portion of the curve (AFR < 1, for the experimental conditions illustrated in figure), a slight increase of the air flow results in a significant improvement of the atomisation (a significant reduction of the SMD), in conditions also referred as in excess of fuel. In the settled/flat portion of the curve (AFR > 1), the air flow is in excess, and the introduction of further air results just in a slight improvement of the atomisation.

Over the whole set of experimental conditions, and therefore over different values of $\dot{m}_F$ and $N_J$, the atomization does not show a direct dependence on the AFR. Figure 3.2 presents, over an AFR-SMD diagram, the three sets of results for the $N_J = 2$ configuration, along with the minimum mass flows for both the $N_J = 3$ and 4 configurations. As the measurements do not align on a single curve, the characterization suggests the significance of both the atomizer geometrical configuration and the fuel mass flow over the atomization process.
Figure 4.1: AJF; Misaligned fuel nozzles
$N_J = 2; \ \dot{m}_F = 0.29 \ [g/s]$

Figure 4.2: AJF; Misaligned fuel nozzles
$N_J = 2; \ \dot{m}_F = 1.54, 0.92, 0.29 \ [g/s]$
$N_J = 3; \ \dot{m}_F = 0.61 \ [g/s]$
$N_J = 4; \ \dot{m}_F = 0.92 \ [g/s]$
The increase of the fuel mass flow has a slight effect on the overall atomisation, as it does not increase the encumbrance of the liquid columns within the vertical air stream of the liquid columns, which hold the same diameter (equal to the nozzle diameter $d_F = 0.5$ mm). The misalignment eases the clearance/disposal of the additional fuel, and avoids its concentration in the axial region, which would affect the downstream spatial development. Even though in a slight extent, the atomization results worsen, as the same amount of atomizing air is required to fragmentise a greater amount of fuel, Figure 3.3.

The increase of the number of jets over the same total fuel flow rate also presents a slight effect on the overall atomisation, Figure 3.4. The air stream atomizes the same amount of air, but results in a thinner atomisation with an inferior number of fuel nozzles, as it allows a more homogeneous development of the downstream region, and allows a more efficient conversion of the atomizing air stream momentum.

The same behaviour appears, in a greater extent, conditions of same $m_F$ over different $N_J$ has also been investigated for $m_F$. In this case, the difference between the two curves appears more marked, even though the behaviour of the $N_J = 3$ curve suggests the presence of a negative geometrical effect, as a consequence of the spatial development around the three misaligned liquid columns.
Figure 4.3 - AJF; Misaligned fuel nozzles

$N_J = 2$ ; $\dot{m}_F = 0.29, 0.92, 1.54$ [g/s]

Figure 4.4 - AJF; Misaligned fuel nozzles

$N_J = 2$ ; $\dot{m}_F = 1.54$ [g/s]

$N_J = 3$ ; $\dot{m}_F = 1.54$ [g/s]

$N_J = 4$ ; $\dot{m}_F = 1.54$ [g/s]
The measurements over different values of $\dot{m}_F$ for $N_j = 3$ and 4 show a similar behaviour, and also in these cases the use of greater fuel flows allow to reach a worse atomisation, which on the other hand requires a reduced AFR.

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**Figure 4.5** - AIF; Misaligned fuel nozzles
$N_j = 3$ ; $\dot{m}_F = 2.47 ; 1.54 ; 0.61$ [g/s]

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**Figure 4.6** - AIF; Misaligned fuel nozzles
$N_j = 4$ ; $\dot{m}_F = 3.40 ; 2.16 ; 1.54 ; 0.92$ [g/s]
4.2 Aligned conditions

As for the misaligned conditions, the atomisation presents a pneumatic behaviour. In conditions of excess of air, the aligned and the misaligned configurations result in similar values of SMD, as in these conditions the air stream is strong enough to disintegrate the liquid columns before their collision. The alignment still leads to a slight general improvement of the atomisation process, as it induces a more homogenous and axisymmetric development of the stream underneath the impingement point, which increases the effectiveness of the atomising air action.

In conditions of excess of fuel, the nozzle alignment affects the atomisation in a manner that depends on both \( N_J \) and \( \dot{m}_J \), as well as on the fuel properties. The three configurations are discussed as separated, and for both the present work fuels:

4.2.1 Two nozzles

For \( N_J = 2 \), the alignment results (in extent to the AFR < 1 conditions) in the formation of a liquid sheet, which presents a fishbone structure for the \( \dot{m}_F = 0.29 \text{ g/s} \), an open rim structure for \( \dot{m}_F = 0.92 \text{ g/s} \), and rimless structure with an almost ruffled surface for \( \dot{m}_F = 1.54 \text{ g/s} \). It is important to remark that, in presence of atomising air, the fuel does not present the same structures, as the air stream deflects the trajectories of the liquid columns. The actual impingement point is translated to a lower position than the geometrical one, and disappears as, for higher air stream intensities, the liquid column fragmentises before reaching the axis. Nevertheless, the shape assumed in airless conditions is assumed as an indicator for the disintegration mechanism.
The formation of the compact fishbone structure results, if compared with the misaligned conditions, in a slight increase of the atomisation. In conditions of intermediate $\dot{m}_l$, the liquid sheet assumes the shape of a narrow open rim, which allows a further better atomisation, and results in a significant difference with the misaligned conditions. As the value is further increased, the additional involved fuel tends to concentrate on the impingement point, as the liquid columns are directed towards each other, and the fuel disposal from the impingement point is not eased as in the misaligned conditions. The formation of the fuel concentration conceals the downstream section from the action of the air flow, and therefore worsens the atomisation on the axis (which includes the sample region). For these reasons, the higher value of $\dot{m}_F$ presents just a slight improvement in respect to the misaligned conditions. The intermediate value $\dot{m}_F = 0.92 \text{ g/s}$ allows the most efficient use of the liquid phase momentum.

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Figure 4.7 · AJF ; Aligned vs Misaligned fuel nozzles

$N_l = 4$ ; $\dot{m}_F = 3.40 ; 2.16 ; 1.54 ; 0.92 \text{ [g/s]}$
Figure 4.8: High speed pictures of the impingement point
AJF; Aligned fuel nozzles
NJ = 2
4.2.2 Three nozzles

For $N_J = 3$, the alignment results in a similar improvement for all three MJ values, as the three resulting stream shapes ease the atomisation in a similar measure. This configuration does not present cover phenomena, as if the impingement of three liquid columns results in a geometrical shape that eases the disposal of the excess fuel. Moreover, this configuration presents, if compared to the other configurations, a general higher improvement in respect to the misaligned conditions, even though, as mentioned, it appears due to the negative effect of the specific geometrical configuration in misaligned conditions, which leads to a less homogeneous development of the spray.

Figure 4.9: AJF; Aligned vs Misaligned fuel nozzles
$N_J = 3$; $\dot{m}_F = 2.47; 1.54; 0.61$ [g/s]
Figure 4.10 - High speed pictures of the impingement point
AJF ; Aligned fuel nozzles
NJ = 3
4.2.3 Four nozzles

The $N_J = 4$ configurations presents a similar behaviour to the configuration with two nozzles. On the minimum $\dot{m}_F$, the columns collision results in the formation of a compact vertical column. On the maximum $\dot{m}_F$, the impingement results in the formation and covering action of a fuel concentration. Both the evaluated intermediate values result in the formation of a ruffled three-dimensional sheet structure, which thin surfaces improve the atomisation process.
Figure 4.12 · High speed pictures of the impingement point
AJF ; Aligned fuel nozzles
Nj = 4
4.3 **Influence of the fuel properties**

The use of JF results, as for the misaligned conditions, in an improved atomisation, as the conventional fuel properties results more suitable for the process.

If compared with the atomization in misaligned conditions on the same fuel and for all the three atomizer configuration, the atomisation improves for the minimum values of $\dot{m}_F$, and presents conditions of fuel concentration and conceal for the maximum values. The JF properties increase the positive effect of the alignment, and lead, in conditions of excess air, to a SMD up to 5 µm smaller for $N_J = 2$ and 4, up to 10 µm smaller for $N_J = 3$.

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**Figure 4.13**: JF vs AJF; Aligned fuel nozzles

$N_J = 2$; $\dot{m}_F = 3.61$; 2.32; 1.67; 1.03 [g/s]

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Figure 4.14 - JF vs AJF; Aligned fuel nozzles

$N_j = 3; \bar{m}_F = 2.64; 1.67; 0.70 \text{ [g/s]}$

Figure 4.13 - JF vs AJF; Aligned fuel nozzles

$N_j = 4; \bar{m}_F = 3.61; 2.32; 1.67; 1.03 \text{ [g/s]}$
5 Closure

5.1 Conclusions

The atomization of an innovative alternative fuel for aeronautical applications has been evaluated through the measurement of its droplet size distribution. Moreover, the atomization has been operated with an innovative technique, consisting in the simultaneous atomizing action of an assisting air stream and of the multiple jet impact. A prototype has been designed and manufactured for the purpose.

The spray characterization has been operated through an optical imaging technique. Besides the measurements of the droplet size distribution, the activities also involved the use of a high speed camera in order to better investigate the relationship between the impact morphology around the impingement area and the resulting measured size distribution.

The measurements showed good results for the innovative technique for atomization, as it allows to reach thin SMD with low AFR values.

The conditions of excess of air do not present a strong dependence on the alignment, even though the greater precision results in an improvement, which is more marked for the JF than the AJF. In conditions of excess of fuel, the jet impingement can have an either positive or negative effect on the atomisation, as it develops in structures presenting an either greater or smaller resistance to the action of the atomising air stream. The use of the optimal fuel mass flow results in the maximisation of the synergic effect, as in these conditions allow the most efficient employment of the liquid phase momentum for the atomisation.

The experimental results show that the increase of the involved fuel worsens the atomisation, in greater extent if the increase is operated with the addition of further fuel nozzles. The use of a greater number of fuel nozzles results in a higher SMD, but allows the atomisation of a greater amount of fuel without the need of an intensification of the fuel pressure (and therefore of a heavier fuel pump).

The atomisation of AJF results in higher SMD values than the atomisation of JF. The different fuel properties result in a stronger resistance to the atomisation for both the pneumatic technique, for the multiple impingement technique and for their combined use.
5.2 **Future work**

An extension of the experimental activities towards the reactive conditions would allow a wider understanding of the overall effect of both the use of the synthetic hydrocarbon compounds and the innovative atomizing technique. It would allow to understand, for example, if the positive effect of the higher LHV of the alternative blending component can overcome the negative effect of their presence for the atomization.

Further experiments operated with different fuels, with different impingement angles and with different jet velocities (different nozzle diameters) could allow a wider understanding over the breakup phenomenon.