

Investigation of atomization and evaporation processes in the vaporizer of a microturbine: a CFD and experimental approach

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ABSTRACT

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The fuel spray and evaporation process in the vaporizer of a microturbine were studied using numerical simulations. The model's input parameters were calibrated based on experimental results obtained through high-speed imaging. The computational fluid dynamics model was applied under design point and idle conditions, using the Kelvin-Helmholtz Rayleigh-Taylor model to describe atomization and a pressure-based evaporation model. The simulation results showed that the Sauter mean diameter of the fuel droplets under idle conditions is approximately seven times larger than at the design point. The experiment served to validate the model and confirm the input parameters, enabling the identification of a fast and reliable calculation model for evaluating the vaporizer's performance. Experimental results confirm that the fuel droplets at the design point are smaller and atomize more rapidly than under idle conditions, thus improving the ignition capability of the microturbine, particularly during startup and low-power conditions.

1. INTRODUCTION

Microturbines have become an important area of research in aviation and military applications. These engines offer outstanding advantages such as lightweight construction, quick start-up capabilities, and low vibration characteristics, making them suitable for UAV applications, sport aircraft, and even self-launching gliders (Nascimento et al., 2013).

Although microturbines are primarily designed for model aircraft, they show significant potential for expansion into UAV applications, driven by technological advancements and the growing demand in these fields. The JETCAT P130RX (JetCat, 2024) was a prominent commercial small gas turbine engine, designed for high stability to meet the performance and reliability requirements of demanding applications. The

structural diagram and key parameters of this engine are shown in Fig. 1, which include specifications for rotational speed, compression ratio, thrust, and fuel consumption at various power levels.

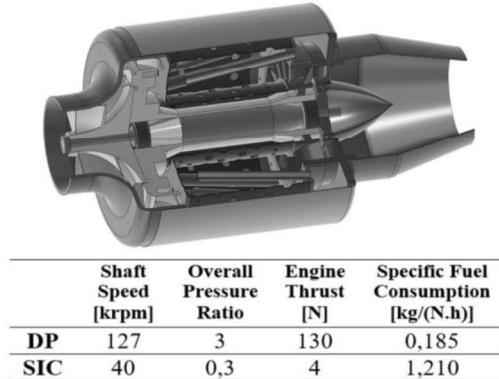


Fig. 1. The JETCAT P130RX microturbine

Microturbines consist of three main components: the compressor, turbine, and combustion chamber. Of these, only the compressor and turbine are directly scalable. The combustion chamber does not scale linearly with the engine diameter and needs to be specifically designed for low-pressure ratios. In smaller engines, the combustion chamber is typically larger than that of larger engines in order to achieve optimal combustion efficiency (Fuchs et al., 2016). However, this efficiency depends on the processes of evaporation, mixing, and fuel reaction, and is particularly sensitive to the residence time of the fuel-air mixture in the combustion chamber. These engines also encounter issues related to startup, including the inability to restart at high altitudes and poor combustion efficiency, primarily due to high flow speeds, small combustor volumes, and the vaporizer design. Therefore, optimizing the combustion chamber design, improving combustion efficiency, and enhancing the engine's startup capability under challenging conditions are key areas of current research.

There were two main methods for preparing liquid fuel for combustion: nozzles and vaporizer (Lefebvre & McDonell, 2017). Nozzles, including pressure, rotary, and air-assisted types, atomized the fuel into fine droplets. However, in microturbines, the vaporizer was the mandatory and irreplaceable method for fuel preparation, owing to the requirements for compact size and cost-effectiveness. In the vaporizer, the fuel-air mixture was injected into tubes immersed in the flame, where it was heated by the tube walls and exited the tube. Early designs of curved tubes experienced overheating issues, but this problem has been addressed by altering the tube shape and employing multi-point fuel injection along with swirl flow. Currently, straight, T-shaped, and L-shaped vaporizers (Lin et al., 2006) are still widely used in the market, with research indicating that the spray performance of all three types is comparable.

The spray breakup process is a complex multiphase interaction, characterized by random instability phenomena occurring at extremely small time and spatial scales (Benjamin et al., 2010). Simulation methods such as Euler-Lagrange (E-L), KIVA, Volume of Fluid (VOF), Level Set (LS), Large Eddy Simulation (LES), Eulerian Multifluid, and Interface-Tracking Methods (Burluka & Borghi, 2001; Hirt & Nichols, 1981; Luo et al., 2019; Taskinoglu & Bellan, 2010) have been employed to study this process. Industrial methods such as E-L, KIVA, and AtoMIST (Luo et al., 2025) are highly effective for large-scale simulations and practical applications, particularly in gas turbine and jet engines. In contrast, fundamental research methods like VOF, LS, LES, and Interface-Tracking Methods are commonly used to study

detailed spray processes and surface simulation, making them well-suited for basic research in unstable environments. However, there is still a lack of simulation models that are consistent with experimental data, particularly for accurately simulating the spray breakup process under real-world conditions.

The paper investigates the fuel spray and evaporation process in a microturbine using CFD simulations under design point (DP) and sub-idle (SIC) conditions. The simulation identifies key characteristics such as fuel spray, atomization, and evaporation, aiming to improve combustion efficiency and engine performance. An experimental system with an equivalent model of a vaporizer was designed to determine the input parameters for the model and validate the results, thereby ensuring the accuracy of the model and assessing engine performance under different operating conditions.

- **Microturbine vaporizing system**

Fuel injection:

In the vaporization systems of microturbines, fuel is injected into the vaporizer through a simple fuel injector, while air from the compressor exhaust flows axially along with the fuel. As the fuel disperses within the tube, it mixes with the air, and the fuel-air mixture exits from the opposite end of the vaporizer. The primary objective of the vaporizers is to vaporize the fuel before it enters the combustion zone, thereby improving combustion efficiency. However, only a small portion of the fuel inside the tube is vaporized initially, although the mixing efficiency is enhanced due to the dispersion of the fuel within the tube. A significant limitation of the vaporization system is its sensitivity to changes in operating

conditions. During startup, the low exhaust gas temperature reduces the effectiveness of heat transfer through the tube walls, impairing the vaporization process and negatively impacting combustion efficiency. Similarly, during rapid acceleration, the sudden injection of fuel can lower the tube temperature, slowing down the vaporization process and reducing combustion efficiency.

Fuel atomization:

The fuel atomization process converts the liquid fuel into small droplets, aiming to increase the surface area-to-volume ratio to enhance evaporation. This process occurs when instability develops at the interface between the liquid and gas phases, leading to the fragmentation of the liquid into small droplets. Atomization is divided into two stages: primary and secondary atomization, as shown in Fig. 2. Primary atomization is the disruption of the liquid phase caused by internal forces such as turbulence and inertia, primarily determined by the momentum flux ratio ($M_{A/L}$). As a result, the final volume of the liquid adopted a shape close to a sphere, maximizing the surface area-to-volume ratio.

$$M_{A/L} = \frac{\rho_A U_{ref,A}^2}{\rho_L U_{ref,L}^2} \quad (1)$$

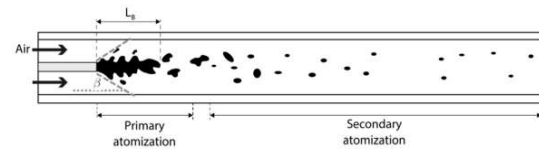


Fig. 2. Schematic representation of fuel atomisation inside a vaporizer

Secondary atomization occurs when aerodynamic forces directly act on the fuel droplets, causing larger droplets to break into smaller ones. The Weber number (We) is used to describe this process, representing the ratio

between aerodynamic forces and surface tension forces. With a high Weber number, secondary atomization dominates the atomization process, determining the final droplet size distribution. Parameters such as breakup length and spray angle also play an important role. An increase in spray angle enhances the breakup of the spray as the contact area with the air increases.

$$We = \frac{\rho U_{ref} l_{ref}}{\sigma} \quad (2)$$

Fuel vaporization:

The droplet evaporation process in a fuel spray involves both heat and mass transfer. Heat is transferred to the droplet through conduction and convection from the surrounding hot gas, while fuel vapor diffuses into the gas flow. Evaporation occurs when fuel molecules at the droplet surface escape and transition to the gas phase, forming a fuel vapor layer near the liquid interface. This process continues until the surrounding vapor becomes saturated, with no further changes in temperature or pressure. In the combustion chamber, the droplets are typically in an unstable evaporation state, with heat being used to warm the droplets. The rates of heat and mass transfer depend on the Reynolds number and the fuel's surface area, which contribute to improved evaporation efficiency.

2. MATERIALS AND METHODS

2.1 CFD simulation

2.1.1 Flow solver

In this study, numerical simulations were performed using the CFD software ANSYS Fluent 2021R1, employing the control volume method to solve the Navier-Stokes equations with Reynolds-Averaged Navier-Stokes (RANS) averaging. The turbulence was modeled using the k- ω SST model, combined with the k- ϵ model for

regions far from the wall and the Kelvin-Helmholtz Rayleigh-Taylor (KHRT) model for the fuel atomization process. The two-phase liquid-gas flow was simulated using the Euler-Lagrange method, where the gas phase is treated as the continuous phase and the dispersed phase is modeled using the Discrete Phase Model (DPM). An unstable DPM model was applied, assuming time independence for the two flow stages. The fuel droplets are assumed to be spherical in shape, with the diameter adjusted based on experimental results. Initial parameters such as injection position and spray cone angle were calibrated using both experimental and theoretical analyses. Finally, a pressure-based evaporation model was used to simulate the fuel vaporization process in the vaporizer.

2.1.2 Geometric configurations

In this study, two geometric configurations were simulated: (i) one configuration representing the vaporizer of the JETCAT P130RX, and (ii) another configuration representing 1/12 of the combustor of a JETCAT P130RX. The vaporizer configuration was analyzed as the main configuration. The computational domain focused on the interior of the microturbine vaporizer, including the fuel injector. The simulated fuel vaporization system is relatively simple, consisting of two concentric cylinders: a larger cylinder representing the vaporizer and a smaller cylinder at the tip of the larger cylinder, which functions as the fuel injector. This computational domain was used to analyze the atomization and evaporation processes occurring within the fuel vaporization system of the microturbine. The combustor configuration and related results were presented in a previous study, and in this work, these results

were used as input for the vaporizer simulation (Huu, & Xuan, 2025).

2.1.3 Mesh generation and boundary conditions

The grid generation for the geometric configurations in this study was performed using ANSYS Mesh software. All meshes used in the study are unstructured meshes, constructed from hexahedral elements. The grid was refined near the walls to ensure that the mesh distance requirements for the SST k- ω turbulence model were met at an acceptable level. A grid convergence analysis was also conducted by examining the solution's dependence on grid density. The vaporizer model with a grid of 1.8 million elements was selected for the calculations, with results confirming convergence. The key results from the simulations will be presented and discussed in the following section.

In the vaporizer simulation model, the boundary conditions of 'velocity inlet' and 'pressure outlet' are set at the inlet and outlet (Fig. 3). The temperature and pressure at the system's inlet and outlet are assumed to correspond to those of the combustor, with a temperature increase of 407 K at the inlet to simulate the heat transfer process. The input parameters for the vaporizer model are derived from the combustion chamber simulation results, as shown in Table 1. The vaporizer wall is not modeled in detail, and it is assumed that the wall thickness does not significantly affect the results, with a temperature assumption of 2000 K. The walls in the simulation are considered reflective, and no sensitivity analysis is performed.

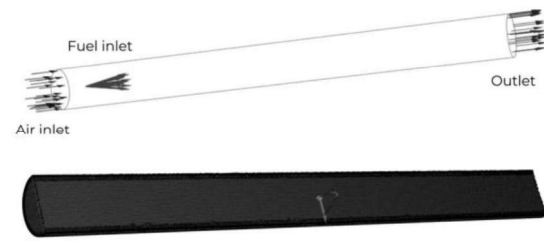


Fig. 3. Boundary conditions and mesh model of the vaporizer

Table 1. Fuel and air injection parameters

Parameters	DP	SIC
$m_f (kg.s^{-1})$	0.000496	0.000113
$U_f (m.s^{-1})$	9.847	1.355
Re_f	1723.0	234.5
Oh_f	0.0188	0.0188
$m_A (kg.s^{-1})$	0.003	0.000467
$U_A (kg.s^{-1})$	63.73	21.27
Re_A	3,149	6,942

2.2 Experimental method

The experimental system for studying multiphase flowed in the vaporizer of a microturbine consists of four main components: the gas system, the liquid system, the burner, and the imaging system. The overall schematic of the system is shown in Fig. 4. The burner was designed to simulate the working conditions of the vaporizer tube in the Jetcat P130RX engine, comprising eight main components, with a standardized injector and parts made of copper to ensure stability. The burner configuration followed the Sydney model, featuring a 7:1 conical ratio to ensure undisturbed airflow. The vaporizer tube was replaced by a heat-resistant quartz tube to observe the spray breakup, evaporation, and mixing processes. The gas system used a small compressor to supply stable airflow, with the gas temperature controlled between 120°C and 200°C. The liquid system delivered the liquid through an electric pump,

with the pressure before the injector being monitored. The imaging system employed the high-speed Photon Fastcam AX100 camera to capture shadowgraphy images, enabling the analysis of spray characteristics.

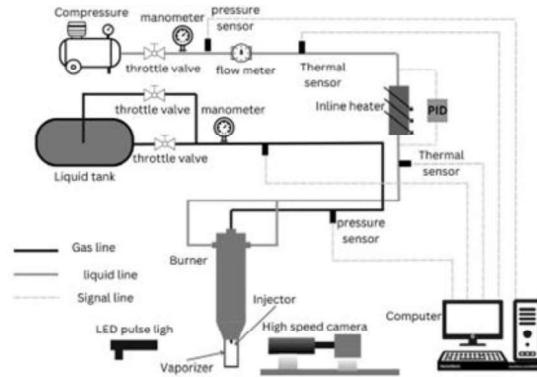


Fig. 4. Schematic of the experimental system

The experimental operating parameters, included temperature, pressure, and flow rates of both the gas and liquid, were defined based on the simulation results of configuration 1. These parameters were crucial for accurately replicating the actual operating conditions of the engine at design point (DP) and sub-idle (SIC) states. By adjusting these parameters, the experimental system ensured that the simulation accurately reflects the specific conditions of spray breakup and fuel evaporation, thereby providing critical data for the analysis and optimization of the microturbine's performance.

The post-processing image processing procedure plays a crucial role in this experimental system, utilizing tools such as the OpenCV library to analyze high-speed images. The process begins with preprocessing, which helps standardize and reduce noise, while efficiently segmenting and extracting data. Image cropping methods were employed to minimize the effects of refraction, focusing on the features of the spray and liquid droplets. Image segmentation allows for accurate measurement of breakup length and

droplet size. The results were compiled and displayed through distribution charts, supporting research and simulations. The entire process was evaluated through error checks and analysis of multiple images, ensuring the reliability of the results.

3. RESULTS AND DISCUSSION

3.1 Experimental results

The experiment in this study was conducted to determine the input parameters for the DPM model in the simulation, while also calibrating the model to ensure that the simulation results closely match real-world conditions. Three frames were employed to identify the characteristics of the breakup process. Frame 1 was used to determine the breakup length (L_B), while Frame 2 was utilized to assess the droplet size distribution at the outlet of the vaporizer. The positions of the frames are shown in Fig. 5.

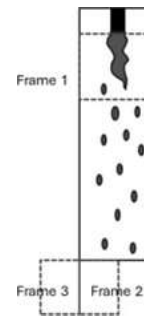


Fig. 5. Frame capture positions for determining the characteristics of the vaporizer

Fig. 6 illustrates the progression of spray breakup in Frame 1. The image shows the oscillatory breakup of liquid clusters under the influence of the gas flow, with the breakup position fluctuating over time. Through image processing, object segmentation, and core liquid length measurement, the breakup length is determined and listed for each mode, as presented in Table 2. The angle β cannot be determined

using the imaging method, as the boundary between primary and secondary breakup is unclear. The value of this angle is referenced from previous studies (Lasheras & Hopfinger, 2000).

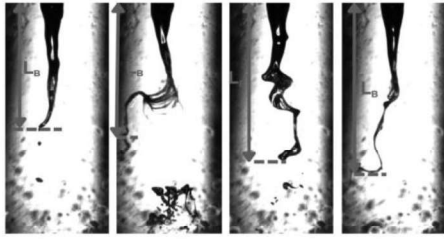


Fig. 6. Spray progression image

Table 2. Characteristic fuel injection parameters

Parameter	DP	SIC
L	6.7	3.6
β (°)	48.24	47.07

Frames 2 and 3 capture instantaneous droplet images at the outlet of the vaporizer. Through image processing techniques, the droplet size distribution is determined. Under DP conditions and with a wall temperature of 27°C, we compared the droplet size distribution between the experimental results and the simulation. The objective is to adjust the simulation model to minimize the discrepancy between these two results. Fig. 7 shows the droplet distribution at the vaporizer outlet for both methods after calibration.

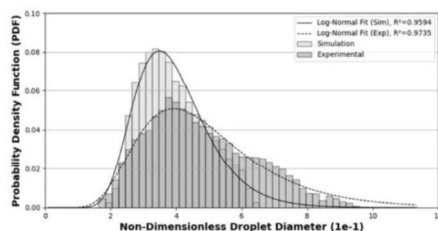


Fig.7. Comparison of droplet distribution between the two methods

3.2 CFD results

3.2.1 Overall spray structure

The spray patterns characteristic of the fuel injection process in the vaporizer are shown in Fig. 8 and 9, with results from both DP and SIC conditions illustrated. Specifically, Fig. 8 highlights the fuel droplet diameter, while Fig. 9 provides a detailed view of the relative velocity between the air and the droplets through observations near the nozzle area. In these figures, the liquid phase of the spray is marked by DPM parcels, representing droplets either with constant size (Fig. 9) or by droplet diameter (Fig.9).

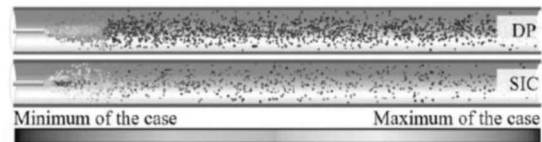


Fig. 8. Fuel droplets diameter at DP and SIC

Overall, from Fig. 8 and 9, it can be observed that the fuel droplets under DP conditions are smaller than those under SIC conditions. This result is expected, as DP conditions are characterized by higher air temperature and velocity, along with strong heat transfer from the tube walls. Furthermore, it can be noted that under DP conditions, the droplet size changes abruptly, occurring just a few lengths after the core flow ends. This behavior is likely associated with the significant acceleration that the droplets experience when their injection velocity combines with the air flow velocity. In the initial stage of atomization, aerodynamic breakup mechanisms dominate, as the relative velocity between the air and the droplets is high. In contrast, under SIC conditions, the transformation occurs more gradually, as the initial relative velocity between the droplets and the air is low, resulting in reduced droplet acceleration.

In Fig. 9, it is observed that downstream of the fuel injector and along the central axis of the vaporizer, the relative velocity between the air and the water droplets is relatively low. This is particularly evident in the results associated with SIC, possibly due to the influence of the fuel injector and its interaction with the air flow, affecting the larger droplets that are characteristic of primary breakup in the core flow region. Furthermore, due to the diminishing aerodynamic breakup effect along the central axis of the vaporizer, relatively larger droplets persist in this region (Fig. 8).

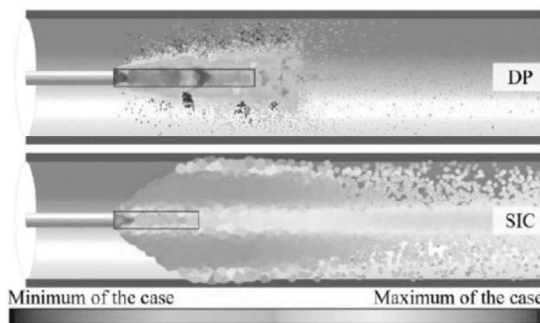


Fig. 9. Close look at air to droplets relative velocity at DP and SIC

3.2.2 Evaporation process

Since SIC simulates the engine start-up process on the ground under low temperatures with no heat transfer, the fuel evaporation process is not considered under these conditions. Therefore, the results apply only to DP conditions. Fig. 10 highlights the fuel evaporation phenomenon in the vaporizer system under DP conditions, showing a low evaporation rate in the core region near the injector, where the droplets are too cold to evaporate effectively. The evaporation rate then increases rapidly in the droplet heating region, particularly in the annular area near the tube wall. The evaporation process is primarily dependent on the relative velocity between the air and the droplets, which is the key

factor driving the observed evaporation model in this study.

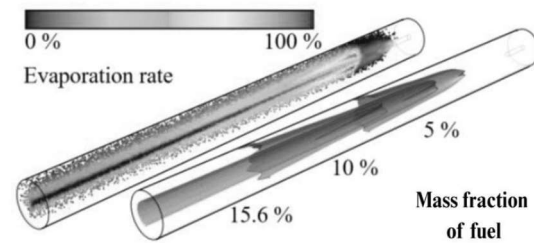


Fig. 10. Fuel evaporation rate and Iso-surfaces of fuel mass fraction at DP

Fig. 11 shows the fuel evaporation rate and other surfaces of the fuel gas mass fraction under DP conditions (the size of the DPM parcels is shown as unchanged). The temperature contours along the vaporizer cross-section, through the central axis, are presented in Fig. 9. The results indicate that heat transfer from the air to the fuel droplets reduces the overall temperature, particularly near the central axis of the vaporizer. The higher temperature near the tube walls is due to these walls being modeled with a constant temperature. Despite the high heat transfer rate, the temperature near the walls remains relatively high.



Fig. 11. Contours of total temperature along a vaporizer longitudinal section at DP

3.2.3 Droplet size distribution

The droplet size distribution of the sprays is determined by post-processing the DPM parcels at the end of the vaporizer, where the fuel spray exits. In addition to the results under DP and SIC conditions, the results for the DP case without evaporation are also discussed to highlight the importance of the evaporation process. The Sauter Mean Diameter (SMD) of the sprays under DP conditions increases by 37% without

evaporation, emphasizing the significant impact of the evaporation process on the breakup performance. The droplet size distribution for the DP, both with and without evaporation, is shown in Fig. 12.

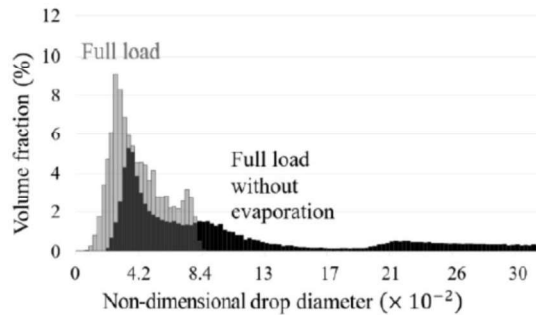


Fig. 12. DP conditions fuel droplet size distributions with and without evaporation

The results indicate that the evaporation process reduces the variability of the droplet size distribution, as shown in Fig. 13, when comparing droplet distributions with and without evaporation. Large droplets in the distribution without evaporation do not appear in the distribution with evaporation, as the evaporation rate increases with droplet diameter. Fig. 12 compares the droplet distribution under DP conditions (with evaporation) and start-up conditions (SIC), showing that engine significantly affect fuel atomization performance, with the SMD under SIC being approximately 7 times larger than under DP. This discrepancy can be explained by the poor breakup efficiency and the lack of pre-evaporation at SIC. Although both distributions have similar widths, under DP conditions, the evaporation process reduces the size of large droplets, leading to a tighter droplet distribution.

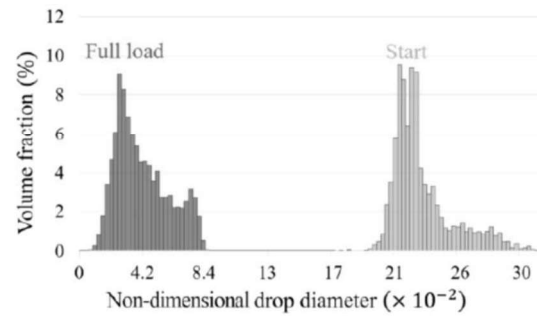


Fig. 13. Comparison of fuel droplet size distributions at DP and SIC

4. CONCLUSION

In this study, the spray breakup and fuel evaporation processes in the vaporizer of a microturbine are investigated by combining simulation and experimental methods. The simulations show that the fuel droplets under DP conditions are smaller than those under SIC conditions, with a sudden change in droplet size after the core flow ends, due to the large acceleration of the droplets. The evaporation process is primarily dependent on the relative velocity between the air and the fuel droplets, as well as the heat transfer from the air to the droplets. Engine start-up conditions significantly affect fuel breakup performance, with the Sauter Mean Diameter at SIC being 7 times larger than at DP. Both the fuel injector and the vaporizer system contribute to ignition issues during start-up. Start-up conditions can be improved by optimizing the air velocity-to-droplet ratio.

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