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Modified Vaporizer for Improved Ignition in Small Jet Engine

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The modification of a fuel vaporizing system, typically used in small jet engines with gross thrust under 1000 N, is discussed. The modification focused on an alternative design of the fuel injection system within the vaporizer to improve atomization and, consequently, vaporization and engine ignition. Operating conditions and all external dimensions of the vaporizer remained unchanged. Three types of impact atomizer were investigated: the existing atomizer, an atomizer with additional air blowing, and an atomizer with an inclined and concave impactor. Droplet size and global spray characteristics under various nozzle pressures and air velocities were measured with phase Doppler particle anemometry and monitored by photography. All modified systems demonstrated better atomization characteristics than the existing design. Droplet Sauter mean diameter, liquid flux, and spray cone angle were investigated using water as the working fluid. An atomization model was developed for the specific atomizer/vaporizer configuration under two operating regimes: 1) liquid breakup due to hydrodynamic instability at low airflow velocities, as in a standard orifice atomizer, and 2) aerodynamic breakup of the large droplets by shear flow of the surrounding air during high airflow velocities as in an air blast atomizer. The characteristics of the modified vaporizers with the new impact atomizers were tested in a jet engine combustor model. Successful spark ignition was demonstrated under operating conditions that were previously outside the ignition envelope.

Nomenclature

d_0	=	orifice diameter, m
$E_{\min}$	=	minimal ignition spark energy, J
FN	=	flow number, m^2 $m_L/(\Delta P_L \cdot \rho_L)^{0.5}$, (kg/s)/[(pa)(kg/m^3)]$^{0.5}$
m	=	mass flow rate, kg/s
Oh	=	Ohnesorge number, $\mu_L/(\rho_L \sigma d_0)^{0.5}$
P	=	total pressure at vaporizer inlet, bar
r	=	radius, mm
r_0	=	radius at vaporizer exit (Fig. 8), mm
V	=	velocity, m/s
V_c	=	velocity at vaporizer axis, m/s
We	=	Weber number
α	=	angle between atomizer orifice axis and impactor (Fig. 1c)
β	=	concave arc angle (Fig. 1c)
ΔP	=	pressure difference between vaporizer inlet and exit bar
$\Delta P/P$	=	relative air pressure drop at vaporizer
ν	=	kinematic viscosity, m/s^2
ρ	=	density, kg/m^3
σ	=	surface tension, N/m

Subscripts

A	=	air
L	=	liquid

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I. Introduction

ONE of the methods for preparing liquid fuel for combustion in gas turbines is the injection of fuel with a small amount of air (usually 5%) into tubes (vaporizer) that are immersed in a flame. The injected fuel–air mixture is heated by the inner tube walls, which, in turn, are heated by the flame, and under ideal conditions a rich gaseous mixture of vaporized fuel and air emerges from the exit.

The combustion air is admitted through different apertures in the liner walls and reacts with the fuel–air mixture issuing from the tubes. The advantages of this vaporizing system, especially important for small jet engines, are low fuel-pump pressure requirements, simple construction, stable operation, and the ability to supply small amounts of fuel vapor to the combustion chamber effectively. The drawbacks are the difficulty in achieving a thermal balance between the heat absorbed by the external vaporizer walls and heat required for vaporization. In addition, the vaporizer adds to the thermal inertia of the combustion system, thus affecting transient response through either partial fuel vaporization or wall overheating. However, as pointed out by Lefebvre,[1] even at high-power conditions the heat transferred to the vaporizer tube is typically insufficient to vaporize more than a small fraction of the fuel. Thus, only at the lowest fuel flow rates can the system be regarded as a true vaporizer. One of the main difficulties associated with the application of vaporizers occurs during ignition. When the vaporizer's wall and the combustor's liner are still cold, no vaporization occurs, and all of the liquid fuel exits in liquid form. In engines equipped with vaporizers it is common to use gaseous fuel with a glow plug for the engine during startup. After a few seconds the engine is hot enough to run on its regular fuel, and the supply of the gaseous fuel is terminated. Another method is the use of an exceptionally powerful glow plug or pyrotechnic cartridge in the kilojoule range.

Jasuja and Low[2] carried out a detailed investigation on the atomization performances of a T-shaped vaporizer. Drop size measurements were obtained while the air pressure drop across the vaporizer $\Delta P/P$ was equal to 5 and 9%. They found that Sauter mean diameter (SMD) values ranged from 30 to 125 μm. The method of fuel atomization within a vaporizer has little significance because final atomization occurs at the vaporizer exit and is due to shear forces created by surrounding air. Therefore, simple atomization devices, such as impact atomizers, are used. Successful ignition depends on many parameters: droplet SMD, mainstream velocity, environment temperature, pressure, equivalence ratio, and more. Ballal and Lefebvre[3] investigated the influence of these parameters on the minimal ignition spark energy $E_{\min}$. They emphasized the strong dependence of

E_{min} on SMD, where the spray average SMD ranged from 40 to 150 μm (diesel fuel). On the other hand, successful ignition was also observed when the droplet SMD was approximately 400 μm (Ref. 4).

The relative air pressure drop across the combustor, $\Delta P/P$, during ignition is very low and varies from 0.3 to 1%. The very small pressure difference between the inlet and exit of the vaporizer and the consequent low air velocity through the vaporizer[3] leads to a large increase in the droplet diameter. This is because the major atomization mechanism is the aerodynamic shear force applied at the tip of the vaporizer by the coflowing air. Because the air velocity is relatively low, the breakup of the liquid film into droplets is insufficient to form small-size droplets. In addition, the cold combustor and vaporizer walls make the ignition process very difficult.

The goal of the present study was to investigate atomization mechanisms and to modify an existing vaporizer in such a way as to improve the atomization and enlarge the ignition envelope in an existing 1000-N growth thrust jet engine.

This work included the following stages: 1) investigation and optimization of the fuel jet impactors; 2) experimental study of the spray characteristics: droplet diameter, droplet distribution, local liquid flux, spray cone; 3) ignition tests of the modified vaporizer in the combustor model; and 4) comparison of test results with CFD simulation data.[5]

Three types of fuel nozzles with impact atomizers were investigated: 1) an existing atomizer (Fig. 1a); 2) an atomizer with additional air blowing at the impingement point (Fig. 1b); and 3) an atomizer with inclined and concave impactor, testing the effect of the inclination and concave section angles (Fig. 1c).

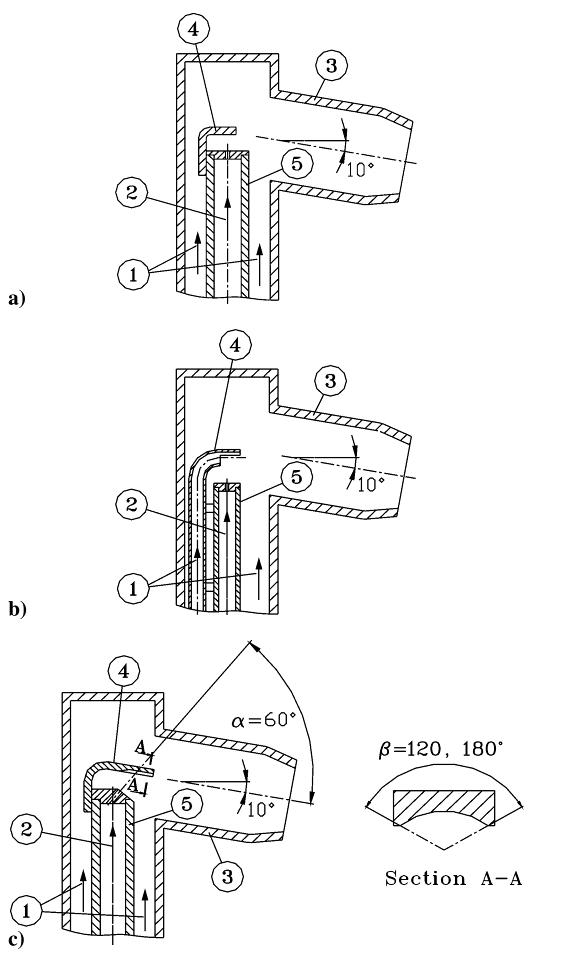

Fig. 1 Schematic of a) typical air supply, b) assisting air supply, and c) impactor inclined atomizer: 1, airflow; 2, fuelflow; 3, case of vaporizer; 4, impactor, and 5, fuel tube.

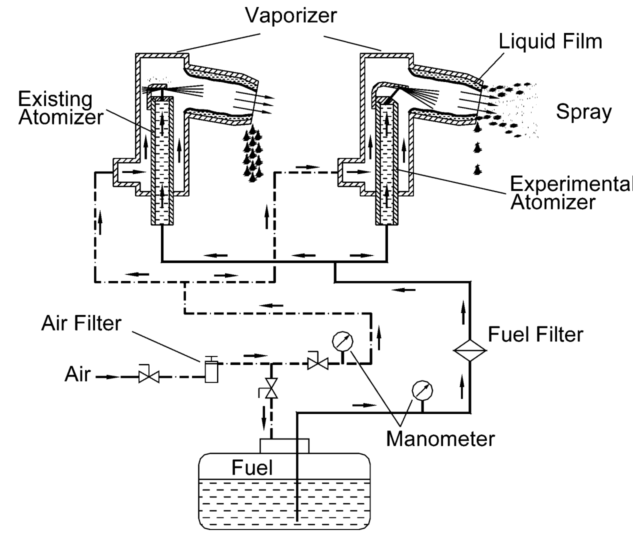

Fig. 2 Experimental setup for atomization quality study.

II. Experimental Setup

The experimental setup for droplet size measurements consists of a nitrogen/air pressurized fuel/water tank, air supply line, pressure gauges, rotameters, valves, and tested atomizers (Fig. 2). The liquid tank has a volume scale to determine mass flow rate. The experimental assembly includes two ports for simultaneous mounting of two atomizers to observe and photograph the atomization characteristics of the existing (reference) and tested (modified) atomizers under identical operational conditions (both housed within the existing vaporizer case). The photographs were taken by an HP-618 digital camera with exposure time of 1/75 s. Droplet diameters were measured by an Aerometrics, Inc., phase-Doppler particle anemometry (PDPA) system. The system (Fig. 3) recorded the droplet size distribution, droplet velocity distribution, and fluid flux.

The measured droplet diameters varied from 1 to 500 μm. A PDPA system was used for recording data. A minimum number of 5000 measurements were recorded for determination of the SMD, velocity distribution, and flux value at each individual point. The measurements were carried out 30 mm downstream of the vaporizer tip at 13 different points of the cross-sectional area. It was found that the liquid film built up on the inner vaporizer walls escapes from the vaporizer edge as a continuous fluid, which transforms into large (rain size) drops. This liquid portion (the nonatomized part) was collected during the experiments in a special measuring glass, and its fraction relative to the overall liquid flow rate was calculated. The atomization quality was based on two parameters, namely, the atomized fraction and the droplet SMD measured by the PDPA system.

The liquid nozzle pressure drop varied from 0.5 to 2 bar, and the air velocity inside the vaporizer varied from 0 to 45 m/s. The air velocity range was chosen according to the actual airflow rate calculated during ignition of the real engine. The airflow rate was measured by a calibrated orifice meter and the liquid flow rate by the Coriolis mass flow measurement system. The air and water temperature was 295 K, the orifice diameter 0.45 mm, and the flow number (FN_{SI}) of the atomizer 1.42×10^{-7} m^2.

III. Test Results and Discussion

A. Existing Atomizer

The conventional impact atomizer generates a flat spray at the impactor surface, and part of the atomized fuel agglomerates as a liquid film on the supporting leg of the impactor tip. This liquid film then flows along the impactor surface and eventually disintegrates into very large drops of approximately 1 mm in diameter or sometimes exits as a continuous liquid. The nonatomized fraction of the liquid, which exits from the vaporizer housing as a continuous liquid, comprises about 20–30% of the liquid mass flow (Fig. 4),

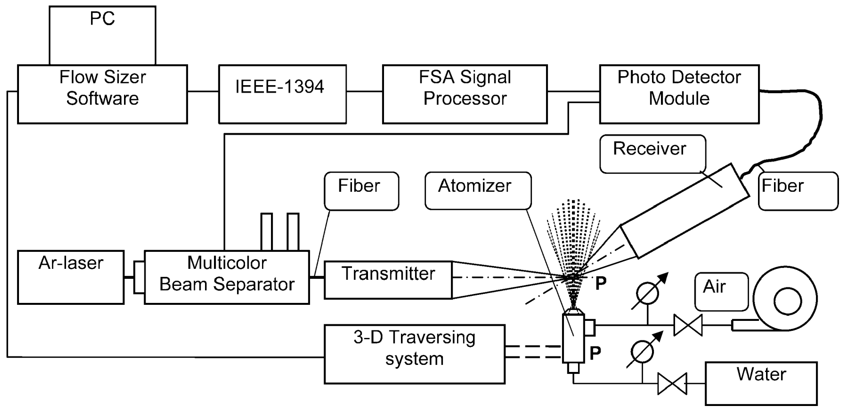

Fig. 3 Measurement system of atomizer performances.

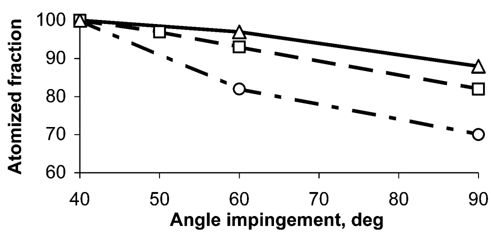

Fig. 4 Dependence of atomized liquid fraction (percent) on an impactor angle α (Fig. 2c), without a vaporizer housing: ○, $\Delta P_L = 0.5$ bar; □, $\Delta P_L = 1$ bar; and △, $\Delta P_L = 2$ bar.

where the impactor is perpendicular to the emerging liquid jet and α is equal to 90 deg (Fig. 1c). When the liquid jet impinges in a non-perpendicular direction and, thus, obtains a tangentional component, the atomized fraction increases. It reaches about 100% at the angle equal to 50 deg (relative to the norm).

The atomization characteristics deteriorate significantly when the atomizer is installed within the vaporizer housing. This is because the injected droplets are directed radially outward from the impactor. Hence, most of the droplets impinge on the inner wall of the vaporizer and agglomerate into a liquid film that flows on the inner wall. Only a very small fraction of the droplets are carried out by the inner vaporizer flow through the vaporizer tube exit. Before ignition, when the vaporizer's wall temperature is about 10–50°C, the bulk of the liquid flowing through the fuel nozzle (98% or more) is eventually delivered to the combustor as a continuous stream. When air velocity is increased, some droplets enter the combustor volume. These droplets are typically generated by the aerodynamic shear forces that break the liquid film down at the vaporizer exit cross section. The liquid film disintegrates into ligaments of liquid and produces large droplets. Only a few small droplets were generated, and their flux was very low. When the inner vaporizer air velocity was 45 m/s, droplet SMD of the atomized fraction was measured and found to be approximately 350 μm. This was a discrete measured value and is not presented in chart form.

B. Air-Assist Impact Atomizer

Air is delivered through a special 3-mm-diam tube just before the impingement point (Fig. 1b). The idea is that the high-speed air will assist in the distribution of the droplets that were generated during impaction in the desired direction, thus, minimizing their agglomeration on the inner vaporizer wall. The tests showed that the liquid film generated at the impingement point of the liquid on the impactor blocked the exit of the assisting air tube. This blockage was overcome, and airflow became effective when the air pressure drop was above 9 mbars (900 Pa) and the liquid pressure drop was equal to 1 bar. However, as the combustor pressure drop ΔP of the existing engine does not exceed 5 mbars (500 Pa) during startup, this atomization method was found to be ineffective. Photographs of the atomization quality are shown in Fig. 5. It seems feasible

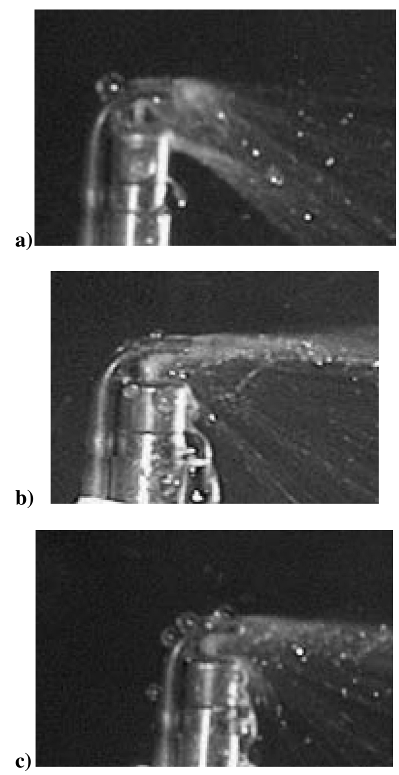

Fig. 5 Atomization quality of impactor with air assisting supply, liquid pressure drop 1 bar: a) without air, b) air pressure drop 0.01 bar (1000 Pa); and c) air pressure drop 0.015 bar (1500 Pa).

that an engine with a potential pressure difference during startup of more than 0.01 bar (1000 Pa) could benefit from such an atomization method.

C. Atomizer with an Inclined and Concave Impactor Shape

It was realized that to minimize droplet agglomeration on the wall of the vaporizer, the spray should attain a preferred direction, toward its exit. The angle between the liquid jet and the impactor (angle α, Fig. 2c) was varied. The modified impactor was designed in such a way as to minimize liquid formation at the vaporizer exit, keeping in mind that part of the liquid must be vaporized during design-point operation.

The angle between the liquid jet and the impactor surface was varied between 40 and 90 deg. When the angle α was below 40–45 deg (Fig. 1), no liquid flow was observed along the impactor surface (100% of the liquid atomized, Fig. 4). However, the droplet diameter increased, probably due to the lower perpendicular component of the relative velocity. Further tests indicated that for an angle α below 60 deg, the amount of liquid contained in the large droplets was significantly smaller. Thus, an inclination angle equal to 60 deg was selected and the test results displayed in this work refer to this angle.

To align the main spray direction with the vaporizer exit, the shape of the impactor was modified to have a cross section shape of an arc with an angle of 120 or 180 deg (Fig. 1c, Sec. A-A). As a result, the trajectories of most of the droplets, after impingement, coincided with the axis of the vaporizer exit tube and substantially less liquid accumulated on the inner walls of the vaporizer. Note that such an impactor shape led to an increase in the droplet diameter. This was foreseen as the velocity component that is normal to the surface impactor is reduced. The dependence of the atomized liquid fraction on the nozzle pressure drop and air velocities is shown in Fig. 6. Both concave impactors demonstrated similar performance. This implies that the concave angle equal to 120 deg is enough to provide atomization of a significant fraction of the liquid. For the existing atomizer, this fraction is only 0.5–2%.

Figure 7 shows spray photographs of the existing and the modified atomizers. Outside the vaporizer housing, the existing impactor provides better atomization (smaller droplets) than the modified one (Fig. 7a), and the spray is mainly in a radial direction. However, whenever the impactor is placed within the vaporizer housing, most of droplets agglomerate on the inner walls, and the existing vaporizer generates only a continuous liquid stream (Fig. 7b). The liquid film begins to disintegrate into large drops at the vaporizer exit when the air velocity through the vaporizer achieves a relatively high value. (The droplet diameter is 1–3 mm at an air velocity of about 30 m/s.) In comparison, the modified vaporizer demonstrates higher atomization quality at the vaporizer exit (smaller droplet size and less liquid agglomeration) over the entire range of air- and fuel flow rates. Note that the modified atomizer forms a spray that is similar to that from a plain-jet airblast atomizer (Fig. 7a, right side). It is directed to the vaporizer exit, and a significant fraction of the liquid escapes from the vaporizer as spray (Fig. 7b, right side).

Because of the short distance between the vaporizer exit and the 90-deg tube bend, the air velocity profile at the vaporizer exit is not uniform. The measured air velocity distribution at the vaporizer exit and its comparison with computational fluid dynamics (CFD) simulations,[5] is shown in Fig. 8. The velocity profile along the Y axis

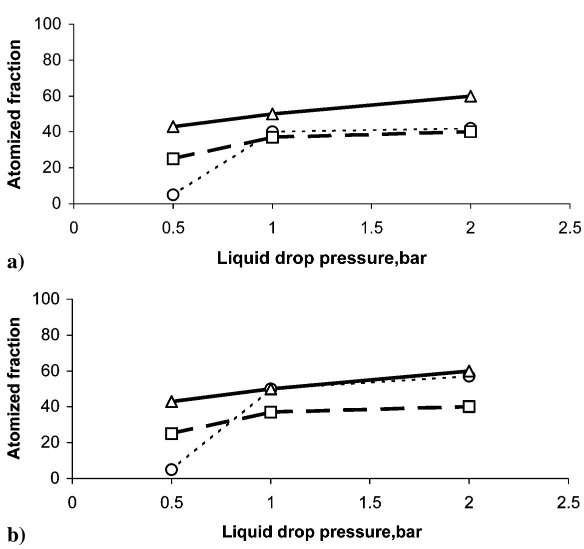

Fig. 6 Dependence of atomized liquid fraction (percent) on pressure drop and air velocity, a) $\beta = 120$ deg, b) $\beta = 180$ deg, with vaporizer housing: ○, $V_{air} = 0$, □, $V_{air} = 20$ m/s, and △, $V_{air} = 45$ m/s.

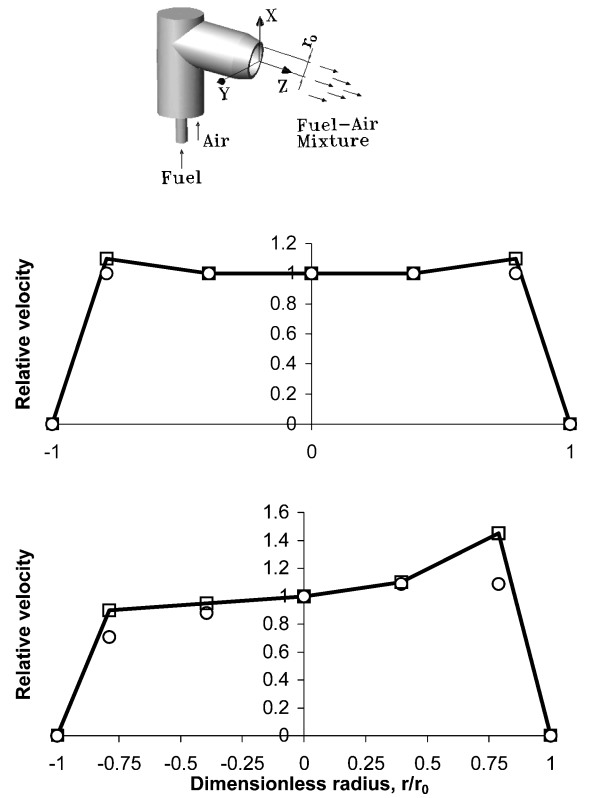

Fig. 8 Normalized relative to center value V_c, air velocity distribution at vaporizer exit: a) along y axis and b) along x axis; ○, measured values and □, CFD simulation.[5]

Fig. 7 Spray atomization of existing (left) and modified atomizers (right) (see Fig. 1a and 1c, $\beta = 180$ deg): a) without vaporizer housing and b) with vaporizer housing; liquid pressure drop 1.5 bar and air velocity 20 m/s.

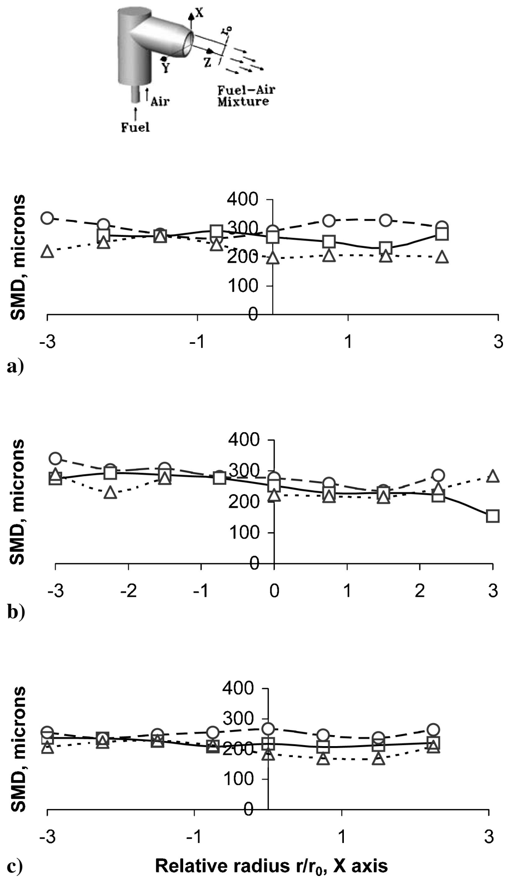

Fig. 9 SMD distribution along vaporizer radius, $\beta = 120$ deg, air velocity $V =$ a) 0, b) 20, and c) 45 m/s: ○, $\Delta P_L = 0.5$ bar; □, $\Delta P_L = 1$ bar; and △, $\Delta P_L = 2$ bar.

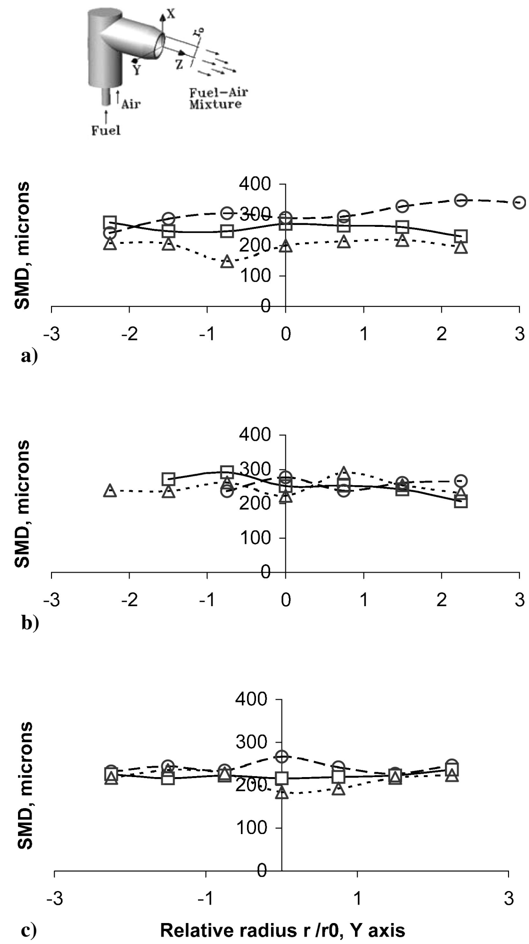

Fig. 10 SMD distribution along vaporizer radius, $\beta = 120$ deg, air velocity $V =$ a) 0, b) 20, and c) 45 m/s: ○, $\Delta P_L = 0.5$ bar; □, $\Delta P_L = 1$ bar; and △, $\Delta P_L = 2$ bar.

is symmetric, and it is asymmetric along the *X* axis. Such a profile is typical for a pipe bend. The experimental results and CFD simulations[5] are in reasonable agreement.

Droplet diameter distribution (SMD) was measured along two perpendicular axes, *X* and *Y*, at 30 mm from the vaporizer tip (Figs. 9 and 10). Measurements were carried out for two concave angles β, 120 and 180 deg (Fig. 1c, Sec. A-A). Because the results for the two vaporizers were similar, only the data for the concave angle of 120 deg are depicted. Note that droplet size does not vary significantly with radial location. Droplet size is reduced with an increase in air velocity and an increase in liquid pressure drop. The effect of the air velocity is stronger for a low liquid pressure drop. The asymmetry of air velocity profiles at the vaporizer exit has an insignificant effect on droplet size due to the relatively weak nonuniformity.

The liquid flux distribution is depicted in Figs. 11 (along the *X* direction) and 12 (along the *Y* direction). Note that outside the charted boundaries a small amount of droplets with SMD less than 150 μm was still observed, but their flux was insufficient to allow for a statistically accurate result. The flux distribution along the *X* axes shows that the maximum value is offset from the spray center to the negative values of the radius. Such an effect is the consequence of the impactor location within the vaporizer. The same effect can be seen in the photographs (Fig. 7).

Measurement results of flux and SMD distributions were used to calculate the cross-sectional flux averaged SMD values. Results for both concave angles are shown in Fig. 13. Note that SMD values are greatly affected by air velocity at low liquid pressure but that the effect is insignificant at higher liquid pressures. This phenomenon can be explained by the two-staged model of the atomization process. The first stage is disintegration of the liquid sheet downstream of the impactor. Our tests performed at the pressure range from 0.5 to 2.5 bar revealed that the liquid sheet converges again to a focal point, probably due to surface tension forces. It has a leaf shape, and the liquid sheet behavior is similar to the "onion" atomization of a low-pressure swirl atomizer. During this process, few droplets are separated from the leaflike liquid sheet. Downstream from the focal point of the leaflike liquid sheet, the liquid disintegrates into droplets due to hydrodynamic instability. It seems that this first stage is similar to the disintegration process that takes place at the plain-orifice atomizer. The second stage is associated with secondary breakup due to the aerodynamic shear forces of the surrounding air. This process is similar to atomization in the plain-jet airblast atomizer, where droplets of large diameter disintegrate under the action of aerodynamic forces.

There are two optional processes for atomization in the combined atomizer/vaporizer configuration: plain-orifice and airblast atomization. We assume that the atomization process (liquid pressure atomization or aerodynamic breakup) that produces droplets of the smallest size is the dominant one. Indeed, one can see from Fig. 13 that liquid pressure drop is crucial at low air velocities. However, at high air velocities, the droplet size decreases significantly even at low liquid pressure. This is because the primary large droplets are disintegrated by the shear airflow. A qualitative description of the assumed disintegration mechanisms is shown in Fig. 14. When the air shear forces exceed the jet instability, the disintegration is performed according to left branch of the curves. Alternatively, when the jet hydrodynamic instability is more significant than the aerodynamic shear forces, the right branch determines the droplet size.

Merrington and Richardson (see Ref. 6) proposed a model for evaluating the droplet size for a plain-orifice atomizer,

$$\mathrm{SMD} = 500 \cdot d^{1.2} \cdot \nu_L^{0.2} \big/ V$$

or it can be rewritten as

$$\mathrm{SMD} = 354 \cdot d^{1.2} \cdot \nu_L^{0.2} \big/ (\Delta P_L / \rho_L)^{0.5} \tag{1}$$

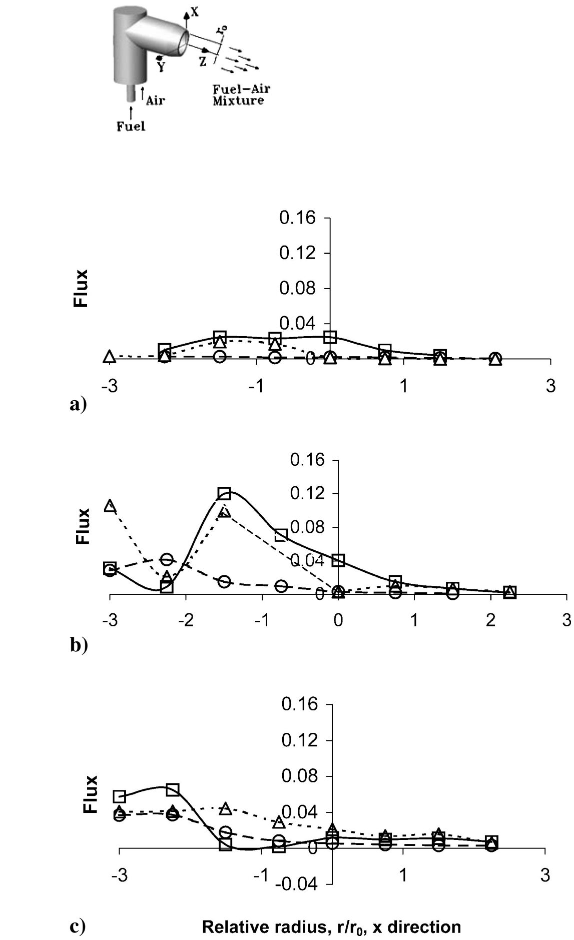

Fig. 11 Liquid flux, cubic centimeters per second centimeters squared, distribution along vaporizer radius, X direction, $Z = 30$ mm and $\beta =$ 120 deg (Fig. 1); air velocity $V =$ a) 0, b) 20, and c) 45 m/s: ○, $\Delta P_L = 0.5$ bar; □, $\Delta P_L = 1$ bar; and △, $\Delta P_L = 2$ bar.

The SMD value for the plain-jet airblast atomizer was calculated according to the empirical equation derived by Rizk and Lefebvre[6] as follows:

$$\mathrm{SMD}/d_0 = 0.48\ We^{-0.4} \cdot (1 + 1/\mathrm{ALR})^{0.4} + 0.15 \cdot Oh \cdot (1 + 1/\mathrm{ALR}) \qquad (2)$$

for air/liquid ratio (ALR). Note that droplet size decreases with the rise of the liquid pressure drop and that the diameter is determined by jet instability in accordance with Eq. (1), whereas droplet size, when determined by the air shear forces, increases, in accordance with Eq. (2), as the air/liquid mass flow ratio and the air/liquid relative velocity decrease. One can see from Fig. 15 that droplet size achieves a maximal value at a certain intermediate point. This maximum shifts to higher values of liquid pressure drop when air pressure drop increases. Suyari and Lefebvre[7] achieved a similar result for low air pressure drop during their study of an air-assist atomizer.

A comparison of our tests with calculated results shows that experimental SMD values correlated well with the assumed mechanism (Fig. 15). The reason for the slightly higher droplet diameter produced by the impactor with the concave angle equal to 180 deg can be explained by the larger impinging surface area of the jet (cylindrical surface rather than plane) and, therefore, a larger equivalent diameter of the impinging jet.

Thus, the modified vaporizers have better atomization quality and the atomized fraction is in the range of 10–70% compared to 1–2% for the existing vaporizer technology. Such a large percentage is in accordance with conventional vaporizer design. In such a design fuel, vaporization occurs on the inner walls of the vaporizer; however, as noted by Lefebvre,[1] the vaporization area is sufficient for vaporizing only a fraction of the fuel flow rate, even at the design point. Calculations of heat transfer from the outer vaporizer walls

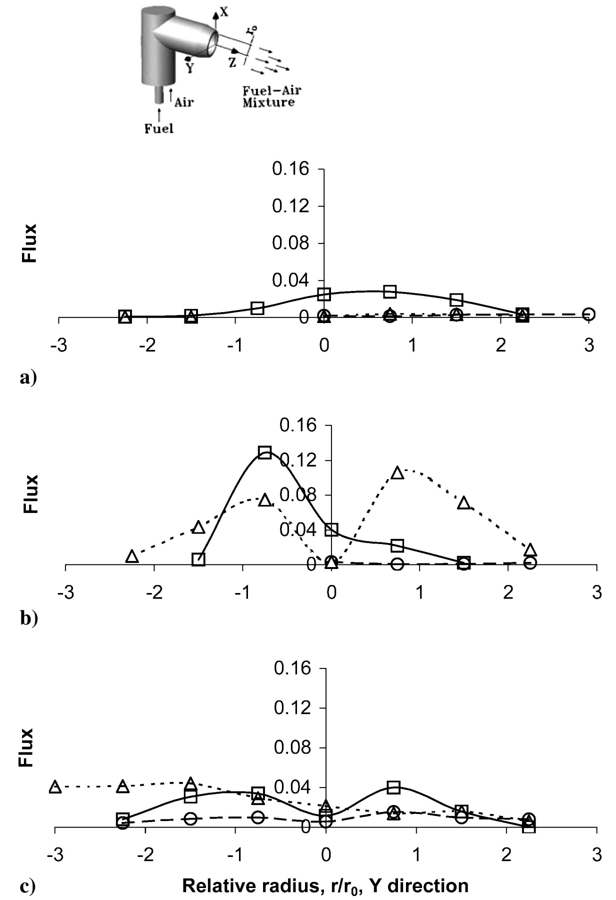

Fig. 12 Liquid flux, cubic centimeters per second centimeters squared, distribution along vaporizer radius, Y direction, $Z = 30$ mm and $\beta =$ 120 deg (Fig. 1); air velocity $V =$ a) 0, b) 20, and c) 45 m/s: ○, $\Delta P_L = 0.5$ bar; □, $\Delta P_L = 1$ bar; and △, $\Delta P_L = 2$ bar.

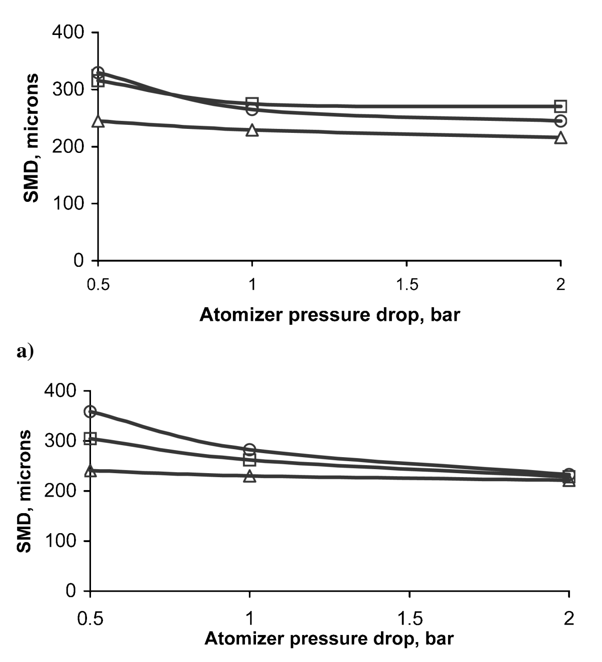

Fig. 13 Effect of atomizer pressure drop on SMD values averaged along cross-section area, concave arc angle $\beta =$ a) 120 and b) 180 deg: ○, $V_{air} = 0$; □, $V_{air} = 20$ m/s; and △, $V_{air} = 45$ m/s.

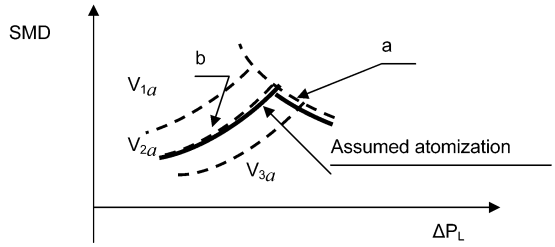

Fig. 14 Schematic of assumed atomization process: a) plain-orifice atomizer and b) airblast atomizer, $V_{3a} > V_{2a} > V_{1a}$.

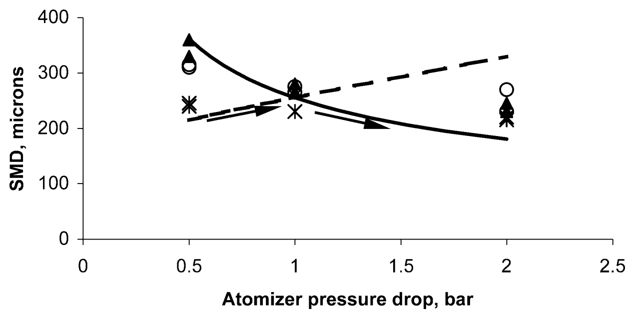

Fig. 15 Comparison between tests results and assumed atomization scheme, Eqs. (1) and (2), for $V_a = 20$ m/s, calculated SMD for airblast atomizer are out of chart boundaries, approximation for air velocity $V_a = 0$ and $V_a = 20$ m/s, → for $V_a = 45$ m/s: ——, airblast; – – –, plain orifice; ▲, test *Va* = 0 m/s; ○, test *Va* = 20 m/s; and ⁎, test *Va* = 45 m/s.

to the fuel based on CFD simulations[5] show that only 20–30% of the fuel evaporates during the standard operation. Thus, the split between the atomized and the nonatomized fuel fractions is acceptable for design point conditions.

IV. Ignition Tests

The modified vaporizers were mounted inside a 30% plane sector of the combustor model, with 3 out of the 10 vaporizers installed in the complete combustor. The model was built with two quartz windows for flame observation and photographs. Air and fuel temperature was 285 K. A spark igniter of approximately 1 J per pulse and a frequency of 10 Hz was used. The ignition tests for the fixed airflow rate were performed by increasing the fuel flow rate until ignition was obtained. The upper ignition limit was outside the maximal possible fuel pressure for the tested model (6 bar). The lowest fuel pressure that allowed successful ignition was 1.6 bar (gauge). Because injection pressure correlates inversely with drop size, the existence of a lower pressure limit means that there is a maximum allowable droplet size for successful ignition. The tests confirmed that a combination of small liquid droplets and low air velocity is necessary for successful ignition, but it also indicates that the droplet SMD is not the only critical factor. The droplet size distribution is an additional parameter that has to be considered. It seems that ignition is possible even for relatively large SMD values; however, this depends on the existence of sufficient amount of small droplets. The ignition test results are shown in Fig. 16.

The two types of impactors demonstrated almost the same performance, but due to smaller droplet size for the atomizer with $\beta = 120$ deg its ignition range is larger. It is seen from Fig. 16 that at a low airflow rate (and low average velocity) the minimum fuel-to-air ratio that is needed for successful ignition is higher than that at higher flow rates. This phenomenon is because at low airflow rate, the absolute amount of fuel flow that is needed for keeping the same fuel-to-air ratio is lower than that at higher air velocities. Consequently, the fuel pressure must be lower. However, the low fuel flow rate is associated with lower fuel pressure and the consequent deterioration in spray quality and in ineffective evaporation. To ensure an adequate amount of small droplets and sufficient fuel vapor, a higher fuel pressure drop and, hence, higher fuel flow rate is required. Consequently, this results in a higher global equivalence ratio during the ignition stage. The need for a combination of low air velocities and small droplets for successful ignition is based on

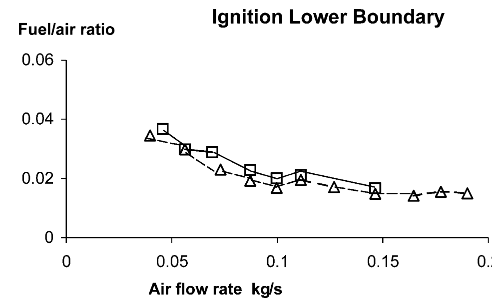

Fig. 16 Ignition test results at 30% plane sector of combustor: –□–, arc = 180 deg, and –△–, arc = 120 deg.

the classical theory of spray ignition where local air velocity should be smaller than the flame velocity to ensure flame stabilization. The small diameters of the droplets are required for fast evaporation and sufficient supply of fuel vapor to the combustion zone.

Note that in the existing system (original design), spark ignition was not possible under any test conditions; ignition could only be achieved by means of a gas torch or pyrophoric fuel.

V. Conclusions

Three types of atomizers were investigated for installation within the vaporizer. The atomizers were tested for liquid pressure drop ranging from 0.3 to 2.5 bar and air velocities ranging from 0 to 45 m/s. The measured parameters were the droplet size and the amount of atomized liquid at the exit of the vaporizer tip during cold operation (relevant for combustor ignition during engine startup). The atomizer types were 1) an existing flat plane impact atomizer, 2) an atomizer with additional air blowing, and 3) an atomizer with an inclined and concave impactor. (The concave angles of the impactor β were 120 and 180 deg.) Droplet flux, velocity, SMD, and air velocity distributions at the vaporizer outlet were measured. The spray measurements indicated better atomization over the whole range of operational conditions, and the following results were obtained:

1) The existing vaporizer does not provide sufficient droplets during the startup phase of the engine: Here, 98–100% of the liquid flows through the vaporizer outlet as nonatomized continuous fluid, thus a supplementary fuel supply system for ignition is required.

2) Modified impact atomizers demonstrated better atomization quality. The atomized liquid fraction exiting the vaporizer tube during the ignition phase was 10–70%, corresponding to liquid pressure drop variation from 0.5 to 2 bar. Average SMD values were 210–330 μm for the concave impactor angle of 120 deg and 220–350 μm for the angle of 180 deg.

3) Successful spark ignition over a wide range of fuel pressure drop and air velocities was demonstrated with the modified impact atomizer, whereas spark ignition of the existing flat plane impact atomizer was not possible. The minimal liquid pressure drop required for successful ignition was 1.6 bar. It has been demonstrated that successful ignition is possible even for large average droplet SMD values as long as there is a sufficient amount of small droplets.

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