AN EXPERIMENTAL STUDY ON MODELING OF FUEL ATOMIZATION FOR SIMULATING THE IDLE REGIME OF A GAS TURBINE COMBUSTOR BY ATMOSPHERIC TESTING

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ABSTRACT
An experimental investigation is carried out on modeling of fuel atomization for the purpose of simulating the idle regime of a gas turbine combustor through atmospheric testing. If the simulation is successfully applied, it will significantly reduce the cost of testing. The simulation must sustain nearly the same fuel spray characteristics and the same aerodynamics at the exit of the frontal device. Air assisting through the main stage of a dual orifice fuel nozzle is employed to match the fuel spray characteristics. Optical diagnostic methods including flow visualization and Adaptive Phase/Doppler Velocimetry are used for the investigation of spray characteristics. Once the fuel spray characteristics are matched by air assisting, the combustor characteristics may then be matched by maintaining the loading parameter constant. The possibility of modeling with air assisting is shown and appropriate conditions for air assisting are found.

NOMENCLATURE
- $D_{32}$: Sauter mean diameter, $\mu$m
- $F_{N}$: flow number, $m^{3}$
- $K_{c}$: loading parameter
- $P$: inlet air total pressure, bar
- $R$: specific gas constant, joule/kg/K
- $T$: inlet air total temperature, K
- $U$: inlet air velocity, m/sec
- $V_{pz}$: volume of the primary zone, $m^{3}$
- $a_{cr}$: critical sound speed, $[2k/(k+1)]R_{T}$
- $k$: specific heat ratio
- $\dot{m}_{a}$: air mass flow rate, g/sec
- $\Delta P$: pressure difference, bar or kPa
- $\alpha$: equivalent air excess ratio, $1/\phi$
- $\beta$: effective evaporation constant
- $\delta_{f}$: flame tube pressure loss coefficient, $\Delta P_{f}/P$
- $\phi$: equivalence ratio
- $\eta$: combustion efficiency
- $\lambda_{v}$: velocity coefficient, $U_{f}/a_{cr}$
- $\theta$: spray root angle, degree
- $\rho$: density, $kg/m^{3}$

Subscripts
- $1$: pilot nozzle
- $2$: main nozzle
- FD: frontal device
- $M$: model
- $R$: real(actual)
- $a$: air
- $aa$: air-assisting
- $cr$: critical
- $d$: droplet
- $e$: evaporation
- $eff$: effective
- $f$: fuel
- $ft$: flame tube
- opt: optimal
- $pz$: primary zone

INTRODUCTION
During the development stage of a gas turbine combustor, a great deal of testing may be done at atmospheric conditions, and the results may be used to make predictions of combustor behavior at high pressure conditions. This study concerns modeling of fuel atomization for simulating the idle regime of combustor at atmospheric condition. Test conditions for a given temperature and pressure are calculated.

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from the loading parameter and the optimal equivalent air excess ratio. In this study, air-assisting through the main nozzle of the fuel injector is employed in order to simulate the spray characteristics. Optical methods including flow visualization using a laser sheet and Adaptive Phase/Doppler Velocimetry are used for the investigation of spray characteristics. Combustion tests will be needed for the more accurate verification of modeling.

Modeling criteria depend on engine operation regimes (Lefebvre, 1983), and they are different due to wide range of parameters at the combustor inlet: $P_a$, $T_a$, $m_a$. For example, ignition, engine start and idle operation all depend on fuel atomization and evaporation, but the effect of atomization is minimized at take-off and cruise regimes in respect of efficiency level, though important in soot formation and NOX emissions (Derr et al., 1988; Lefebvre, 1995).

Fuel atomization and fuel/air interaction should be properly modeled to simulate burning processes as closely as possible. First of all, the droplet size distributions and the spray angles should conserve the same properties as in the actual idle conditions. Gas temperature in the model tests should be determined to simulate the fuel evaporation rate. If air temperature may not be elevated to the actual value, finer atomization may be applied. The combustion efficiency depends on the primary zone parameters. As the engine operating regime changes, the combustion efficiency changes over a wide range. The maximum efficiency at the optimal value of $\alpha$ varies with combustor type. So, $\eta_{max} = \eta(\alpha_{max})$ depends on air/fuel distribution and $\alpha_{max} = f(P_a, T_a, D_{32}, V, \mu, \lambda, \text{fuel type})$. This dependence is important for the combustor modeling because if $\eta_{max}$ and $\alpha_{max}$ are the same in the model and actual combustor tests, then the characteristics of burning will be similar. In this case, the model test may give useful information.

Efficiency is low when $\alpha_{max}$ is very rich or very lean where the subscript e indicates evaporated part of liquid fuel and small droplets with $D_{32} < 10 \mu m$. If $\alpha_{max} = 1$ in optimal conditions and $m_{in}/m_{in,2} = \text{constant}$ (air distribution in the flame tube is not affected by burning), then $\alpha_{max}$ may be given as follows when $\omega < 1$:

$$\alpha_{max} = \frac{m_{in}}{m_{in,2}} = \frac{\beta_{eff} P_{in} V_{in}}{m_{in,2} D_{32}^2}$$  \hspace{1cm} (1)

Similar results were reported by Lefebvre et al. (1989) and Odgers et al. (1993).

Assuming that $\alpha_{max} = 1$ is the same in the model and actual test, Eq.(1) may be reorganized to give

$$D_{32}^2 = C_1 \beta_{eff} \frac{P_{in} V_{in}}{m_{in,2}} \frac{m_{in}}{m_{in,2}}$$  \hspace{1cm} (2)

where $P_{in} = P_a R T_a$ and $T_a$ is a representative gas temperature in primary zone. Using the following relation for the air mass flow rate,

$$m_a = \frac{C_2 P_a}{T_a} \frac{m_{in}}{\lambda_a}$$  \hspace{1cm} (3)

and

$$D_{32}^2 = C_1 \beta_{eff} \frac{P_{in} V_{in}}{m_{in,2}} \frac{m_{in}}{m_{in,2}}$$  \hspace{1cm} (4)

Eq.(1) may be rewritten as follows

$$D_{32}^2 = C_1 \beta_{eff} \frac{P_{in} V_{in}}{m_{in,2}} \frac{m_{in}}{m_{in,2}}$$  \hspace{1cm} (5)

Assuming that the loading parameter $K_a$ is the same in the model and actual test, where

$$K_a = \frac{m_{in}}{P_a T_a} \frac{P_{in,2} V_{in}}{m_{in,2}}$$  \hspace{1cm} (6)

and

$$D_{32}^2 = C_1 \beta_{eff} \frac{P_{in} V_{in}}{m_{in,2} \lambda_a}$$  \hspace{1cm} (7)

If $\beta_{eff} = P_a^{0.25} T_a^{-2}$, the drop size will remain constant and

$$D_{32,w} = D_{32, M}$$  \hspace{1cm} (8)

However, this should be verified experimentally.

From Eq.(3) and Eq.(6),

$$\frac{m_{in}}{m_{in,2}} = \frac{P_{in,2} V_{in}}{P_{in} V_{in}}$$  \hspace{1cm} (9)

where $P_{in} = P_{in,2}$, $V_{in} = V_{in,2}$.

Since the pressure loss coefficient $(\Delta P_{in}/P_a)$ is proportional to $\lambda_a^3$, $\Delta P_{in} = \frac{\Delta P_{in,2}}{\Delta P_{in,1}} = P_a^{0.5} \lambda_a^3$  \hspace{1cm} (10)

For given pressure and temperature, the model test conditions may be calculated from Eq.(9) and Eq.(10). Since the low pressure atomization at the modeling condition is poor, air assisting is employed to enhance the atomization characteristics. The assisting air flowrate through the main nozzle is less than 10% of the swirl air flowrate.

**EXPERIMENTAL APPARATUS AND PROCEDURE**

**Experimental apparatus**

A schematic of the dual orifice atomizer employed in this study is shown in Fig.1.(a). The mass flow rate characteristics of this atomizer may be specified by a flow number which is the ratio of the mass flow rate to the square root of the injection pressure multiplied by the liquid density. The flow numbers for the pilot and main nozzles are $F_N = 1.75 \times 10^{-4}$ m$^2$ and $F_{NQ} = 1.47 \times 10^{-5}$ m$^2$, respectively. The root spray angle of the pilot nozzle is about 70°, and that of the main nozzle is about 90°. The pilot nozzle has two 60° helical slots, a fuel swirl chamber and an exit orifice of 0.8mm. The main nozzle has six 60° helical slots, a fuel swirl chamber and an exit orifice of 2.4mm.

Geometry of the counter rotating swirler is shown in Fig.1.(b). There are twelve flat vanes in each of the inner and the outer swirler. The vane angle of the inner swirler is 40°, opposite to the inner swirl direction, and that of the outer swirler is 45°, opposite to the inner swirl direction. The effective area of air passage is 0.875 cm$^2$ for the inner swirler and 1.17 cm$^2$ for the outer swirler.

The experimental setup is shown in Fig.2. This includes a test chamber, a pressurized water/fuel supply system, an air supply system, an injector assembly, a liquid collection and suction system, a visualization system and an Adaptive Phase/Doppler Velocimetry system.

Air from the compressor passes through a regulator/filter assembly, a flowmeter, an electric heater, a control valve, and enters to the frontal device adaptor. Temperature and pressure of the air are measured at this adaptor. Details of the injector module fixed to the adaptor are shown in Fig.3.

The water/fuel supply system is designed to accommodate a maximum liquid flow rate of 0.3 l/min at the pilot nozzle and 1.8 l/min (600 l/min for air) at the main nozzle. The maximum pressure for the
injection system is 1.5MPa for liquid and 0.5MPa for air. Continuous and steady liquid injection is obtained from the water tank pressurized by nitrogen.

![Image](https://example.com/image.png)

(a) Dual-orifice Fuel Injector

(b) Swirler

Fig.1 Fuel Injector and Swirler

To assess the global structure of spray, visualization with a laser sheet is performed. The Ar-ion laser light is transmitted via a single-mode fiber optic cable to the collimating micro-objective lens on the optical bench. After being collimated, the laser sheet is produced with a cylindrical lens and collimated by a convex lens. The beam thickness is about 0.3mm at beam waist and the height is fixed at 50mm. Spray images are captured with a color CCD camera (Pulnix TMC-74) with 768(H) x 493(V) pixels which is oriented perpendicular to the laser sheet. The captured image is processed with a color frame grabber (Data Translation DT2871). The CCD camera is equipped with a magnifying objective and the exposure time is 1/60sec.

The Adaptive Phase/Doppler Velocimetry (APV) system manufactured by TSI, Inc. is used to obtain the size and velocity information of droplets. A two-component system using green (514.5nm) and blue (488nm) beams from an Ar-ion laser operating at (model 9832, 83mm Diameter). The color burst uses a Bragg cell operating at 40MHz to shift laser beam frequency. The polarization of beams is 90°. In the transmitting probe, the beam spacing is 50mm and the probe beam diameter is 2.82mm. The transmitting probe uses a 363mm focal length lens to yield a measurement volume diameter/length of 90.5µm/1.31mm for the green and 85.8µm/1.24mm for the blue. The fringe spacing is 3.73µm for the green and 3.54µm for the blue, and the number of fringes is 24.2 for both.

The receiving system is composed of a dual adaptive receiver (model TRCFP-3) and a color-link (model 9230). The dual receiver is a physically independent but identical receiver with external inter-changeable masks (heights 7,10,15mm). The effective collection aperture is controlled by these masks. Also the included angle between the receivers can be changed up to 20°. The above two capabilities allow the elevation angle of the receiver to be selected according to size range and measurement resolution. The signal processor (IFA755) is a digital burst autocorrelation signal processor with maximum frequency of 90MHz.

In the present experiments, the receiver optics are located 30° off-axis from the forward scatter direction, the included angle between the receivers is 0°, and the (standard) mask height is 10mm (for droplet size range up to 126µm) or 15mm (for droplet size range up to 86µm). The signal processor is set to have a single measurement per burst, coincidence time of 100µsec, minimum cycles per burst of 8, and minimum threshold of 110mV. The APV simulation software, SIMAP (for Mie scattering calculations) supplied by TSI, Inc. is used to find the phase-diameter relation for a given optic geometry. The accuracy of the APV system is checked against a monodisperse aerosol generator (Aerometrics DPG100). The error is found to be less than 3%. The transmitting probe and the receiving optics are mounted on a common rail which is fixed to a 3-axis traverse system with 0.01mm resolution.

**Experimental Conditions**

For a KARI combustor (Seol et al.,1996), the idle conditions are as follows: $P_{in}=320$kPa, $T_{in}=430$K, $m_{e,FD}=68.25$g/sec per nozzle (corresponding $\Delta P_{FD}=16$kPa), $\alpha=5$ and $m_{e,FD}=15.94$g/sec (corresponding $\Delta P_{FD}=0.9$kPa) and $\alpha=5$, $m_{e,FD}=0.83$g/sec (corresponding $\Delta P_{FD}=0.43$bar) per nozzle. At idle temperature, the modeling conditions are: $P_{in}=101.3$kPa, $T_{in}=293$K, $m_{e,FD}=10.94$g/sec (corresponding $\Delta P_{FD}=0.9$kPa) and $\alpha=5$, $m_{e,FD}=15.94$g/sec (corresponding $\Delta P_{FD}=0.68$bar) per nozzle. At low pressure, atomization is poor: the spray cone is not fully opened and the SMD is large (about 90µm). Therefore, air-assisting through the main nozzle is used to acquire nearly the same spray characteristics between the idle condition and the model condition. Water is used in all tests. The APV measurements are conducted at four axial locations from the nozzle exit, 30mm, 40mm, 60mm, and 90mm as shown in Fig.3. Table 1 lists all the experimental conditions.
Fig. 2 Experimental Setup

(a) Idle regime
($\Delta P_d = 9.2\text{bar}, \Delta P_{fr} = 16\text{kPa}$)

(b) Modeling condition without air-assist
($\Delta P_d = 0.8\text{bar}, \Delta P_{fr} = 2.8\text{kPa}$)

(c) Modeling condition with air-assist
($\Delta P_d = 0.8\text{bar}, \Delta P_{fr} = 2.8\text{kPa}, \Delta P_{ai} = 1.0\text{bar}$)

Fig. 3 Injector Assembly and Measurement Location

Fig. 4 Visualization of Sprays
are different. It is believed that this difference is due to the difference in the initial momentum of droplets (injection pressures of the reference and the modeling sprays are 9.2bar and 0.8bar, respectively).

### Table 1 Experimental Conditions

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<th>FrONTAL device pressure drop $\Delta P_{fb}$ (kPa)</th>
<th>Air-assisting pressure drop $\Delta P_{a}$ (bar)</th>
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### RESULTS AND DISCUSSIONS

#### Visualization Results

Images of the spray obtained in the central plane are shown in Fig.4. At idle regime (a), the spray cone angle is about 80° and the main stream of droplets is located near the edge of the spray cone.

At modeling conditions ($T_i=420k$, $P_i=1.013bar$, $\Delta P_{in}=0.8bar$, $\Delta P_{fb}=2.8kPa$) without air-assist (b), the spray is nearly a jet-type and droplets are very large. With air-assisting through the main nozzle (c), the spray becomes similar to the reference (idle) spray. Though the spray cone angle is nearly the same, droplets at the modeling spray become similar to the reference (idle) spray. Though the spray cone angle is nearly the same, droplets at the modeling conditions, as visually observed, are finer than the reference spray. In the far-field from the frontal device exit, the distributions of droplets are different. It is believed that this difference is due to the difference in the initial momentum of droplets (injection pressures of the reference and the modeling sprays are 9.2bar and 0.8bar, respectively).

#### Spray Characteristics of the Reference Spray

In Fig.5, the spray characteristics measured at x=40mm for the atomizer without the frontal device are shown. This figure shows the well-known spray characteristics of a simplex atomizer. This spray has a maximum SMD of about 90µm near the edge and a minimum SMD of about 40 µm at the center of the spray. At the maximum value of volume flux, the representative drop size (SMD) is equal to 65 - 70µm.

The radial location and the value of the maximum volume flux at x=40mm are 17mm and 20 x 10^6 cc/cm^2/sec. The volume flux and the number density near the edge of spray ($r=35-40mm$) is negligible.

The spray characteristics with air through the frontal device are shown in Fig.6. The atomization may be characterized by two mechanisms. One is the pressurized simplex atomization in the center of the spray. The other is the air-blast atomization by air through the swirlers in the edge of the spray. Due to these, there are three minima in SMD ($D_m$) distribution: at the center and near the edges, and there are four maxima in SMD distribution: at $r \approx \pm 13mm$ and near the edges (when $x=40mm$). Such distributions occur since the spray cone collides with the swirler wall and the liquid film is disintegrated by the air blast mechanism. The outer maxima in $D_m$ appear because small part of fluid collides with the outer swirler wall due to the centrifugal force. The reference distance for comparison is x=40mm, because at smaller distance, the inner part of the spray is not distinct, and at larger distance, mixing of the spray with ambient air becomes significant. In a downstream region ($x=90mm$), distribution of SMD and volume flux become more uniform since the air flow through the swirler disintegrates and disperses the large droplets.

Similar results have been reported by A. Brena de la Rosa et al. (1992) for a swirler/atomizer assembly, by C. Presser et al. (1990) for a moveable vane swirl burner, and by H.Y. Wang (1993) and V.G. McDonell (1994) for the CFM56 swirl cup assembly.

To investigate the effects of temperature on spray characteristics, measurements were repeated at the idle temperature of 420K. In Fig.6, it is shown at x=40mm and x=60mm that the effect of temperature is not significant except at the center of the spray.

### Spray Characteristics of the Modeling Spray

The goal of spray modeling is to acquire the same spray pattern at low $\Delta P_{in}$ corresponding to the low pressure/temperature condition of combustor operation. Spray characteristics (SMD, spray angle, size distribution, etc.) must be similar to the real characteristics in order to have the same combustion efficiency. In addition to this, the loading parameter, $K$, should be also the same. Accordingly, as the pressure, the temperature and the air mass flow rate decrease in model combustor, air-assisting should be applied properly. Firstly, to know the effect of air-assisting on the spray, the SMD, the volume flux, and the number density distribution were measured both without air-assist and with air-assist.

In Fig.7, it is shown that the jet-type spray produced without air assisting has a SMD of about 90µm, and that the SMD distribution is uniform. The number density and the volume flux are very low. It is believed that there are a few large droplets (200 – 300µm) which are beyond the measurement range of the present APV system (from 0 to 126µm).
distribution is similar to the reference spray without the frontal device (Fig. 5). As shown in Fig. 7, modeling with an appropriate air-assisting is possible. The air assisting pressure should be determined experimentally for a given fuel injector.

Fig. 7 The Effect of Air-assisting on Atomization of Simplex Pilot Nozzle at X=40mm
(Ta=295K, P0=1.013bar, ΔPin=0.9035bar, ΔPout=0.6bar)

Fig. 8 shows the spray characteristics at various air-assisting pressure from ΔPout=0.33bar to ΔPout=1.4bar. When air-assisting is applied together with air supply through the frontal device, the spray pattern and SMD are similar to the reference spray shown in Fig. 6. The increase of air-assisting pressure decreases the representative SMD value from about 45μm to about 35μm. At the inner region of the spray (from r=-10mm to r=+10mm), the SMD and its distributions are similar regardless of the increase in air-assisting pressure. An adequate pressure for air-assisting may be determined from the representative SMD for modeling conditions.

Fig.8 The Effect of Air-assist Pressure on Spray Characteristics at X=40mm
(Ta=295K, P0=1.013bar, ΔPin=0.9bar)

Fig.6 Spray Characteristics of Pilot Nozzle at Idle Regimes
- Reference Spray (ΔP1=9.2bar, ΔP2=16kPa)

As the air through the main nozzle (air-assisting) is added, the spray pattern is significantly changed. The drop size is reduced and the SMD distribution becomes saddle-backed as in the reference spray. The number density and the volume flux are increased, and the
Fig. 9 Spray Characteristics at Various Modeling Conditions at X=40mm (P=1.1013bar)
(at 295K: ΔP_1=0.43bar, ΔP_2=0.8kPa, ΔP_m=0.6bar;
at 340K: ΔP_1=0.55bar, ΔP_2=1.2kPa, ΔP_m=0.8bar;
at 420K: ΔP_1=0.80bar, ΔP_2=2.8kPa, ΔP_m=1.0bar)

To show the spray characteristics at different modeling conditions (temperature), SMD and volume flux are measured at the conditions obtained from Eq.(9) and Eq.(10). SMD distributions at different modeling conditions are similar as shown in Fig.9. This confirms that the present modeling criteria are valid. The validity of the modeling criteria for a fuel spray will be verified in a subsequent work by the authors.

Comparison of the spray characteristics between the reference spray and the modeling spray at various axial distances is given in Fig.10 and Fig.11. The modeling sprays show, in general, the characteristics similar to the reference spray. As the modeling temperature approaches the idle temperature, the modeling sprays become more representative of the reference spray.

CONCLUSIONS
The modeling of sprays for simulating the idle regime of combustor at atmospheric conditions was carried out. Modeling criteria were obtained, and modeling conditions were calculated with the criteria. Visualizations and measurements of the characteristics of the modeling sprays were conducted to compare with the reference spray. The main conclusions of the present study are as follows:

The visualization showed qualitatively that a low pressure spray can be similar to a high pressure (idle) spray if it is assisted by air. The APV measurement showed that the distribution of droplet size and fuel concentration of a high pressure (idle) spray may be simulated by a low pressure (atmospheric), air-assisted spray. Spray characteristics at various modeling conditions appeared very similar, indicating that the modeling criteria used in the present study are valid.

Once the simulated spray characteristics are obtained, it is supposed that the combustor characteristics of idle regime may be simulated at atmospheric conditions by maintaining the loading parameter constant. However, this should be verified in combustion tests. The present study on the modeling of spray characteristics is the first stage work for the modeling of combustor characteristics.
Fig. 11 Volume Flux Distributions at Various Modeling Conditions
(at 295K: ΔP₁ = 0.43 bar, ΔP₂ = 0.9 kPa, ΔP₃ = 0.6 bar;
at 340K: ΔP₁ = 0.55 bar, ΔP₂ = 1.2 kPa, ΔP₃ = 0.8 bar;
at 420K: ΔP₁ = 0.6 bar, ΔP₂ = 2.8 kPa, ΔP₃ = 1.0 bar)

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