# Technical Notes

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## Lean Direct Wall Injection Mode Atomization of Liquid Jets in Swirling Flow

Xiaohui Gong,* Kyung J. Choi,† and Nicholas P. Cernansky‡
*Drexel University, Philadelphia, Pennsylvania 19104*

### Introduction

THE environmental and energy challenges for gas turbines require new combustion concepts.[1] The technique described in this study is called lean direct wall injection (LDWI), and it can be described as injection of a liquid fuel jet from the combustor wall, without premixing and prevaporization, directly into the swirling flow of the main combustor.[2,3]

Liquid jet atomization is a critical process for LDWI because the fuel is not premixed and prevaporized and the combustion efficiency and NOx emission of this concept depend heavily on the fuel distribution. The behavior of a liquid jet injected transversely into a high-velocity crossflow has been examined in both supersonic and subsonic flows largely through experiment.[4–7] However, results from angled injection in the crossflow regime are not directly applicable to the swirling flow regime. It will be necessary to produce uniform and rapid atomization of the fuel jet in LDWI to form a uniform gaseous-phase fuel and air mixture in the practical application. It was the purpose of this investigation to examine the effects of atomization factors on the breakup and atomization processes of liquid jets in swirling flow.

In the present study, as the first stage toward understanding the combustion phenomena in a LDWI mode, the hydrodynamic behavior of wall-injected liquid jets in confined cold swirling air flows were investigated.

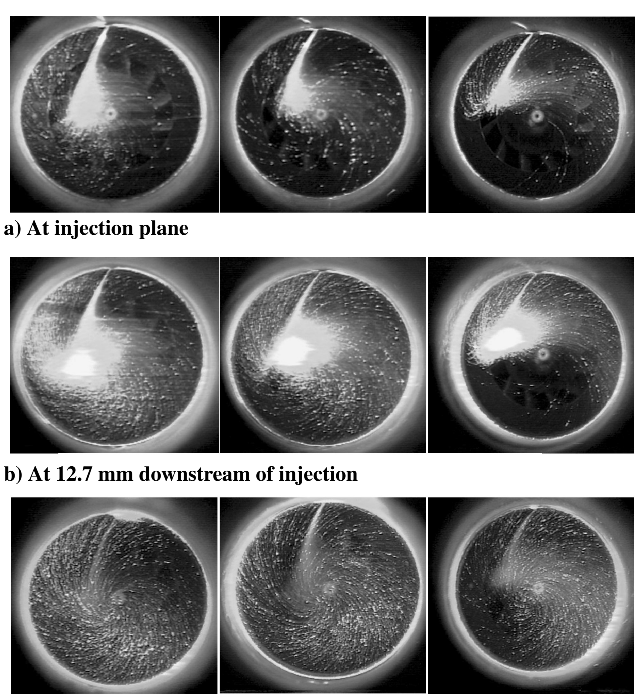
### Results and Discussion

Three vane-type swirlers with thin vanes of different constant chord and angle were designed in accordance with the dimensions calculated in a computational study[8] to produce swirling flow with a recirculation zone. Swirl numbers (SN) calculated are 0.49, 0.86 and 1.48, corresponding to the swirler vane angles $\alpha$ of 30, 45, and 60 deg respectively.

Liquid jets injected from five simple round hypodermic injectors with diameters $D$ of 1.19, 0.84, 0.60, 0.515 and 0.344 mm were used to characterize the initial breakup and subsequent jet atomization in the swirling airflows. With water as the test liquid, the parameters that affect the atomization phenomena, such as momentum rate ratio of air to jet, liquid jet inclination angle, and swirler configurations, which are directly related to SN were experimentally investigated.

Figure 1 shows instantaneous photographs of atomization phenomena of the same injector with $D = 0.515$ mm at different inclination angles $\theta$ at three different planes with $\text{SN} = 0.86$, $\alpha = 45$ deg, air moment rate $\dot{M}_{\text{air}}$, $\rho \text{AV}^2$, of 0.889 N, and jet momentum rate $\dot{M}_{\text{jet}}$ of 0.086 N. The photographs show the typical effects of the liquid jet inclination angles at the $r - \theta$ plane on the atomization phenomena. The jet atomization phenomena were very sensitive to the liquid jet inclination angle in the $r - \theta$ plane. Misalignment of an injector can cause an unbalanced impingement of liquid particles onto the inner wall of the test section (Fig. 1 left- and right-hand sides). It was also found that with $\theta = 35 \pm 1$ deg, the distribution of droplets remained relatively uniform. Experiments were conducted for all five injector sizes of interest to check if the injector diameter has an influence on the optimum angle. All experiments show similar results, namely, there is an optimum inclination angle for each specified swirler regardless of injector size, that is, $\theta = 35$ deg for swirler with $\alpha = 45$ deg (Fig. 1 center) and $\theta = 42$ and 32 deg for $\alpha = 60$ and 30 deg, respectively.

There are optimum momentum rate ratios of air-to-jet for each injector for different swirlers if injectors are fixed at these optimum angles. An example is given in Fig. 2. With $D = 0.60$ mm, $\text{SN} = 0.86$, $\theta = 35$ deg, and $\dot{M}_{\text{air}} = 9.54\dot{M}_{\text{jet}}$, tests were conducted based on



a) At injection plane

b) At 12.7 mm downstream of injection

c) At 25.4 mm downstream of injection

**Fig. 1 Effect of injection angle on atomization at three different axial locations with $\text{SN} = 0.86$, $\dot{M}_{\text{air}} = 0.889$ N, $\dot{M}_{\text{jet}} = 0.086$ N, and injector located 25.4 mm downstream of swirler: left, $\theta = 30$ deg; middle, $\theta = 35$ deg; and right, $\theta = 40$ deg.**

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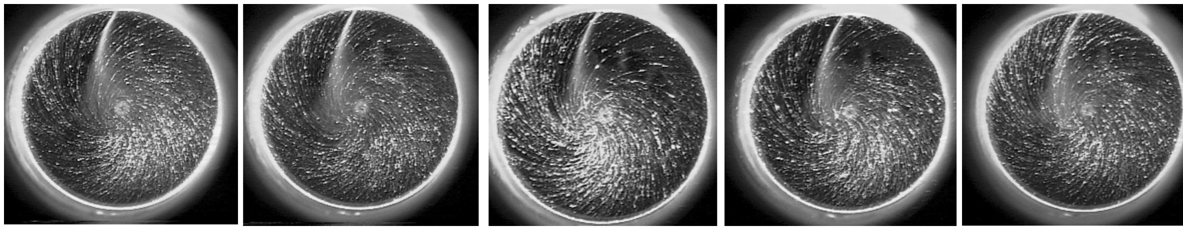
*Ph.D. Student, Department of Mechanical Engineering and Mechanics. Student Member AIAA.

†Research Professor (retired), Department of Mechanical Engineering and Mechanics. Member AIAA.

‡Professor, Department of Mechanical Engineering and Mechanics. Associate Fellow AIAA.



a) b) c) d) e)

**Fig. 2 Optimum atomization at the same air–liquid momentum rate ratio, $\dot{M}_{\text{air}} = 9.54\dot{M}_{\text{jet}}$, D = 0.60 mm, SN = 0.86 and 25.4 mm downstream of injection, and $\theta = 35$ deg: a) $\dot{M}_{\text{air}} = 0.889$ N, $\dot{M}_{\text{jet}} = 0.093$ N; b) $\dot{M}_{\text{air}} = 0.854$ N, $\dot{M}_{\text{jet}} = 0.088$ N; c) $\dot{M}_{\text{air}} = 0.753$ N, $\dot{M}_{\text{jet}} = 0.079$ N; d) $\dot{M}_{\text{air}} = 0.622$ N, $\dot{M}_{\text{jet}} = 0.066$ N; and e) $\dot{M}_{\text{air}} = 0.504$ N, $\dot{M}_{\text{jet}} = 0.054$ N.**

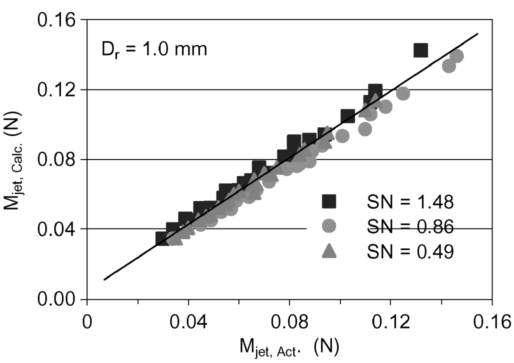



**Fig. 3 Generalized correlation of air/liquid momentum rate ratio for optimum atomization.**

the following procedure: With a fixed air momentum rate, that is, $\dot{M}_{\text{air}} = 0.889$ N (Fig. 2a) $\dot{M}_{\text{jet}}$ was changed until an optimum atomization was found, $\dot{M}_{\text{jet}} = 0.093$ N in this case; then, the air momentum rate was changed to $\dot{M}_{\text{air}} = 0.854$ N (Fig. 2b), and following the same procedure in shown in Fig. 2a, another optimum $\dot{M}_{\text{jet}}$ was found as $\dot{M}_{\text{jet}} = 0.088$ N, and so on. Ultimately, an optimum $\dot{M}_{\text{air}}/\dot{M}_{\text{jet}} = 9.54$ was found for all six air momentum rates. Using the same method, $\dot{M}_{\text{air}}/\dot{M}_{\text{jet}} = 13.47$, 10.28, 7.52, and 5.94 were found for $D = 0.344$, 0.515, 0.84, and 1.19 mm, respectively.

Similar results were also found for swirlers with SN = 0.49 and 1.48. For SN = 0.49, $\dot{M}_{\text{air}}/\dot{M}_{\text{jet}} = 66.6$, 36.7, 33.9, 26.0, and 20.6 were found for injector with $D = 0.344$, 0.515, 0.60, 0.84, and 1.19 mm, respectively. For SN = 1.48, $\dot{M}_{\text{air}}/\dot{M}_{\text{jet}} = 8.0$, 5.60, 5.21, 3.88, and 3.16 were found for injector with $D = 0.344$, 0.515, 0.60, 0.84, and 1.19 mm, respectively.

Figure 2 also shows an example of the effect of air momentum (or air velocity) on the atomization. Airflows with high momentum rate (Fig. 2a) generated faster radial dispersion and produced smaller size particles in the interesting planes.

The following equation was generated to indicate the correlation between optimum atomization and air momentum rates $\dot{M}_{\text{air}}$, jet momentum rates $\dot{M}_{\text{jet}}$, and injector diameter $D$ for each swirler, where $D_r = 1$ mm is as a reference diameter employed to cancel out units in the right side of the equations:

$$\dot{M}_{\text{air}}/\dot{M}_{\text{jet}} = A(D_r/D)^{1.5} \tag{1}$$

where $A = 23.3, 6.70$, and 3.57 for $\alpha = 30$, 45, and 60 deg, respectively.

The fact that swirler configurations play an important role in the jet breakup process leads to the following correlation for optimum atomization and air momentum rates $\dot{M}_{\text{air}}$, jet momentum rates $\dot{M}_{\text{jet}}$, injector diameter $D$, and swirler configurations:

$$\dot{M}_{\text{jet}}/\dot{M}_{\text{air}} = 0.41(D/D_r)^{\frac{2}{3}}(\text{SN})^{\frac{1}{4}}(\sin\alpha)^3 \tag{2}$$

In Fig. 3, the vertical axis indicates the calculated $\dot{M}_{\text{jet}}$ based on tested $\dot{M}_{\text{air}}$ and Eq. (2), and the horizontal axis indicates the measured experimental$\dot{M}_{\text{jet}}$. It shows a good agreement between the experiment results and the calculations.

## Conclusions

The current experimental investigation allows us to make the following conclusions.

1) For LDWI, the atomization phenomena are sensitive to parameters such as jet inclination angle, momentum rate ratio of air-to-jet, swirl number, and injector diameter.

2) There are optimum jet inclinations angles at which uniform atomization can be quickly reached. In this study, optimum jet inclination angles were found as 32, 35, and 42 deg under swirler vane angles $\alpha = 30$, 45, and 60 deg.

3) For the three different swirler configurations tested, each injector exhibited a linear relation between air momentum rate and liquid jet momentum rate for optimum atomization. Five different injectors were tested for each swirler, and a modified correlation that collapsed the data for each swirler was found.

4) It was possible to develop a generalized correlation between air momentum rate and liquid jet momentum rate for optimum atomization based on swirler configuration and injector diameter.

However, the discussions and conclusions were based on image observation and, hence, are qualitative. Further image processing and analysis is needed to determine quantitatively the atomization parameters in a confined geometry, such as centrality of particles, degree of spread of particles, and total area ratio of particles. Droplet size also has a strong impact on the combustor design. Further cold-flow experiments need to be conducted at high air pressure and velocity to verify the accuracy of the correlations of the present study before they can be considered adequate for LDWI combustion at high velocity and high temperature.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