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Rectangular liquid jets injected transversely into subsonic crossflow

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ABSTRACT: Rectangular liquid jets injected into gaseous crossflow were experimentally investigated. In this study, water was used as the working fluid. Four rectangular injectors with aspect ratios of 1, 2, 3 and 4 were manufactured to study the physics of jet flow. The backlight shadowgraphy technique along with high-speed photography was employed to capture the instantaneous physics of the liquid jet flow. Based on the flow visualizations, different breakup regimes including column breakup, arcade breakup, bag and multiple breakup were identified. Trajectory and width of the liquid jets were measured using an in-house image processing program. Effects of momentum ratio, aspect ratio and gas velocity on trajectory and width were investigated. The results showed that the momentum ratio was most effective on the jet trajectory while aspect ratio was of least importance. Also, a mathematical model was suggested to estimate the trajectory of liquid jets. In this model, jet Weber number, gas Weber number and aspect ratio were introduced as the variables. Furthermore, it was revealed that aspect ratio directly influenced the width of liquid jets.

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1. Introduction

Liquid jet injection into gaseous crossflow is a fundamental phenomenon in fluid mechanics that has been widely studied [1]. It is one of the most effective techniques to achieve favorable fuel-air mixture. Because of such important application, many studies were performed to gain a better understanding of the underlying physics of jet injection. In these studies, different flow characteristics such as jet breakup, jet trajectory, droplet dispersion and mixing rate have been investigated [2]. Chen et al. [3], Wu et al. [4] and Mazalon et al. [5] investigated the main characteristics of liquid jet flow. Chen et al. [3] introduced three regimes to describe the consecutive stages of atomization development: 1) liquid core, 2) the ligament, and 3) the atomization or droplet regime. Mazalon et al. [5] proposed different regimes of column breakup based on the Weber number. They provided a range of Weber numbers for each regime. Gas Weber number is defined as $We_g=\rho u_g^2 D/\sigma$, where ρ is the liquid density, u_g is the gas velocity, D is the diameter, and σ is the liquid surface tension. Traditionally, circular nozzles are widely used in different liquid injection systems. However, recently attention has emerged toward non-circular injectors, where by inducing new physics into the liquid flow can be used as passive flow controllers [6]. Recently, the flow dynamics of some rectangular liquid jets was comprehensively studied by Tadjfar and Jaberi [7]. It was shown that axis-switching phenomenon was the main instability of rectangular liquid jets that greatly influenced the flow structure of rectangular liquid jets. Recently, Rezaei and Tajfar [8] studied the trajectory and breakup of elliptical jets injected into the gaseous crossflow. They obtained correlations for jet trajectory and studied the characteristics of bag formation and breakup.

In the present study, rectangular liquid jets are introduced into crossflow for the first time and the physics of the fluid was experimentally studied.

2- Experimental Setup

Experimental setup used in this research consists of three main systems: wind tunnel, liquid injection system and flow visualization.

Experiments were performed in the open circuit, multiphase wind tunnel at the Turbulence and Multiphase Flow Laboratory. The rectangular test section has a cross-section of 300 * 300 mm^2 and a length of 1300 mm. Compressed nitrogen gas was used to apply high pressure over the water storage tank with a capacity of 70 liters. A pressure regulator was also employed to control and fix the pressure. A rotameter equipped with a needle valve was implemented to control and measure the volumetric flow rate of liquid flow. Four rectangular injectors with aspect ratios of 1, 2, 3 and 4 were used.

In this study, the momentum ratios of 20, 30 and 40 were tested at different Weber numbers. High-speed camera with maximum speed of 1200 fps was used that could take shots with the minimum exposure time of 62.5 μs. In order to achieve the profile of the liquid jet that could represent the bulk of the flow, a special image processing program was developed.

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3- Results and Discussion

In this study, the effects of momentum ratio, aspect ratio and volumetric flow rate on the jet trajectory and width were experimentally investigated.

The jet trajectory of RC(2) for the momentum ratios of 20, 30 and 40, and for the jet Weber number Wej = 328.1 is plotted in Fig. 1(a). As shown, the higher the momentum ratio, the greater its penetration into the gaseous crossflow. As the momentum ratio decreases, the gas flow velocity increases so that the aerodynamic effects intensify. These effects cause the liquid jet to bend more in the direction of airflow. Fig. 1(b) shows the jet trajectory for different Weber numbers at the constant momentum ratio of 10. This figure clarifies the influence of escalating air and liquid jet velocities on the trajectory for the RC (4) injector. The results indicate that the Weber number has a significant effect on the liquid jet trajectory. As the Weber number increases, the aerodynamic effects gradually intensify, causing the liquid jet to bend more into the airflow direction. As can be seen in Fig. 1(c), the aspect ratio does not have a significant effect on the jet trajectory and almost the same results are obtained for all of the four nozzles.

According to the experimental results obtained for the liquid jet trajectory, a mathematical model is presented which can be used to estimate the liquid jet trajectory at different flow conditions. The experimental results showed that the Weber number is also effective in the liquid jet trajectory, so this parameter was also included in the model. The correlation is given in Eq. (1) as:

$$\frac{z}{D_j} = 1.516 AR^{-0.078} We_j^{0.46} We_g^{-0.42} \left(\frac{x}{D_j} \right)^{0.45} \qquad (1)$$

The width of the jet was also measured to better investigate the physics of the liquid jets emanated into the low-speed gas flow. Jet width is a parameter that can be used as a measure of the effectiveness of atomization. The wider the jet, the better and more liquid can be dispersed into the air flow and the better mixing will achieve. It was found that momentum ratio had a significant effect on jet width. The lower the momentum ratio, the lower the strength of the liquid jet against the gas flow and thus width was increased. By increasing jet Weber number in the constant momentum ratio, gas Weber number will increase. So that the interaction between gas and liquid increases. Thus the liquid jet dispersion and width increase. It was also revealed that jet width was increased with aspect ratio, which was due to the wider jet cross-section in front of the gas flow. Variation of jet width with an increase of momentum ratio is presented in Fig. 2 for RC(3) jet.

4- Conclusions

In this study, the flow characteristics of rectangular liquid jets injected into the subsonic gaseous crossflow were investigated. Liquid jet flow was visualized by shadowgraph method with the aid of high-speed photography. Using in-house codes developed for image processing, trajectory and width of the jet were measured. In order to investigate the effects of aspect ratio, four rectangular nozzles with aspect ratios of 1, 2, 3 and 4 were implemented.

According to the experiments, Weber number and momentum ratio had a significant effect on the jet trajectory. It was shown that by decreasing the momentum ratio, aerodynamic effects get stronger so that the liquid jet trajectory bends more in the gaseous crossflow. Increasing the gas Weber number increases the drag force on the liquid jet and therefore column of liquid jet bends more through the

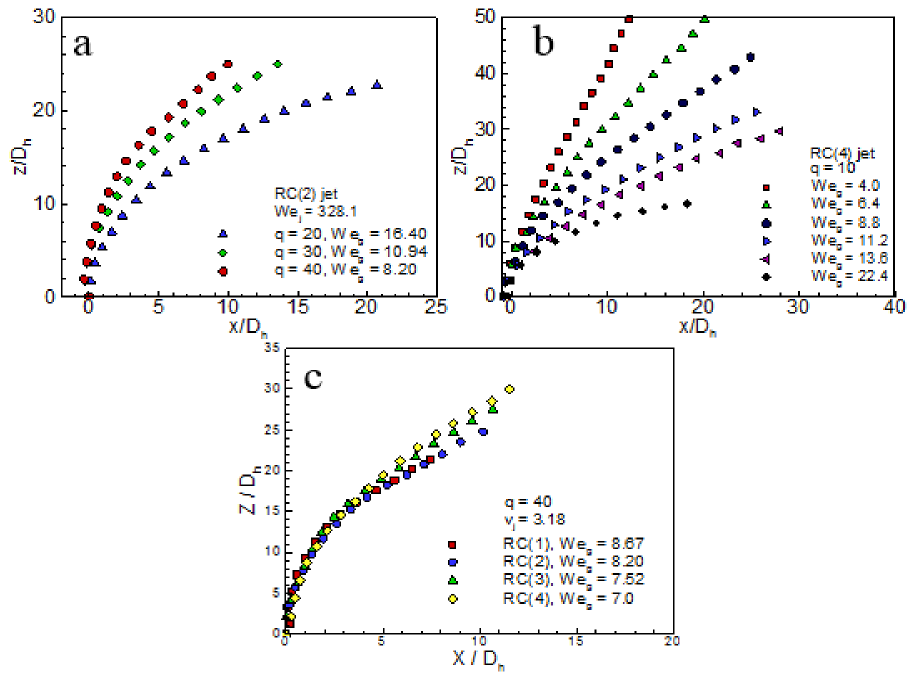

Fig. 1. Trajectory results obtained for a) RC (2) at the momentum ratios 20, 30 and 40 We_j=328.1. b) Effect of gas Weber number for RC (4) at momentum ratio of 10. c) Effect of aspect ratio for the momentum ratio of 40.

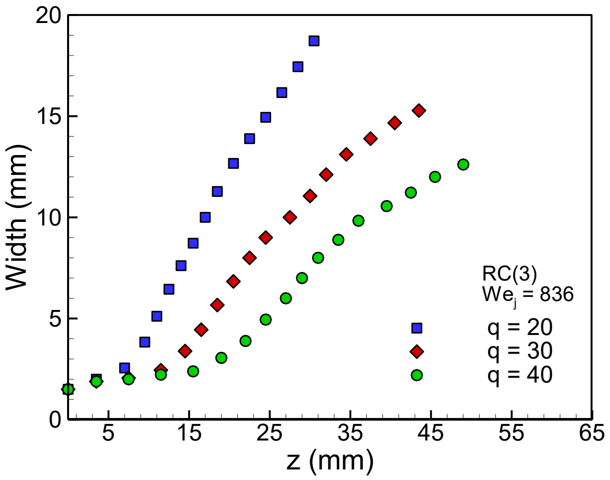

Fig. 2. Variation of RC(3) jet width at different momentum ratios for constant jet Weber number of 836.

gaseous crossflow. Furthermore, it was observed that aspect ratio had no significant effect on jet trajectory. An empirical mathematical model was suggested to estimate the trajectory of liquid jets. Finally, width of liquid jet was measured and its variations with different parameters was examined.

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