Study on the Velocity Distribution of Turbulent Steam Jet from the Non-Circular Nozzle Exit

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1. Introduction

Turbulent jet flow has many applications in various industries such as nuclear power plant, fuel injection, combustion, and propulsion, etc. The containment space of a light-water reactor in nuclear power plants can be filled with water vapor and hydrogen gas during a severe accident such as coolant loss accident occurs due to the pipe fracture. The hydrogen concentration can be affected by water vapor concentration. Thus, the distribution and behavior of the water vapor have a direct impact on the risk of hydrogen explosion accidents in the containment building. The steam jet is one of the main mechanisms for water vapor condensation in the early stages of accident scenarios. It is important to study the flow and condensation characteristics of the turbulent steam jet because it is directly related to the safety of the reactors.

The fracture of the coolant pipe can be caused by local wall thinning, and such a fracture surface may appear in the form of non-circular orifice holes. Previously, several researchers have numerically and experimentally studied steam jets discharged from the pipe under various initial conditions [1, 2]. However, there is no study about steam jet discharged from non-circular nozzle exits. In this study, we investigated the velocity distributions of water vapor jets generated from orifice nozzles with non-circular exits.

2. Experimental Methods

Fig. 1 shows the schematic diagram of experimental setup. The pressure and mass flow rate of steam jet were controlled to 2 bar and 30 kg/h, respectively. The steam jet was discharged in the direction of gravity through a 10.1 mm diameter orifice nozzle. The orifice nozzle part was composed of a diffuser and a sharp-edged orifice plate (OP). Four different orifices such as circle, square, triangle, and cross shape were tested. In our experiments, the Reynolds number of steam jet was in the range of 80,000 to 85,000. The velocity of water droplets in a turbulent steam jet was measured using a phase Doppler particle analyzer (PDPA; TSI Inc.). In this experiment, the axial and radial velocities were measured at Z/D = 0.8~70 of the turbulent jet.

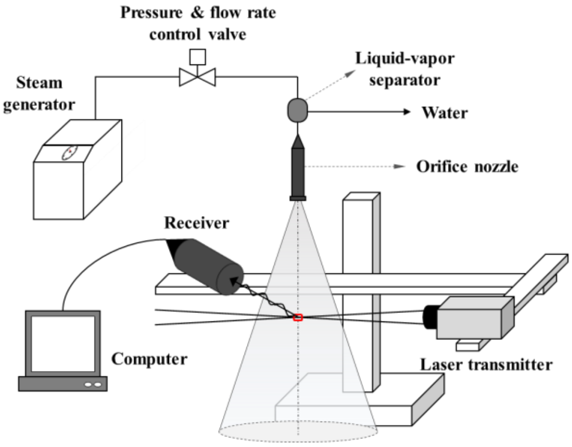

Fig. 1. A schematic diagram of experimental setup.

3. Results and Discussions

3.1 Exit velocity profile

Steam jet from the orifice nozzle was measured from Z/D = 0.8 because PDPA laser light could access to the region of Z/D < 0.8. Fig. 2 shows mean velocity profile at the Z/D=0.8 in 4 OP nozzles and pipe nozzle. U_c is the centerline mean velocity. In general, it is known that the velocity profile at the exit of the pipe nozzle forms a fully developed turbulent flow rate profile, such as a top-hat shape [2]. However, OP nozzles had a constant velocity and then decreased rapidly as radial distance increased. The maximum value of centerline velocity was 120 m/s with the cross OP, and the minimum value at 92 m/s with the circle OP nozzle.

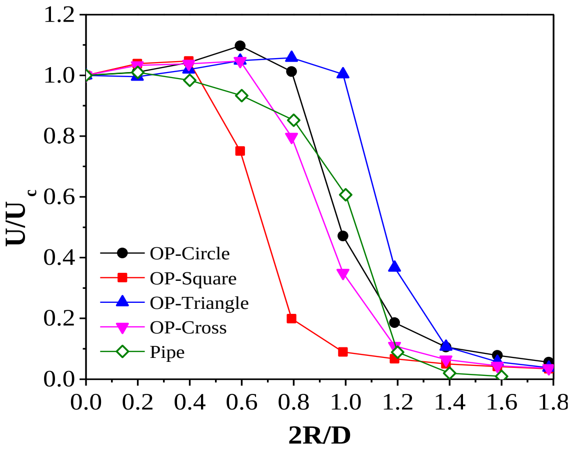

Fig. 2. Mean velocity profile at Z/D=0.8.

3.2 Axial velocity profile

Fig. 3 shows the mean streamwise velocity decay along the jet centerline. U_m is the maximum of U_c. The difference between the OP and the pipe nozzle is clear in near-field. According to Mi and Nathan, air jets generated from orifice nozzles did not have a maximum velocity at the exit due to the effect of vena contracta. Thus, the centerline velocity increases in the near-field and then decreases from the intermediate-field [3]. The steam jet in this study showed that the vena contracta is present for all OP steam jets, and the velocity increased rapidly after the potential core, Z/D = 4~5. In comparison, the circular pipe had the same U_m and U_c in the potential core, and the vena contract did not appear.

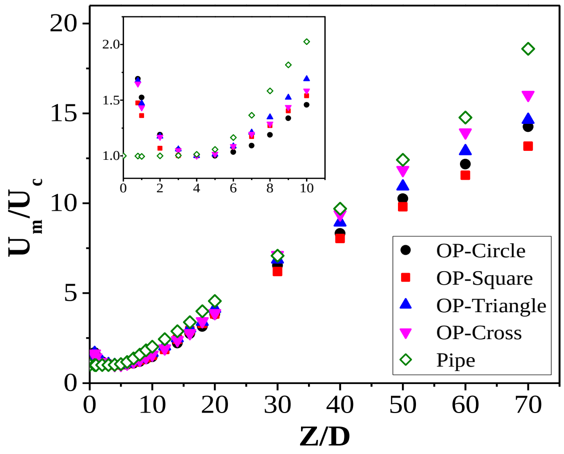

Fig. 3. Mean streamwise velocity decay along the jet centerline.

3.3 Velocity self-similarity

Fig. 4 shows the non-dimensional radial velocity of the water vapor jet from circle orifice Fig. 4 shows the self-similarity characteristics of the radial velocity distribution at various Z/D s in the fully developed region. The self-similarity of velocity distribution can be fitted with the following Gaussian fitting equation.

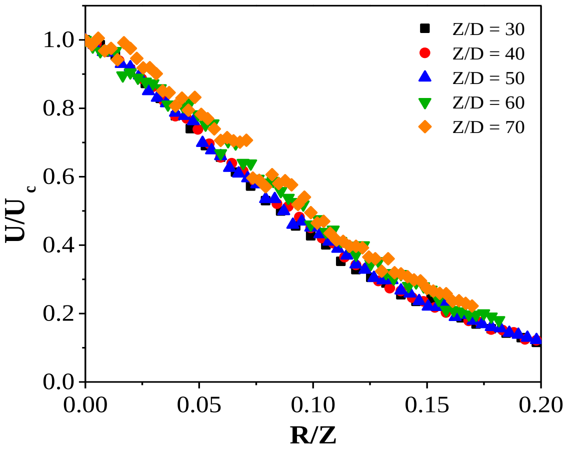

Fig. 4. Velocity self-similarity of water vapor jet from circle OP nozzle.

$$\frac{U}{U_c} = \exp\left[-C_v\left(\frac{\mathrm{R}}{\mathrm{Z}}\right)^2\right] \qquad (1)$$

The velocity Gaussian constant (C_v) was obtained by using the least squares method. The velocity self-similarity equation constant for all orifices are shown in Table I. The average constant value for all orifices is 76.13, which is similar to values from previous research on steam jets discharged from the circular pipe. [1, 2].

Table I: Velocity Gaussian constants from all OP nozzles.

Orifice	**C_v**
Circle	72.27
Square	74.87
Triangle	74.18
Cross	81.86
Average	76.13

4. Conclusions

In this study, we investigated on the velocity distribution of steam jet generated from orifice nozzles having different exit shapes. We found that the steam jet generated from orifice nozzles exhibits different characteristics from pipe nozzles under the effect of vena contracta. In addition, the normalized velocity profiles indicated that there is a self-similarity in the fully developed region. Because the orifice plate was similar to the fracture surface of a pipe undergoing wall thinning, the present study can be helpful to understand the condensation characteristics of the steam jet in the containment.

5. Acknowledgements

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REFERENCES

[1] D. Kim, J. Kim, S. Cho, K. Cho, and W. G. Shin, W. G, Experimental and numerical study of a condensing steam jet, Journal of Nuclear Science and Technology, pp. 1-18, 2022.
[2] J. Cha, S. Lim, T. Kim, and W. G. Shin, The effect of the Reynolds number on the velocity and temperature distributions of a turbulent condensing jet. International Journal of Heat and Fluid Flow, Vol. 67, pp. 125-132, 2017.
[3] J. Mi and G. J. Nathan, Statistical properties of turbulent free jets issuing from nine differently-shaped nozzles. Flow, Turbulence and Combustion, Vol. 84, pp. 583-606, 2010.