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# Helium-Air Exchange Flow Rate Measurement Through a Narrow Flow Path

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## 1. Introduction

Buoyancy-driven exchange flows of helium-air were investigated through horizontal and inclined small openings. Exchange flows may occur following a window opening as ventilation, fire in the room, over the escalator in the underground shopping center as well as a pipe rupture accident in a modular high temperature gas-cooled nuclear reactor. Fuel loading pipe is located in the inclined position in the pebble bed reactor such as Modular reactor (Fumizawa, 2005, Kiso, 1999) and AVR(El-Wakil, 1982, Juni-1965, 1965).

In safety studies of High Temperature Gas-Cooled Reactor (HTGR), a failure of a standpipe at the top of the reactor vessel or a fuel loading pipe may be one of the most critical design-base accidents. Once the pipe rupture accident occurs, helium blows up through the breach immediately. After the pressure between the inside and outside of the pressure vessel has balanced, helium flows upward and air flows downward through the breach into the pressure vessel. This means that buoyancy-driven exchange flow occurs through the breach, caused by density difference of the gases in the unstably stratified field. Since an air stream corrodes graphite structures in the reactor, it is important to evaluate and reduce the air ingress flow rate during the standpipe rupture accident.

Some studies have been performed so far on the exchange flow of two fluids with different densities through vertical and inclined short tubes. Epstein(Epstein, 1988) experimentally and theoretically studied the exchange flow of water and brine through the various vertical tubes. Mercer et al. (Mercer, 1975) experimentally studied an exchange flow through inclined tubes with water and brine. He performed the experiment in the range of  $3.5 < L/D < 18$  and  $0 \text{ deg} < \theta < 90 \text{ deg}$ , and pointed out that the length-to-diameter ratio  $L/D$ , and the inclination angle  $\theta$  of the tube are the important parameter for the exchange flow rate. Most of these studies were performed on the exchange flow with a relatively small difference of the densities of the two fluids (up to 10 per cent). However, in the case of HTGR standpipe rupture accident, the density of the outside gas is at least three times larger than that of the gas inside the pressure vessel. Few studies have been performed so far in such a large range of density difference. Kang et al. (Kang, 1992) studied experimentally the exchange flow through a round tube with a partition plate. Although we may think that the partitioned plate, a kind of obstacle in the tube, decrease the exchange flow rate, he found that the exchange flow rate is increased by the partition plate because of separation of an upward and downward flow.

The objectives of the present study are to investigate the behavior of the exchange flow, i.e., exchange flow through the round long tube by several flow visualization method, then to evaluate the exchange flow rate by the PTV and PIV methods and mass increment with helium-air system. Therefore the following methods are investigated in the present study.

1. Smoke wire method
2. The optical system of the Mach-Zehnder interferometer
3. The method of the mass increment

## 2. Smoke wire method

### 2.1 Experimental apparatus and procedure

The smoke wire method was used for the present investigations. Figure 1 shows a typical sketch of the apparatus. It consists of a smoke pulse generator, thin Nichrome wire with oil and a test chamber. This figure also shows the high-speed camera system, and it transfers the visual digital data to the personal computer for data acquisition. The experimental procedure is as follows. The test chamber is filled with pure helium. By removing the cover plate placed on the top of the tube, exchange flow, i.e., exchange flow of helium and air is initiated. At such condition, the smoke pulse generator ignites the high voltage. Immediately a smoke appeared and visualized the helium up flow and the air down flow in the flow path in the long tube. Test chamber diameter and height are 350 mm, the long tube on the test chamber diameter(=D) are 17.4 and 20mm, length of it(=L) are 200 and 319mm. They denote  $L/D=10$  and  $L/D=18.3$  respectively. It simulates a typical long tube. The inclination angle  $\theta$  is 30 deg. The smoke wire conditions are as follows. The voltage is around 250 (V), current duration is 30 m sec, and the oil of thin wire is CRC-556. The high-speed camera system using D-file records the visual data up to 1600 frames in a second. Upward flows peak velocity measured by PTV method.

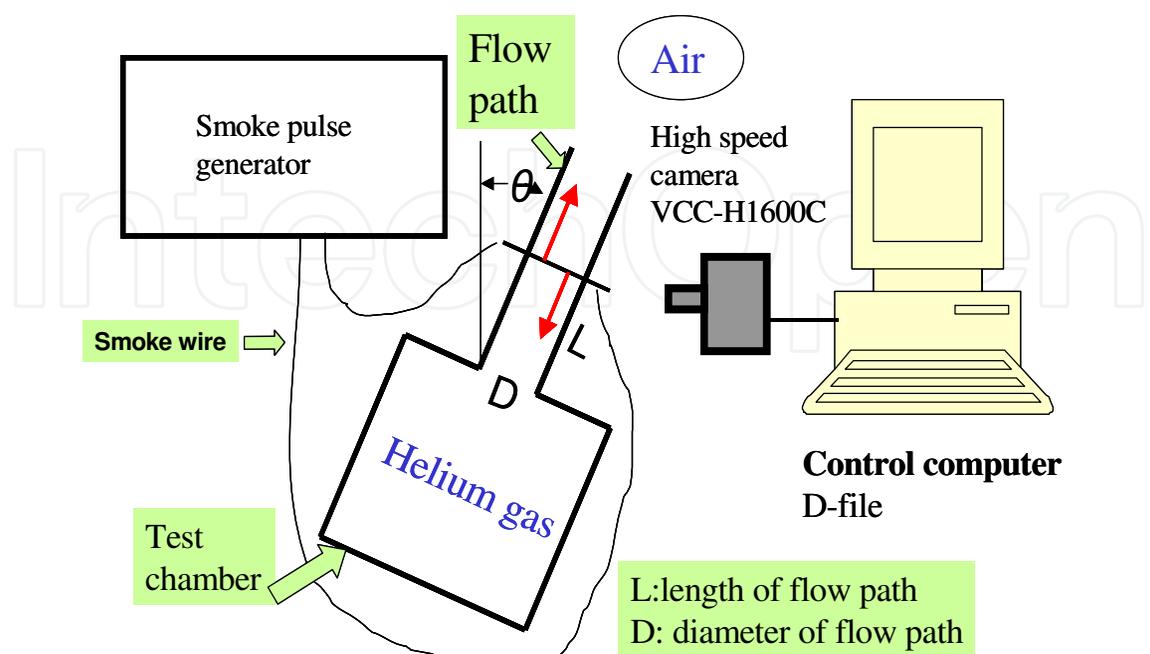


Fig. 1. Exchange Flow Apparatus of Smoke Wire Method High speed camera system

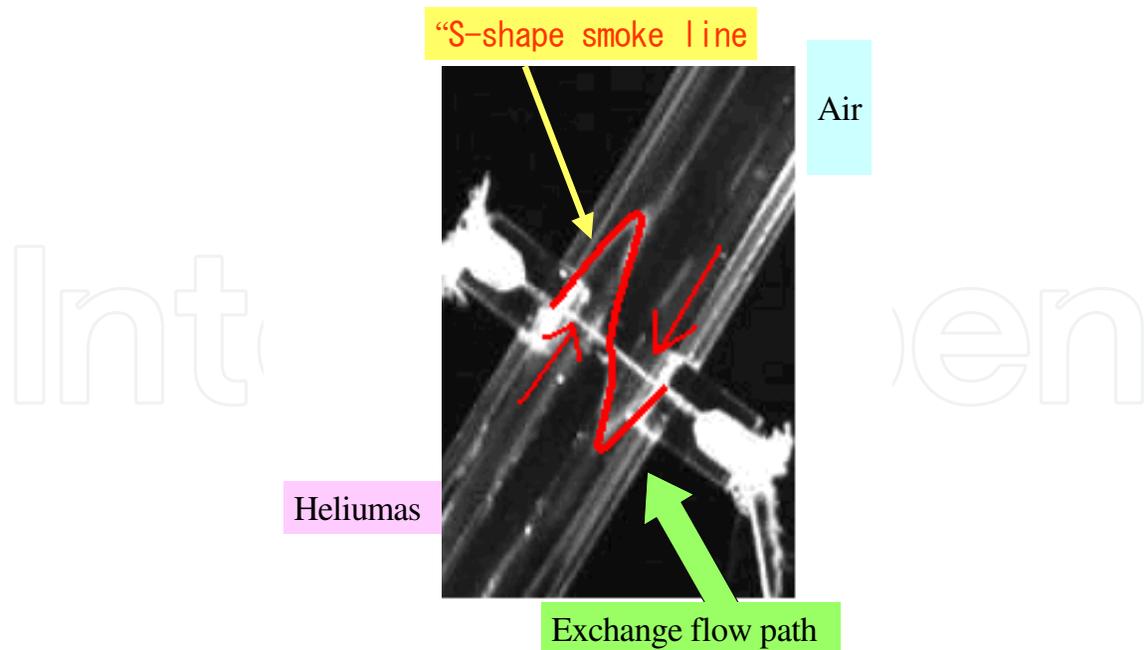


Fig. 2. Mechanism of exchange flow

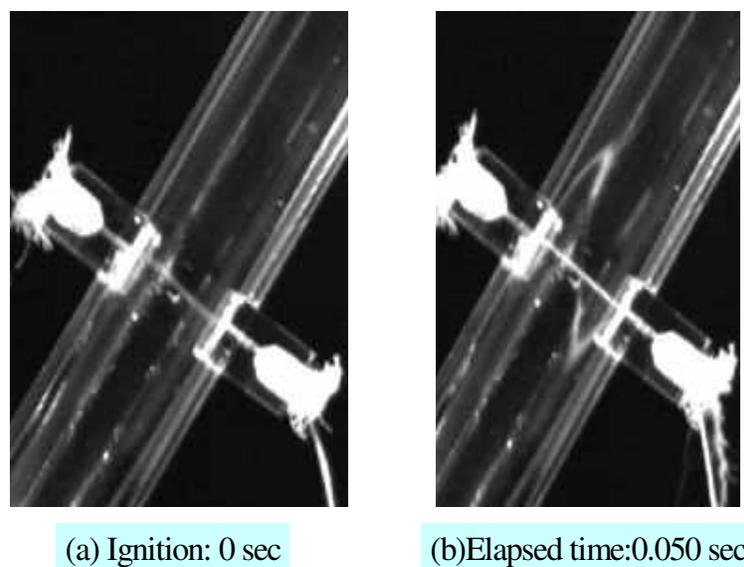


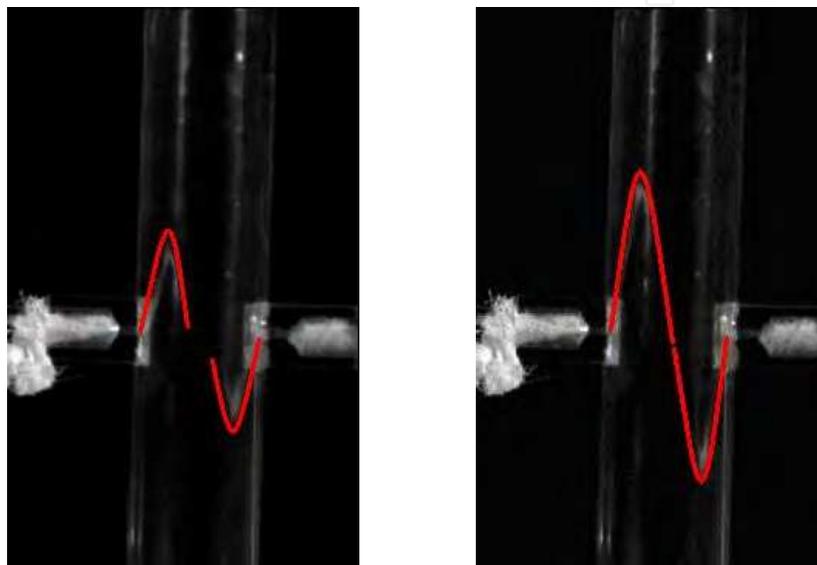
Fig. 3. The visualized data listed along the elapsed time ( $L/D=18.3$ , flame rate=200 f/s,  $\theta=30$  deg)

## 2.2 Results

The typical exchange flow in the tube was visualized in the figure 2. The visualized exchange flow resembles to the S-shape. The flames are detected 200 and 500 flames in a second by the high-speed camera. The visualized data listed along the elapsed time in the figures 3 and figure 4, respectively. It is clearly visualized that helium up-flow along left hand side and air down-flow along right hand side. Figure 5 shows time history of the upward flow peak velocity measured by PTV. In the case of  $L/D=18.3$ , the average velocity value  $U_0$  is evaluated as 0.315 m/s. In the case of  $L/d=10$ , the average velocity value  $U_0$  is

evaluated as 0.662 m/s. It means that high exchange velocity detects in low L/D ratio. Figure.6 shows the visualization data of PIV measurement of 0.050sec after ignition ( $L/d=18.3$  and flame rate= $200$  f/s). The adopted mesh size is  $40 \times 10$  points in the flow area. The upward peak velocity was measured to 0.517 m/s. It means the value is higher than average velocity in this case. The exchange flow rate  $Q$  is derived as follows assuming parabolic flow profile, where  $r$  is the radius of flow path of the horizontal direction.

$$Q = \frac{2\pi U_0 r^2}{9} \quad (1)$$



(a) Elapsed time 0.062 sec

(b) Elapsed time 0.082 sec

Fig. 4. The visualized data listed along the elapsed time ( $L/D=10$ , flame rate= $500$  f/s,  $\theta=30$  deg)

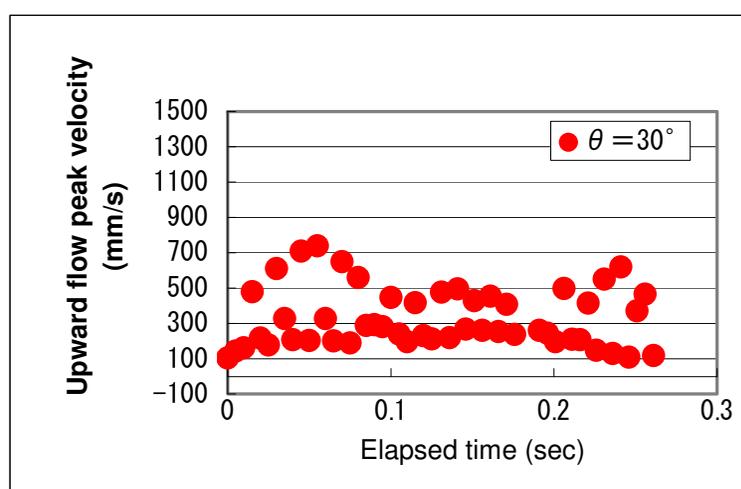


Fig. 5. Upward flow peak velocity measured by PTV method ( $L/D=18.3$ )

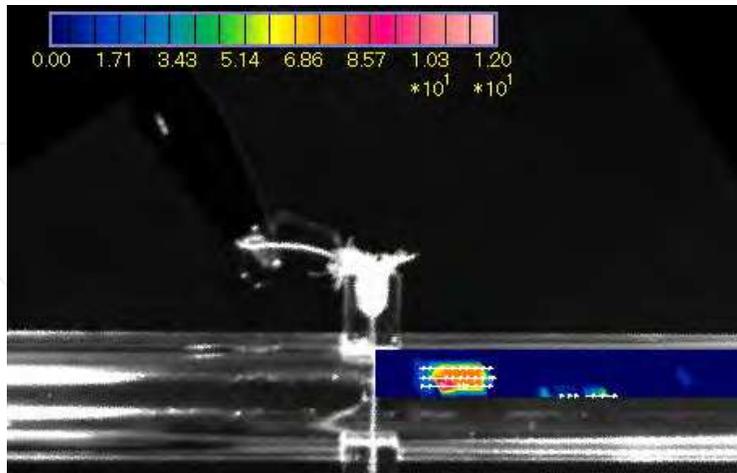


Fig. 6. The visualization data of PIV measurement of 0.050sec after ignition ( $L/D=18.3$  and flame rate= $200 \text{ f/s}$ ,  $\theta = 30 \text{ deg}$ )

In PIV method, the exchange flow rate  $Q$  is calculated as  $1.47 \times 10^{-5} \text{ m}^3/\text{s}$  under the condition of  $L/D=18.3$ . Therefore, the densimetric Froude number  $Fr$  is evaluated as 0.202, in this condition Reynolds number  $Re$  is 79.2. In the condition of  $L/D=10$ , the densimetric Froude number  $Fr$  is evaluated as 0.287.

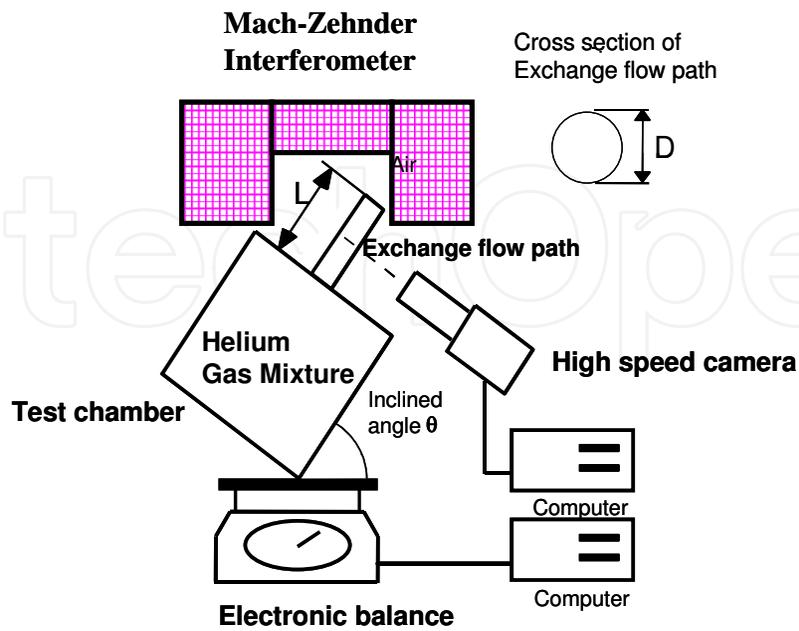


Fig. 7. Experimental apparatus of optical system and mass increment

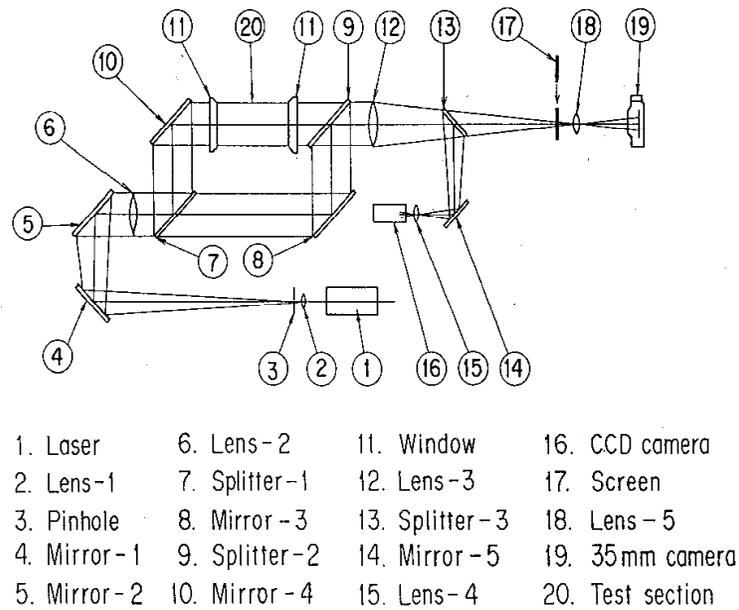


Fig. 8. The mechanism of optical system of the Mach-Zehnder interferometer, MZC-60S

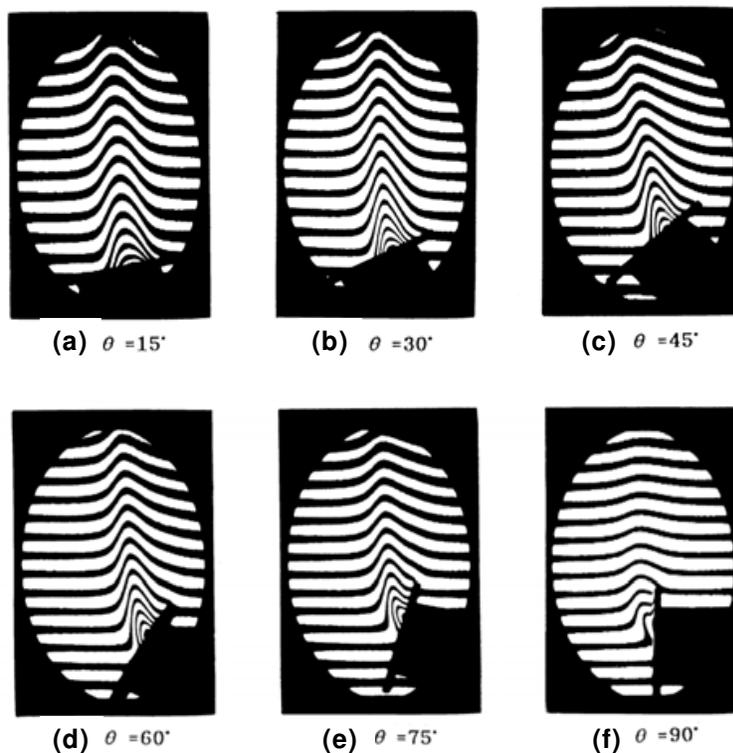


Fig. 9. The typical interference fringes for the inclined long round tube ( $L/D=5$ )

### 3. Optical system of mach-zehnderinterferometer

#### 3.1 Experimental apparatus and procedure

The optical system of the Mach-Zehnder interferometer, MZC-60S is shown in figure 7 and figure 8 to visualize the exchange flow. After being rejoined behind the splitter, the test and reference laser beams interfere, and the pattern of interference fringes appears on the screen.

If the density of the test section is homogeneous, the interference fringes are parallel and equidistant (Keulegan, 1958). If it is not homogeneous, the interference fringes are curved. An inhomogeneity in the test section produces a certain disturbance of the non-flow fringe pattern. The digital camera and high-speed camera using D-file is able to attach to the interferometer.

### 3.2 Results

Figure 9 shows the typical interference fringes for the inclined long round tube ( $L/D=5$ ). The curved interference fringes indicate that the lighter helium flows in the upper passage of the tube. The straight fringes indicate that the heavier air flows in the bottom of the tube. It is clearly visualized that the exchange flows take place smoothly and stable in the separated passages of the tube. This leads to less resistance for the exchange flow in the inclined tubes compared to the vertical ones. In the case of 30 deg, the curvature of the interference fringes is larger than that at other angles, indicating that the exchange flow rate and the densimetric Froude number are the largest at 30 deg.

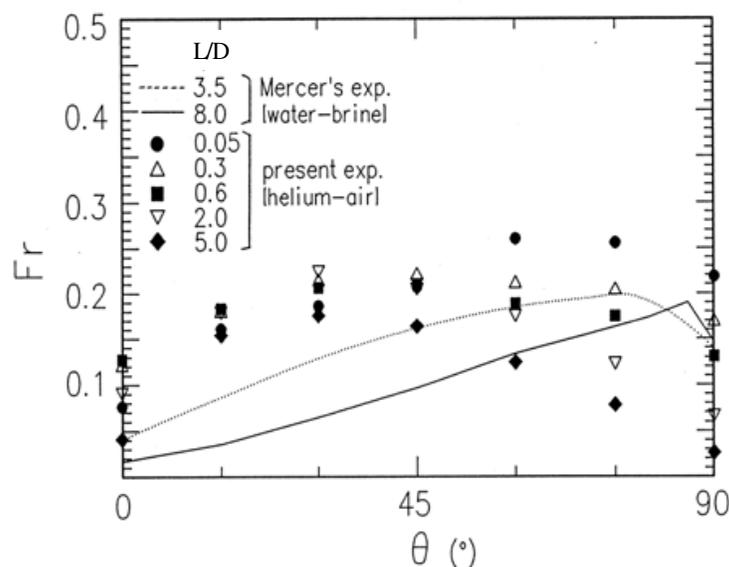


Fig. 10. The relationship between  $Fr$  and inclination angle  $\theta$  with  $L/D$  as a parameter

## 4. Method of mass increment

### 4.1 Experimental apparatus and procedure

The method of the mass increment was used for the investigations. Figure 7 shows a rough sketch of the apparatus. It consists of a test chamber, an electronic balance and a personal computer for data acquisition. The experimental procedure is mentioned in Sec. 2.1. Air enters the test chamber and the mass of the gas mixture in the test chamber increases.

The mass increment  $\Delta m$  is automatically measured by the electronic balance with high accuracy. From mass increment data, the density increment of the gas mixture  $\Delta \rho_L = \Delta m/V$  is calculated. The density increment means the difference of densities of the gas mixture from the density of pure helium in the test chamber. Then, volumetric exchange flow rate is evaluated by the following equation:

$$Q = \frac{V}{\rho_H - \rho_L} \cdot \frac{d(\Delta\rho_L)}{dt} \quad (2)$$

The densimetric Froude number is defined by the following equation derived from the dimensional analysis suggested by Keulegan (Merzkirch, 1974):

$$Fr = \frac{Q}{A} \sqrt{\frac{\rho}{gD\Delta\rho}} \quad (3)$$

In the above equations,  $V$  is the volume of test chamber,  $\rho_H$  the density of air,  $\rho_L$  the density of gas mixture in the test chamber,  $\Delta\rho_L (= \rho_H - \rho_{He})$  = the density increment of the gas mixture,  $t$  the elapsed time,  $U(=Q/A)$  the exchange-velocity,  $\rho(= (\rho_H + \rho_{He})/2)$ ,  $D$  the diameter and  $g$  the acceleration of gravity. The experiments are performed under atmospheric pressure and room temperature using the vertical and inclined round tubes, and using the vertical annular tube. The density of the gas mixture is close to that of helium in the present experiment. The sizes of the tubes are as follows. The diameter of the round tube  $D$  is 20 mm, which is much smaller than that of the test chamber. The inclination angle  $\theta$  ranges from 15 to 90 deg and the height  $L$  ranges from 0.5 to 200 mm.

## 4.2 Results and discussion

It is already known that it is regarded as constant within a time duration when the gas in the upward flow can be assumed helium (Fumizawa, 1989). Figure 10 shows the relationship between  $Fr$  and inclination angle  $\theta$  with  $L/D$  as a parameter. For inclined tubes,  $Fr$  is larger than that for vertical tubes. The black circles show the experimental data for the orifice (i.e.  $L/D = 0.05$ ) and the black rhombuses for the long tube (i.e.  $L/D = 5$ ). Densimetric Froude number reaches the maximum at 60 deg for the orifice and 30 deg for the long tube. It is found that the angle for the maximum  $Fr$  decreases with increasing  $L/D$  in the helium-air system. On the other hand, Mercer's experiments with water and brine indicated that the inclination angle for the maximum  $Fr$  was about 80 deg in the several long tubes investigated. It may depend on the difference of dynamic viscosity between the gas and the liquid.

## 5. Conclusion

1. Flow visualization results indicate that the exchange flows through the inclined round tube take place smoothly and stable in the separated passages of the tube.
2. The visualized inclined exchange flow resembles to the S-shape.
3. In the inclined round long tube, the inclination angle for the maximum densimetric Froude number decreases with increasing length-to-diameter ratio for the helium-air system. On the other hand, this angle remains almost constant for the water-brine system.

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## 7. Nomenclature

A: flow passage area (m<sup>2</sup>)

D: inner diameter of the tube of the flow path (m)

D<sub>c</sub>: inner diameter of test chamber (m)

Fr: densimetric Froude number defined by eq.(3)

g :acceleration of gravity (m/s<sup>2</sup>)

H<sub>c</sub>: inner height of test chamber (m)

L: height of the tube of the flow path (m)

Q :volumetric exchange flow rate defined by eq.(1) (m<sup>3</sup>/s)

r: radius of flow path of the horizontal direction (m)

T: elapsed time (s)

U: exchange-velocity (=Q/ A) (m/s)

U<sub>0</sub>: maximum exchange-velocity (m/s)

V: volume of test chamber (m<sup>3</sup>)

### Greek

m: mass increment in test chamber (kg)

$\Delta \rho_L$ : density increment (=  $\Delta m/V$ ) (kg/m<sup>3</sup>)

$\theta$ : inclination angle of flow path from perpendicular line (deg)

$\rho$ : mean density (=  $\rho_H + \rho_{He}$ )/ 2 (kg/m<sup>3</sup>)

### Subscripts

L : lighter fluid (gas mixture)

H : heavier fluid (air)

He: helium

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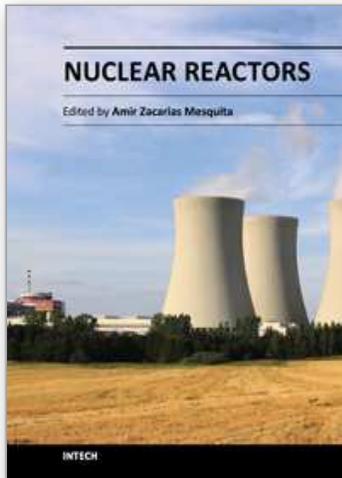
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