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개구부에 삽입한 수직평판이 헬륨 · 공기치환류에 미치는 영향

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Effect of Partition within Opening on Helium-Air Exchange Flow

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Key words : HTTR (High Temperature Engineering Test Reactor), Exchange Flow, Fluids Interference, Partition Length, Mach-Zehnder Interferometer

Abstract

This paper describes experimental investigations of helium-air exchange flow through single opening and partitioned opening. Such exchange flows may occur following rupture accident of stand pipe in high temperature gas cooled reactor. A test vessel with a small opening on top of test cylinder is used for experiments. An estimation method of mass increment is developed and applied to measure the exchange flow rate. A technique of flow visualization by Mach-Zehnder interferometer is provided to recognize the exchange flows. Flow measurements are made with the opening, for partition ratios H_p/H_l in the range 0 to 1, where H_p and H_l are partition length and height of the opening, respectively. In the case of H_p/H_l of 0, flow passages of upward flow of the helium and downward flow of the air within the opening are unseparated (bidirectional), and the two flows interfere within the opening. The unseparated flow increases strength of flow resistance and therefore, the exchange flow rate is minimum through range of the partition ratios. Two flow zones, i.e., separated (unidirectional) flow zone and unseparated (bidirectional) flow zone, exist with increasing the partition length. The exchange flow rate increases with increasing the separated flow zone. It is found that a maximum exchange flow rate exists at H_p/H_l of 1. As a result of comparison of the exchange flow rates by changing the partition ratio, the fluids Interference in the unseparated zone is found to be an important factor on the helium-air exchange flow rate.

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1. Introduction

A high temperature engineering test reactor (HTTR), which is a small scale HTGR, is now being constructed at the Japan Atomic Energy Research Institute (JAERI) to establish and upgrade high temperature gas cooled reactor (HTGR) technologies[1],[2]. In safety study of the HTGR, a rupture of stand pipe at top of the reactor vessel is considered as one of the most critical design-base accidents.

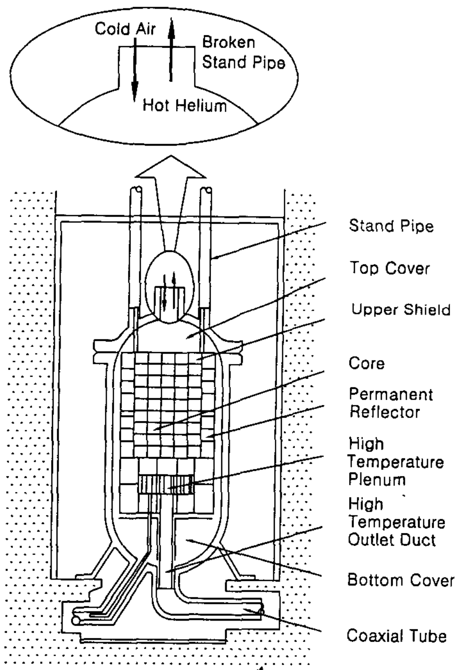


Fig. 1 Schematic diagram of helium-air exchange flow at rupture accident of standpipe in HTTR

Figure 1 shows a schematic drawing of the HTTR. It is a graphite moderated high temperature gas-cooled reactor of 30 MW thermal power and 950 °C outlet helium coolant temperature[1],[2]. When stand pipes rupture, helium coolant gas in high pressure flows immediately through breach out of the reactor vessel. After pressure of the reactor vessel has fallen to that of the atmosphere, the air flows into the reactor vessel, which is caused by buoyancy force due to density difference between the helium inside the reactor vessel and the air outside. The penetrated air reacts with high temperature graphite structure, and it causes corrosion of the graphite components, which results in a severe damage of in-core reactor structures. Therefore, it is important to evaluate the penetrated air flow rate during the accident.

From a survey of the literature, it appeared that some papers dealt with buoyancy-driven exchange flow with brine-water[3]~[6] and air-air[7],[8]. Epstein[3] made measurements of the buoyancy-driven exchange flow with a single opening, for opening ratios H_l/D_l in the range 0.01 to 10, where H_l and D_l are height and diameter of the opening, respectively. Epstein suggested four different flow regimes, as H_l/D_l increased through this range. Most of the above studies on the buoyancy-driven exchange flow have been carried out with a single opening and small density difference. However, the density of cold air outside reactor vessel is at least three times larger than that of gas mixture (helium and hot air) inside the reactor vessel at the stand pipe rupture accident. Fumizawa[9]~[11] conducted experiments for the helium-air exchange flow through the single opening. He reported that experimental results on the helium-air system agreed with those for the Epstein's brine-water system as shown in Fig. 2[9]. There were no studies for the exchange flow through partitioned opening (opening with a vertical partition) in the previous studies of the buoyancy-driven exchange flow. From a fundamental point of view, there is a big difference of flow passages between the partitioned opening and the single opening. Thus, it is necessary to compare exchange flow rate and flow pattern between the two types of opening. In this study, an experiment to investigate effect of the partition ratios H_p/H_l on exchange flow rate is performed, where H_p and H_l are partition length and height of the opening, respectively.

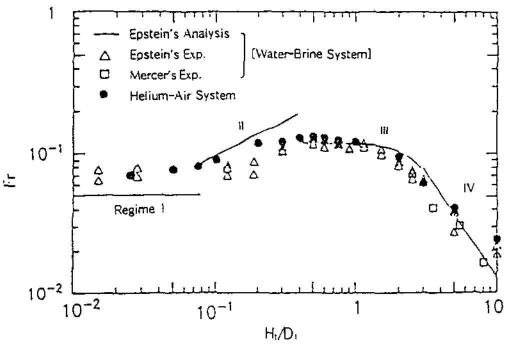


Fig. 2 Comparison of Froude numbers between helium-air system and brine-water system[9]

2. Experimental Apparatus and Procedures

Figure 3 illustrates an experimental apparatus to evaluate the exchange flow rate for the partitioned opening and the single opening systems. The experimental apparatus is composed of a test vessel, an electronic balance, and a personal computer for data acquisition. The test vessel consists of a test cylinder and opening made from plexiglass. The opening configurations studied are presented in Fig. 4. A vertical partition of rectangular plate is in alignment with center line of the opening to make the partitioned opening as shown in Fig. 4(b), where partition thickness is 0.0005 m. Diameter of the opening D_l is 0.02 m and the partition ratios H_p/H_l are 0, 0.5, and 1, where H_p and H_l are the partition length and height of the opening. Diameter of the test cylinder D_2 is 0.2 m and height of the test cylinder H_2 is 0.4 m. The opening with $H_P/H_l=0$ is the single opening. The test vessel geometry is tabulated in Table 1. The experiments were carried out under the atmospheric pressure and room temperature. The test vessel was filled with pure helium gas initially. The opening's top was sealed with a thin rubber stopper as shown in Fig. 3. On removal of the rubber stopper placed on the top of the opening, the buoyancy-driven exchange flow was initiated and the heavier air was introduced into the test vessel. Thus, the mass of gas mixture in the test vessel increased. Figure 5 shows optical components of Mach-Zehnder interferometer to visualize the exchange flow. Illumination beam (He-Ne laser supplied from light source, wave length 633 nm) collimated by lens 2 is split by beam splitter 1 inclined at 45° into a test beam and a reference beam. The test beam reflected by coated surface of the beam splitter 1 is reflected by mirror 4 in order to cross the test section closed by windows. The beam is then transmitted through the beam splitter 2, forming a test section image on observation screen. At the same time, the reference beam transmitted through the beam splitter 1 is successively reflected by mirror 3 and coated surface splitter 2 before being superimposed on the test beam. The beam splitter 2 imposes the same optical path delay on the test beam that the beam splitter 1 does on the reference one. Consequently, The test beam and the reference beam are mixed beyond the beam splitter 2. The test beam and the reference beam interfere, and interference fringe pattern appears on the screen. If density of the test section is homogeneous, straight parallel equidistant interference fringes appear[12]. If it is inhomogeneous, distorted interference fringes appear. Three programs, i.e., program for measuring mass increment, program for calculation of density increment, and program for calculation of Froude number are used for data processing in the present experiment. The mass increment Δm_t of the gas mixture is measured by means of the electronic balance at regular intervals.

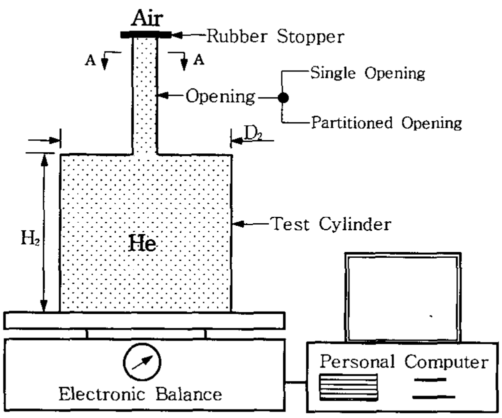


Fig. 3 Schematic diagram of experimental apparatus

$$\Delta m_t = m_{Lt} - m_{H(0)} \qquad (1)$$

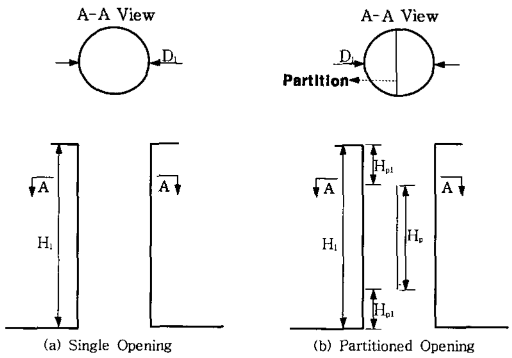
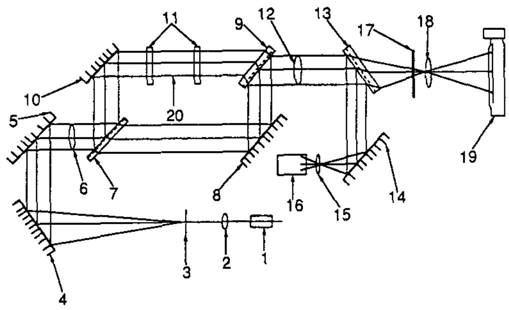


Fig. 4 Schematic diagram of single opening and partitioned opening



1. Laser	2. Lens1	3. Pinhole
4. Mirror 1	5. Mirror 2	6. Lens 2
7. Splitter 1	8. Mirror 3	9. Splitter 2
10. Mirror 4	11. Window	12. Lens 3
13. Splitter 3	14. Mirror 5	15. Lens 4
16. CCD Camera	17. Screen	18. Lens 5
19. 35mm Camera	20. Test Section	

Fig. 5 Optical components of Mach-Zehnder interferometer

The gas mixture's density increment $\Delta \rho_L$ is calculated from the mass increment, and it is given by

$$\Delta \rho_L = \frac{\Delta m_t}{V} \qquad (2)$$

, where V[9] is volume of the test vessel. The exchange flow rate Q through the opening is evaluated by the density increment. Mass balance on the gas mixture gives

$$V\frac{d\Delta\rho_L}{dt} = Q\rho_H - Q\rho_L \quad (3)$$

The exchange flow rate is expressed in the form of Froude number Fr, and it is defined as

$$Fr = Q\sqrt{\frac{\rho_m}{D_1^5 g(\rho_H - \rho_L)}} \quad (4)$$

3. Results and Discussion

Figure 6 illustrates variation of the density increment with time. As expressed in Eq. (2), the density increment of the gas mixture in the test vessel increases because of the exchange flow. Finally, it approaches the density difference between the air and the helium. The exchange flow rate is plotted in the form of dimensionless Froude number. Figure 7 shows variation of the Froude number with time. The Froude numbers at H_p/H_l of 0.5 appear to be constant, and they are almost constant before 200 second at H_p/H_l of 1. They fluctuate after about 200 seconds and thus, these data are not sufficient to explain the trend of the exchange flow rate. Figure 8 is prepared to illustrate relationship between the Froude number and the density increment. This figure shows the variations of Froude numbers are almost constant in the range of $0 \le \Delta\rho_L \le 0.51$ kg/m^3. This means that the density difference between the air and the gas mixture, i.e., buoyancy force is almost constant. Therefore, the Froude number in Fig. 9 is defined as average value of the

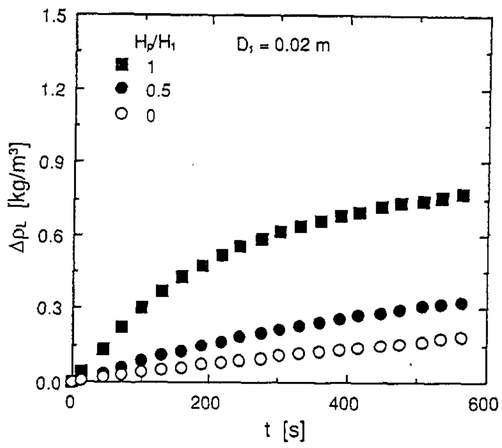


Fig. 6 Variation of density increment with time

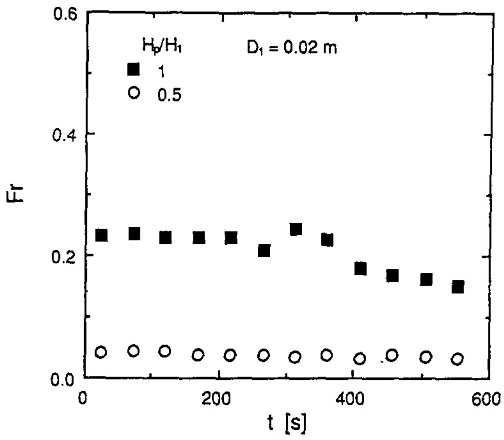


Fig. 7 Variation of Froude number with time

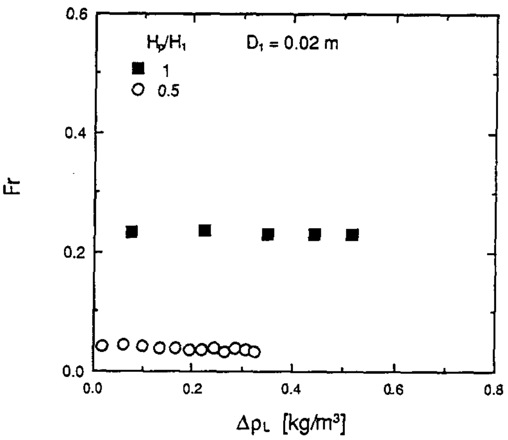


Fig. 8 Varation of Froude number with density increment

Froude numbers in the range of $0 \leq \Delta\rho_L \leq 0.51$ kg/m^3. As already mentioned, experiments for flow visualization were conducted by Mach-Zehnder interferometer to compare flow patterns. Figure 10 shows examples of Mach-Zehnder interferograms for the partition ratios 0, 0.5, and 1. The distorted interference fringes show that the helium flows out of the opening and the straight fringes indicate that the air flows into the opening. Figure 11 shows the air flow in the test cylinder. The air flows vertically into the test cylinder and the air circulates as shown in Fig. 12[13]. The air is mixed with the helium well because of the circulated air flow. The distorted interference fringes do not appear in single opening system (no partition, $H_p/H_1=0$) because of the unseparated flow (bidirectional flow) within the opening as shown in Fig 10. The exchange flow rate at H_p/H_1 of 0 is minimum through range of the partition ratios as shown in Fig. 9. The distorted

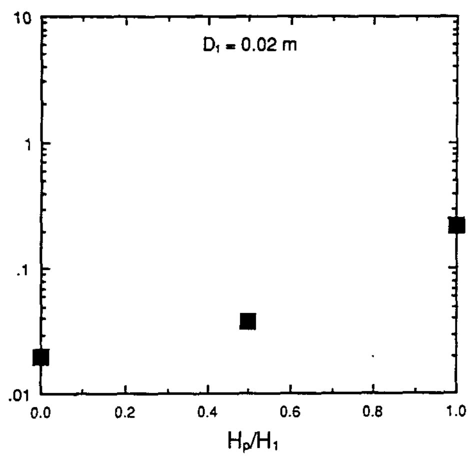


Fig. 9 Comparison of Froude numbers with partition ratio

interference fringes begin to appear with increasing the partition ratio. It means that the helium flows out of the opening and thus, the exchange flow rate increases with increasing the partition ratio as shown in Fig. 9. Two flow zones, i.e., the separated flow zone and the unseparated zone, exist with increasing the partition ratio. The exchange flow rate increases with increasing the separated flow zone as shown in Fig. 9. Fortunately, there was a support for flow visualization of the separated flow by Daigo[14] to be included as a part of this study, as shown in Fig. 12. It is clearly visualized that the helium flows out of left side of the partitioned opening and the air flows into right side of the partitioned opening. It means that the partition forms the separated flow zone within the opening. The gas mixture flow swings a little from left to right in lateral direction at the opening entrance, and condition of the exchange flow at the opening entrance is observed to be unstable as shown in Fig. 12. It indicates that the fluid interference takes place as a resistance to the exchange flow. Based on flow visualizations of Fig. 10, it is clearly revealed that amplitudes of the interference fringes at H_p/H_1 of 1 are larger than those of the interference fringes at H_p/H_1 of 0 and 0.5. The exchange flow due to less flow resistance gives rise to higher amplitude of the fringe. It expedites the exchange flow and air flows into the test vessel easily. Therefore, the exchange flow rate at H_p/H_1 of 1 is maximum through this range as shown in Fig. 9. It indicates that the fluids interference in the unseparated flow zone takes place as a resistance to the exchange flow. A model of two zones to explain mechanism of the exchange flow is suggested as shown in Fig. 13. The separated flow increases the exchange flow

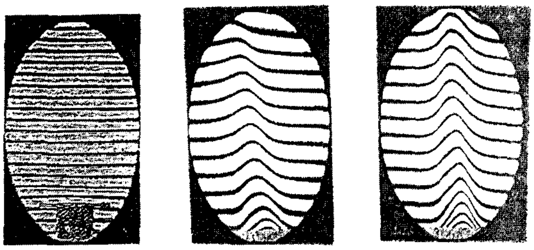


Fig. 10 Comparison of flow visualizations with partition ratio

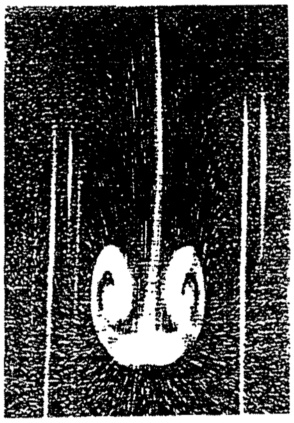


Fig. 11 Flow visualization of air flow in test cylinder[13]

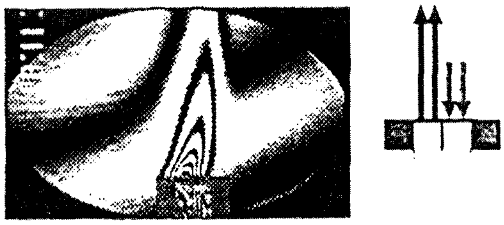


Fig. 12 Flow visualization of separated flow within partitioned opening[14]

rate and the unseparated flow leads to flow resistance. Finally, the exchange flow rate increases with increasing the separated flow zone as shown in Fig. 9.

4. Conclusions

In this paper, the effect of the fluids interference within the opening on the exchange flow rate was confirmed experimentally and discussed. Attention has been focused mainly on flow resistance of the unseparated flow zone. Further study will be required to understand effect of the partition on the exchange flow by mathematical modeling. Conclusions of this paper are summarized as follows:

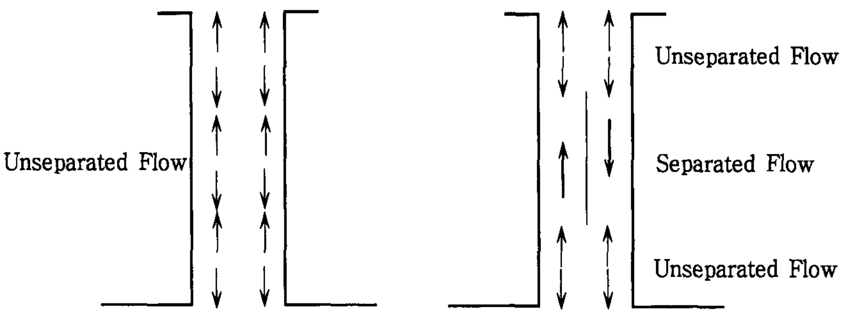


Fig. 13 Schematic diagram of flow patterns within opening

1) The fluid interference in the unseparated zone is found to be an important factor on the helium-air exchange flow.

2) The exchange flow rate increases with increasing the partition ratio. It is found that a maximum exchange flow rate exists at H_p/H_l of 1.

3) The helium-air exchange flow can be visualized by Mach-Zehnder interferometer.

Nomenclature

D_1	diameter of opening (m)
D_2	diameter of test cylinder (m)
Fr	Froude number
g	acceleration due to gravity (m/s^2)
H_l	height of opening (m)
H_2	height of test cylinder (m)
H_P	partition length (m)
H_{Pl}	$(H_l-H_p)/2$ (m)
m	mass (kg)
Δm	mass increment (kg)
Q	exchange flow rate (m^3/s)
t	elapsed time (s)
V	volume of test vessel (m^3)
ρ	density (kg/m^3)
ρ_m	mean density = $(\rho_H+\rho_L)/2$ (kg/m^3)
$\Delta\rho_L$	density increment (kg/m^3)

Subscripts

H	heavier fluid (air)
He	helium
L	light fluid (gas mixture)
t	elapsed time
0	initial condition

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References

[1] JAERI, "Present Status of HTGR Research and Development", JAERI Report, 1992.

[2] Hishida, M., "Researches on Air Ingress Accidents of HTGR", Proc. Int. Conf. on Design & Safety of Advanced Nuclear Power Plants, pp. (18.4-1)-(18.4-7), 1992, Tokyo.

[3] Epstein, M., "Buoyancy-Driven Exchange Flow Through Small Openings in Horizontal Partitions", Trans. of ASME, Vol. 110, pp. 885-893, 1998.

[4] Mercer, A. and Thompson, H., "The Exchange Flow in Inclined Ducts", J. Br. Nucl. Energy Soc., Vol. 14, pp. 327-334, 1975.

[5] Mercer, A. and Thompson, H., "The Purging Flow in Inclined Ducts", J. Br. Nucl. Energy Soc., Vol. 14, pp. 330-340, 1975.

[6] Leach, S. J. and Thompson, H., "An Investigation of Some Aspects of Flow into Gas Cooled Nuclear Reactors Following an Accidental Depressurization", J. Br. Nucl. Energy Soc., Vol. 14, pp. 243-250, 1975.

[7] Brown, W. G. and Solvason, K. R., "Natural Convection Through Rectangular Openings in Partitions-1", Int. J. Heat Mass Transfer, Vol. 5, pp. 859-867, 1962.

[8] Brown, W. G. and Solvason, K. R., "Natural Convection Through Rectangular Openings in Partitions-2", Int. J. Heat Mass Transfer, Vol. 5, pp. 869-878, 1962.
[9] Fumizawa, M., "Experimental Study of Helium-Air Exchange Flow Through a Small Opening", Kerntechnik, Vol. 57, pp. 156-160, 1992.
[10] Fumizawa, M., "Experimental Study on Flow Rate Measurement of Buoyancy-Driven Exchange Flow", J. Nuclear Technology, Vol. 109, pp. 236-245, 1995.
[11] Fumizawa, M., "Experimental Study on Helium-Air Exchange Flow Through a Small Opening", Proc. 3rd Int. Symposium on Fluid Control, Measurement, and Visualization, pp. 333-338, 1991, San Francisco California.
[12] Yang, W. J., Handbook of Flow Visualization, Hemisphere Publishing Corporation, New York, pp. 205-210, 1989.
[13] Fumizawa, M., "2nd Report: Visualization of 3-D Structure of Exchange Flow", J. of V.S.J., Vol. 13, pp. 261-264. 1993.
[14] Tsuru, D., "Multiple Flow Pattern in Buoyancy-Driven Exchange Flow Through Double Openings", Proc. 6th Int. Conference on Nuclear Engineering, pp. 1-10, 1998, California.

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