◎ 硏究論文

Helium-Air Exchange Flow Through Openings with Vertical Partitions

Tae-il Kang*

수직평판을 삽입한 개구부의 헬륨 및 공기 치환류

강 태 일

Key words : HTTR (High temperature engineering test reactor), Exchange flow, Fluids interference, Unseparated flow, Extended partition, Mach-Zehnder interferometer

Abstract

This paper describes experimental investigations of helium-air exchange flow through openings with vertical partitions. Such exchange flows may occur following rupture accident of stand pipe in high temperature gas cooled reactor. Exchange flow rates are investigated experimentally by using partitioned opening and opening with extended partition to assess fluids interference of the exchange flow at the stand pipe rupture accident. A test vessel with the two types of opening on top of test cylinder is used in the 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. Amplitude and progress of interference fringes of the flows are observed and used as a support in comparison with the exchange flow rates. Flow passages of upward flow of the helium and downward flow of the air for both two types of the opening are separated by inserted partition within the opening, but in the case of partitioned opening, unseparated flow is formed at the opening entrance and the two flows interfere. The exchange flow rate for the partitioned opening is not greater than that of the opening with extended partition because of the fluids interference at the entrance of opening. Finally, the fluids interference at the opening entrance is found to be one of important factors on the helium-air exchange flow rate.

* Member of KSME, Chang Shin College(receipt : 2000. 2)

Nomenclature

D_1	diameter of opening (m)
D_2	diameter of test cylinder (m)
D_f	effective diameter of opening (m)
F_r	Froude number
g	acceleration due to gravity (m/s^2)
H_1	height of opening (m)
H_2	height of test cylinder (m)
H_P	length of extended partition (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)
δ	partition thickness (m)
ρ	density (kg/m^3)
ρ_m	mean density=(H+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

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. Figure 1 shows a schematic drawing of the HTTR[1,2] and the HTTR is a graphite moderated high tempera-

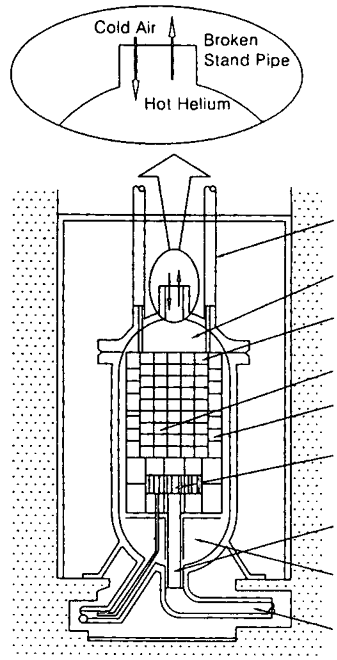


Fig. 1 Schematic diagram of helium-air exchange flow at rupture accident of standpipe in HTTR

ture gas-cooled reactor of 30 MW thermal power and 950°C outlet helium coolant temperature. 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[3,4,5,6] and air-air[7,8]. Epstein[3] made measurements of the

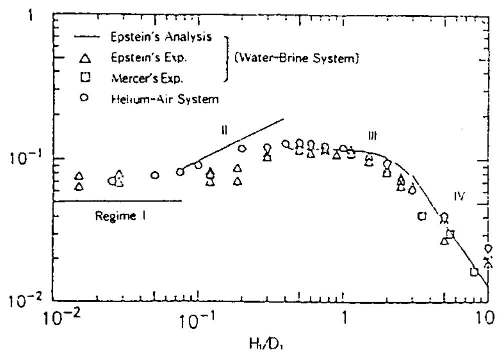


Fig. 2 Comparison of Froude numbers between helium-air system and brine-water system[9]

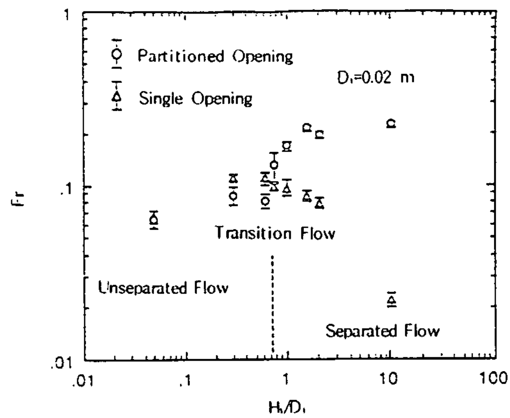


Fig. 3 Comparison of Froude numbers between single opening system and partitioned opening system[12]

buoyancy-driven exchange flow with a single opening, for opening ratios H_1/D_1 in the range 0.01 to 10, where H_1 and D_1 are height and diameter of the opening, respectively. He suggested four different flow regimes, as H_1/D_1 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[9,10,11] conducted experiments for the helium-air exchange flows with the single opening. He reported that experimental results on the helium-air system with the single opening agreed with those for the Epstein' s brine-water system with single opening 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. Kang et al.[12,13,14] performed experiments on the helium-air exchange flow with the partitioned opening and the single opening for opening ratios H_1/D_1 in the range 0.05 to 10 as shown in Fig. 3[12]. 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 configuration between the two types of opening. At lower opening ratios ($H_1/D_1 \leq 0.75$), the exchange flow rates for the partitioned opening system were almost the same as those for the single opening system. However, at higher opening ratios ($H_1/D_1 \geq 0.75$), they were greater than those for the single opening system, because upward flow of the helium and downward flow of the air were separated by the vertical partition within the opening. In Kang' s paper[14], he pointed out effect of fluids interference within the single opening which reduces the exchange flow rate. Based on visual observations by video camera, it is suggested that there is a possibility of the fluids interference at entrance of the partitioned opening. The partition is extended out of the partitioned opening at he entrance and therefore, effect of the fluids interference between the two fluids is blocked by the extended partition. In this study, an experiment to investigate effect of the extended partition on the fluids interference and the exchange flow rate is performed.

2. Experimental Apparatus and Procedures

Figure 4 illustrates an experimental apparatus to evaluate the exchange flow rate for the partitioned opening and the opening with extended partition. 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. 5. A vertical partition of rectangular plate is in alignment with center line of the opening to make the partitioned opening as shown in Fig. 5, where partition thickness δ is 0.0005 m. Diameter of the opening D_1 is 0.01 m and height of the opening H1 is 0.1 m. Length of a side of extended partition H_p is 0.07 m. Diameters and heights of the test cylinder are presented in Table 1. The partition of partitioned opening is extended out of the opening at the entrance to make the opening with extended partition and therefore, the effect of fluids interference between the two fluids is blocked by the extended partition. 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. 4. 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 6 shows optical components of Mach-Zehnder interferometer to visualize the

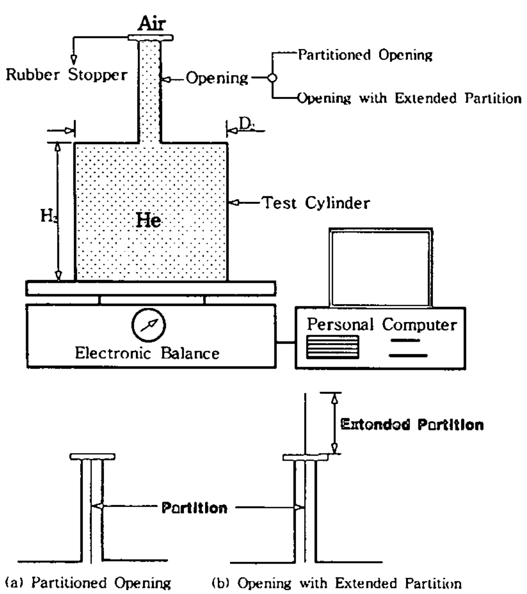


Fig. 4 Schematic diagram of experimental apparatus

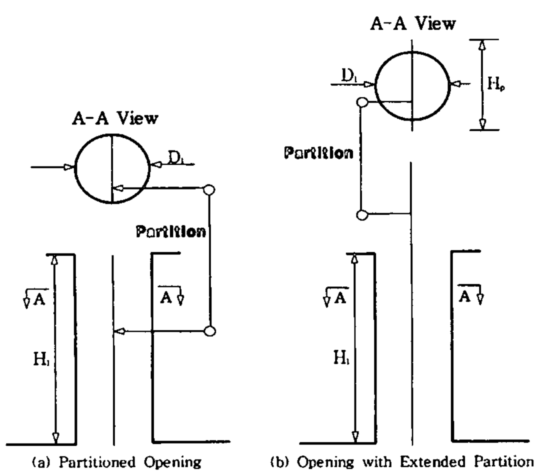


Fig. 5 Schematic diagram of partitioned opening and opening with extended partition

Table 1. Test vessel geometry

Opening Type	D_1 (m)	H_1 (m)	D_2 (m)	H_2 (m)	H_p (m)
Partitioned Opening	0.01	0.1	0.1	0.2	
Opening with Extended Partition	0.01	0.1	0.19	0.4	0.07

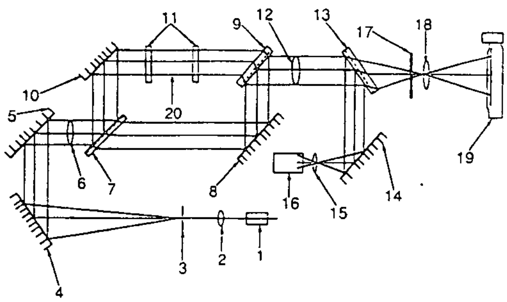


Fig. 6 Optical components of Mach-Zehnder interferometer

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[15]. 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.

$$\Delta m_t = m_{L_t} - mH_{e_0} \tag{1}$$

The gas mixture' s density increment L is calculated from the mass increment, and it is given by

$$\Delta \rho_L = \frac{\Delta m_t}{V} \tag{2}$$

, 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

$$V\frac{d\Delta\rho_L}{dt} = Q\rho_H - Q\rho_L \tag{3}$$

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

$$Fr = Q\sqrt{\frac{\rho_m}{D_f^5 g(\rho_H - L)}} \tag{4}$$

In the present experiment, the effective diameter D_f is used in Eq. (4) because the openings are not round, and it is given by

$$D_f = \sqrt{\frac{4}{\pi}\left(\frac{\pi D_1^2}{4} - D_1\delta\right)} \tag{5}$$

3. Results and Discussion

Figure 7 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 density increment of the partitioned opening is greater than that of the opening with extended partition because the volume of the test vessel with partitioned opening is smaller than that of the test vessel with the opening with extended partition as shown in Table 1. The exchange flow rate is plotted in the form of dimensionless Froude number. Figure 8 shows variation of the Froude number with time. The Froude number for the opening with extended partition is almost constant with time because buoyancy force, i.e., the density difference between the air and the gas mixture is almost constant. The Froude number for the partitioned opening appears to be constant value before about 200 second. They fluctuate after about 200 second and thus, these data are not sufficient to explain the trend of the exchange flow rate.

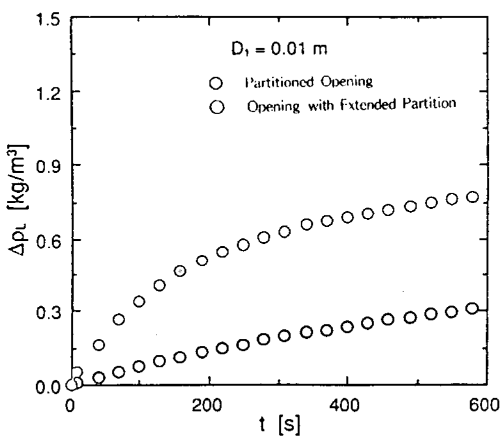


Fig. 7 Variation of density increment with time

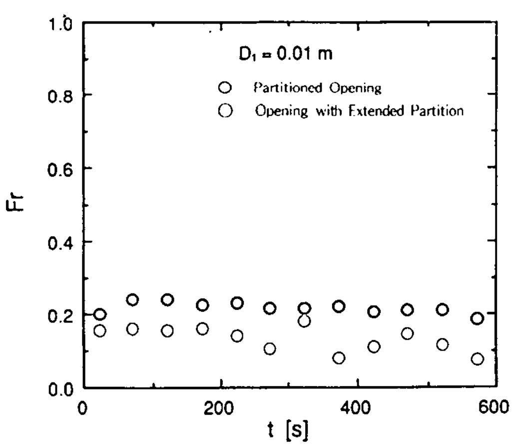


Fig. 8 Variation of Froude number with time

Figure 9 is prepared to illustrate relationship between the Froude number and the density increment. Figure 9 shows that difference in the Froude numbers between the opening with extended partition and the partitioned opening results from the effect of fluids interference. This figure shows the variations of Froude numbers for the both opening systems are less than 9% in the range of 0 L 0.5 kg/m³. This means that the density difference between the air and the gas mixture, i.e., buoyancy force is almost constant in this range. Therefore, the Froude number in Table 2 is defined as average value of the Froude numbers in the range of $0 \leq \Delta\rho_L \leq 0.5$ kg/m³. As was already mentioned, experiments for flow visualization were conducted by Mach-Zehnder interferometer to compare flow patterns. For our understanding of the flow visualization of the helium-air exchange flow, an example of interference fringe pattern of the single opening system (no

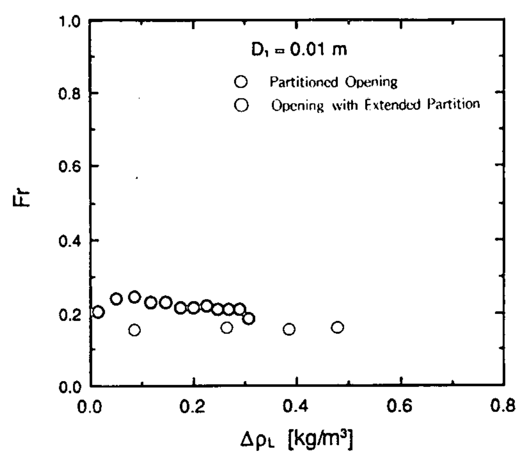
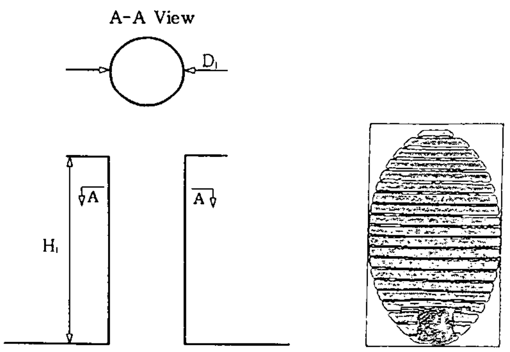


Fig. 9 Variation of Froude number with density increment

Table 2. Comparison of Froude numbers between two types of opening system

Opening Type	Froude number
Opening with Extended Partition	0.21
Partitioned Opening	0.15

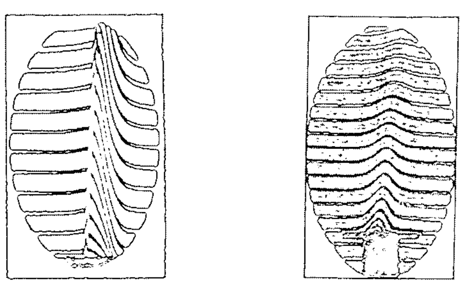
partition, $H_1/D_1=10$) is introduced in Fig. 10. The distorted interference fringes do not appear as $Fr \to 0$, because there is almost no exchange flow and the strong fluids interference within the opening occurs as shown in Fig. 10. Figure 11 shows Mach-Zehnder interferograms of fringes of the air and the gas mixture for the opening with extended partition and the partitioned opening at H_1/D_1 of 10. The distorted interference fringes show that the gas mixture flows out of the opening and the straight fringes indicate that the air flows into the opening. Figure 12 shows the air flow within the test cylinder. The air flows vertically into the test cylinder and the air circulates within the test cylinder as shown in Fig. 12[16]. The air is mixed with the helium well because of circulated air flow. According to observations by video camera, the gas mixture flows out of the opening with extended partition and the fringes of the gas mixture do not fluctuate laterally as shown in Fig. 11. This means that the flow of the gas mixture is stably separated from the air flow out of the opening entrance by the extended partition. Absence of the fluids interference leads to less resistance for the exchange flow through the opening with extended partition, as compared with the exchange flow through the partitioned opening. However, the gas mixture flow through the partitioned opening 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. 11. It indicates that the fluids interference takes place as a resistance to the exchange flow. Two flow zones, i.e., the separated flow zone and the unseparated zone,



(a) Single Opening (b) Flow Visualization

$H_1/D_1=0$

Fig. 10 Flow visualization of single opening system with Mach-Zehnder interferometer



(a) Opening with Extended Pantition (b) Partitioned Opening

$H_1/D_1=0$ t=60s

Fig. 11 Comparison of flow visualizations with Mach-Zehnder interferometer

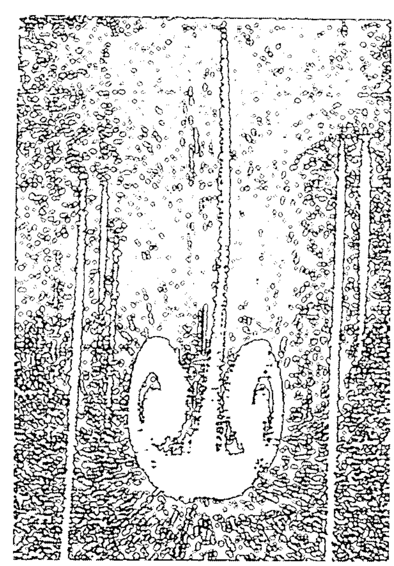


Fig. 12 Flow visualization of air flow in test cylinder[16]

exist for the case of the partitioned opening. The separated flow shown in Fig. 13 within the partitioned opening was investigated by Daigo[17]. It is clearly visualized that the helium flows out of left inside of the partitioned opening and the air flows into right inside of the partitioned opening. The partition forms the separated flow zone within the opening. Based on the flow visualizations of Fig. 11, it is clearly revealed that amplitudes of the interference fringes for the opening with extended partition are larger than those of the interference fringes for the partitioned opening. The exchange flow due to less flow resistance at the entrance of opening with extended partition gives rise to higher amplitude of the fringe. The extended partition expedites the exchange flow and the air flows into the test vessel easily. Therefore, the exchange flow rate of the opening with extended partition is greater than that of the partitioned opening as shown in Table 2. Two flow configurations for the both openings to explain mechanism of the exchange flow are suggested as shown in Fig. 14. The separated flow at the entrance of opening with extended partition increases the exchange flow rate and the unseparated flow at the entrance of partitioned opening leads to flow resistance. Finally, the exchange flow rate for the opening with extended partition increases by removing the unseparated flow zone as shown in Table 2 and the difference in Froude numbers for the both openings is caused by the separated flow due to the extended partition.

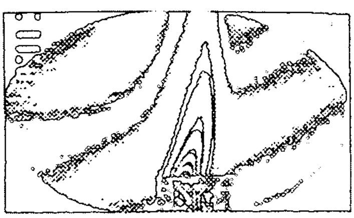


Fig. 13 Flow visualization of separated flow within partitioned opening[17]

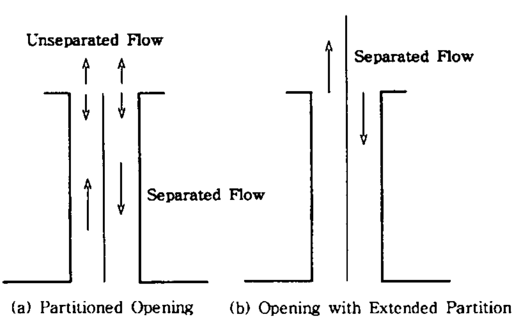


Fig. 14 Schematic diagram of flow configurations for partitioned opening and opening with extended partition

4. Conclusions

An experimental study of the helium-air exchange flow through the openings with vertical partitions has been carried out in order to understand characteristics of the penetrated air flow at the rupture accident of the stand pipe in the HTGR. In this paper, the effect of the fluids interference at the opening entrance on the exchange flow rate was confirmed experimentally and discussed. Conclusions of this paper are summarized in four groups as follow:

1) The fluids interference between upward and downward flows at the entrance of partitioned opening is found to be one of important factors on the helium-air exchange flow rate.

2) The exchange flow rate of the opening with extended partition is greater than that of the partitioned opening because of the absence of the fluids interference at the opening entrance.

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

4) The present study is useful in understanding helium-air exchange flow at the rupture accident of the stand pipe in the HTGR.

Further study will be required to explain the fluids interference by mathematical modeling.

Acknowledgments

The author wishes to thank professor H. Madarame of the University of Tokyo and Dr. M. Fumizawa of Nuclear Power Engineering Corporation for a number of useful discussions.

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, Tokyo, pp. (18.4-1)-(18.4-7), 1992.
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, San Francisco California, pp. 333~338, 1991.
12. Kang, T. I., "Helium-Air Exchange Flow Through a Partitioned Vertical Opening with a Partition", Proc. 5th Int. Topical Meeting on Nuclear Reactor Thermal Hydraulics, Salt Lake City, Vol. II, pp. 541~546, 1993.
13. Kang, T. I., "Helium-Air Exchange Flow Through Multiple Openings", Proc. 6th Int. Symposium on Transport Phenomena, Seoul City, Vol. I, pp. 1374~1379, 1993.
14. Kang, T. I., "Helium-Air Exchange Flow Through an Opening with a Partition", Trans. of JSME, Vol. 59, pp. 172~178, 1993.
15. Yang, W. J., Handbook of Flow Visualization, Hemisphere Publishing Corporation, New York, pp. 205~210, 1989.
16. Fumizawa, M., "2nd Report; Visualization of 3-D Structure of Exchange Flow", J. of V.S.J., Vol. 13, pp. 261~264. 1993.
17. Tsuru, D., "Multiple Flow Pattern in Buoyancy-Driven Exchange Flow Through Double Openings", Proc. 6th Int. Conference on Nuclear Engineering, California, pp. 1~10, 1998.

저 자 소 개

강태일(姜泰一)
1958년 12월생. 1982년 부산대학교 기계공학과 졸업. 1998년 한국해양대학교 대학원 기관학과 졸업(공학석사). 1993년 일본 동경대학 공학부 졸업(공학박사). 1994~1996년 삼성중공업 연구소(선임연구원). 1996년~현재 창신대학 건축설비과 학과장, 건축설비기술연구소장. 당학회회원.