⊙ 研究論文

Effect of Opening Partition Length on Helium-Air Exchange Flow

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개구부 삽입부의 길이가 헬륨 및 공기의 치환류에 미치는 영향

강 태 일

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

Abstract

This paper describes experimental investigations of helium-air exchange flow through 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 partitioned 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 interact 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 interaction 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. Figure 1 shows a schematic drawing of the HTTR[1,2] and the HTTR is a graphite moderated high temperature gas-cooled reactor of 30 MW thermal power and 950℃ 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.

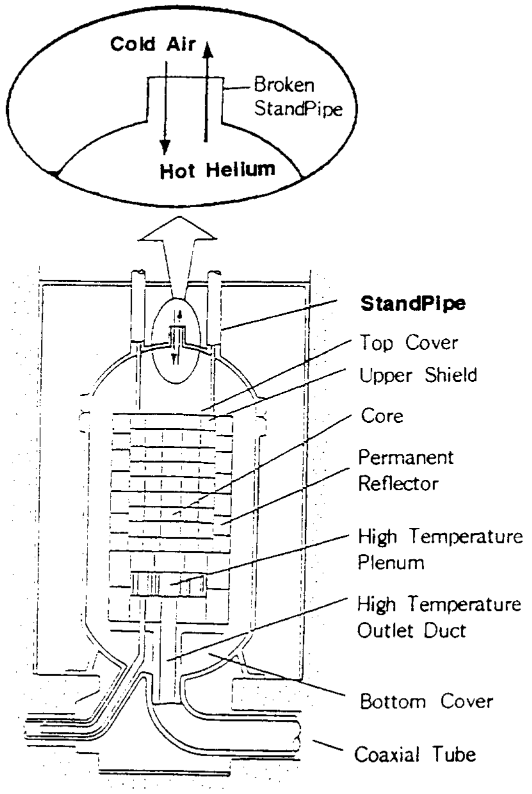


Fig. 1 Schematic diagram of helium-air exchange flow at rupture accident of standpipe in HTTR

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 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

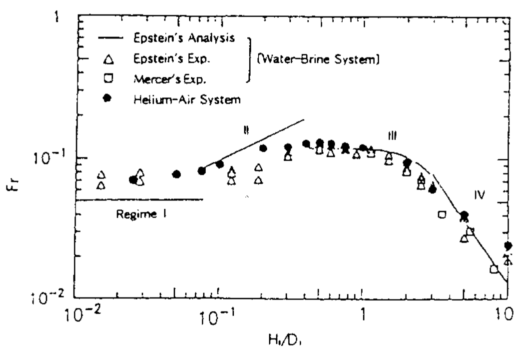


Fig. 2 Comparison of Froude numbers between helium-air system and brine-water system[9]

the stand pipe rupture accident. Fumizawa[9,10,11] conducted experiments for the helium-air exchange flows with two types of the single opening, vertical single opening and inclined single opening. He reported that experimental results on the helium-air system with the vertical single opening agreed with those for the Epstein' s brine-water system with the vertical single opening as shown in Fig.2[9]. It was also found that the inclination angle for maximum measured Froude number decreased with increasing the opening ratio in the helium-air system, while Mercers' s experimental results indicated that the angle remained almost constant in the brine-water system as shown in Fig. 3[10]. In Kang' s paper[12,13,14], he pointed out effect of fluids interaction within the opening which reduces the exchange flow rate. Two flow configurations, i.e., separated flow (unidirectional flow) and unseparated flow (bidirectional flow) were suggested in his study. Therefore, in this study, an experiment to investigate effect of separated flow zone on exchange flow rate is performed by changing the partition ratios H_p/H_1, where H_p and H_1 are partition length and height of the opening, respectively.

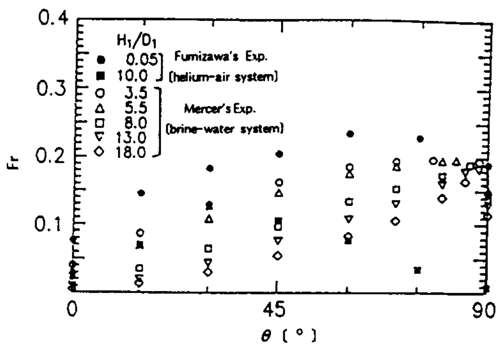


Fig. 3 Relation between Froude number and inclination angle[10]

2. Experimental Apparatus and Procedures

Figure 4 illustrates an experimental apparatus to evaluate the exchange flow rate for the partitioned opening system. Essential features of the experimental apparatus are described with aid of Fig. 4. 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 configuration studied is presented in Fig. 5. A vertical partition of rectangular plate is in align-

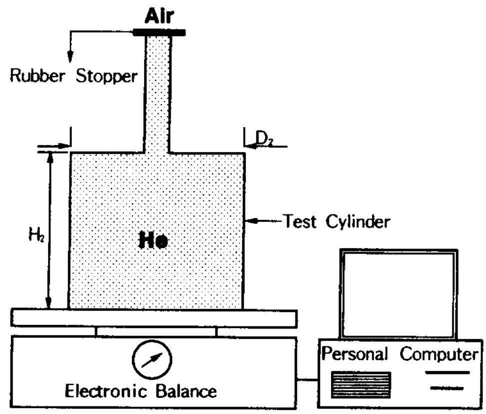


Fig. 4 Schematic diagram of experimental apparatus

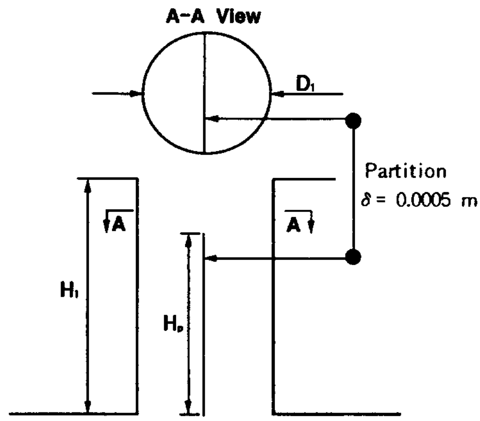
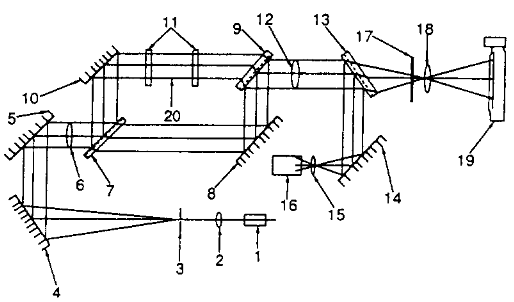


Fig. 5 Schematic diagram of partitioned opening

ment with center line of the opening to make the partitioned opening as shown in Fig. 5, 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, 0.25, 0.5, 0.75, and 1, where H_p and H_l are partition length and height of the opening. Diameter of the test cylinder D_2 is 0.194 m and height of the test cylinder H_2 is 0.4 m. The opening with $H_P/H_l = 0$ is 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. 4. On removal of 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 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 measured 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.

Table 1. Test vessel geometry

Opening Type	D_l m	H_l m	H_p m	D_2 m	H_2 m
Partitioned Opening	0.02	0.02	0.005 0.01 0.015 0.02	0.194	0.4
Single Opening	0.02	0.02	0	0.194	0.4



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. 6 Optical components of Mach-Zehnder interferometer

$$\Delta m_t = m_{Lt} - m_{He0} \tag{1}$$

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

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

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

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

In case of opening with H_p/H_1 of 1, the effective diameter D_f is used in Eq. (4) because the opening is not round, and it is given by

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

where D_f is D_1 for the opening with partition ratios H_p/H_1 in the range 0 to 0.75.

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 due to the exchange flow. Finally, it approaches the density difference between the air and the helium. Figure 8 shows variation of the Froude number with time. The Froude numbers for the partition ratios H_p/H_1 in the 0.25 to 0.75 appear to be constant, and they are almost constant at H_p/H_1 of 10 before 200 second. Figure 9 is prepared to illustrate comparison of relationship between the Froude number and the density increment. This figure shows the variations of Froude numbers are almost constant in the range of $0 \le \Delta P_L \le 0.5$ kg/m³. This means that

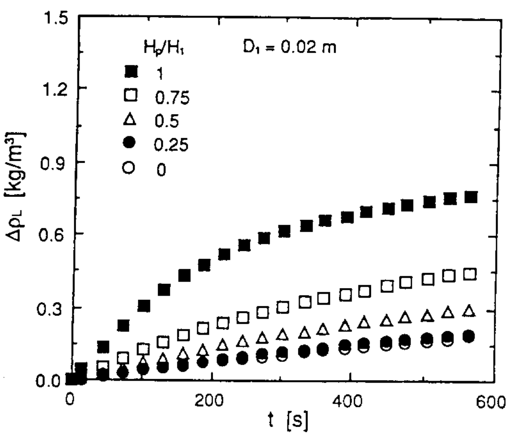


Fig. 7 Variation of density increment with time

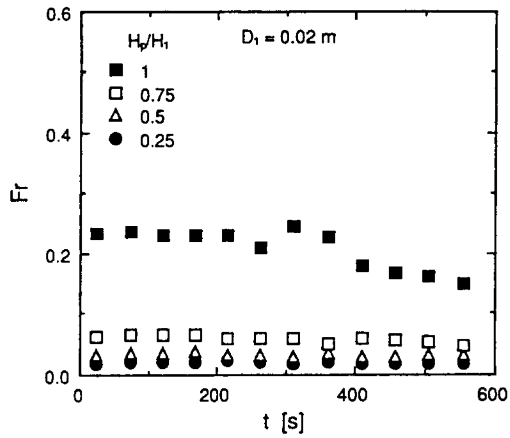
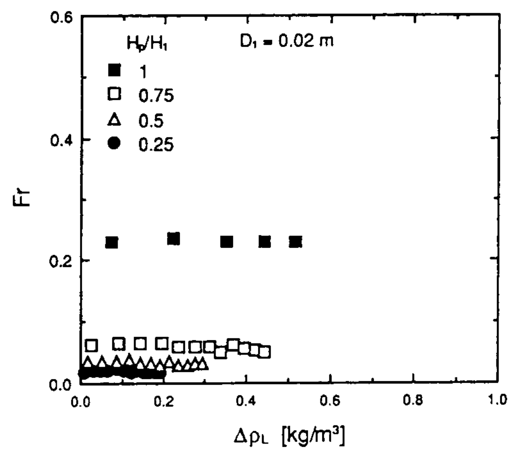


Fig. 8 Variation of Froude number with time



the density difference between the air and the gas mixture, i.e., buoyancy force is almost constant. Therefore, the Froude number in Fig. 10 is defined as average value of the Froude numbers in the range of $0 \leq \Delta P_L \leq 0.5$ kg/m^3. As was already mentioned, experiments for flow visualization were conducted by Mach-Zehnder interferometer to compare flow patterns. Figure 11 and 12 show examples of Mach-Zehnder interferograms for the partition ratios 0, 0.25, 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 13 shows the air flow in the test cylinder. The air flows vertically into the test cylinder and the air circulates as shown in Fig. 13[16]. The air is mixed with the helium well due to circulated air flow. The distorted interference fringes do not appear in single opening system (no partition, $H_p/H_1 = 0$) due to unseparated flow (bidirectional flow) within the opening as shown in Fig 11. The exchange flow rate at H_p/H_1 of 0 is minimum through range of the partition ratios as shown in Fig. 10. The distorted 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. 10. 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. 10. The separated flow shown in Fig. 14 within the partitioned opening was investigated by Daigo[17]. 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. The partition forms the separated flow zone within the opening. Based on flow visualizations of Fig. 11 and 12, it is clearly revealed that amplitudes of the interference fringes at H_p/H_1 of 1

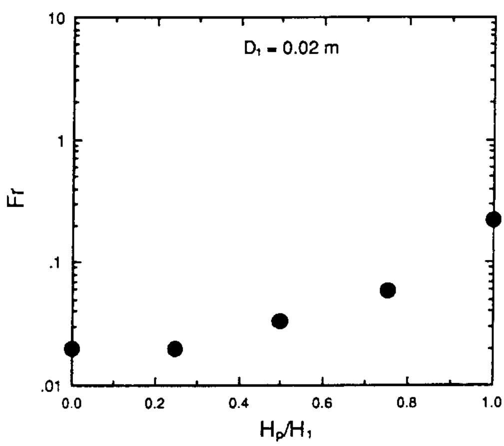
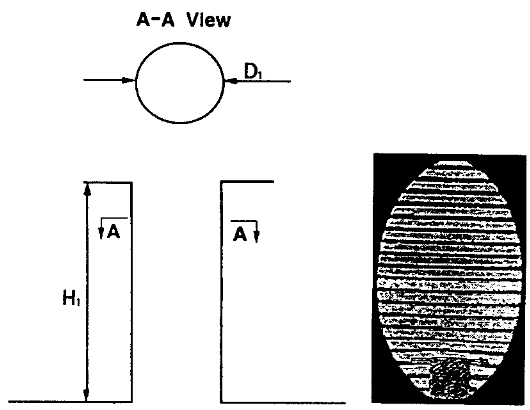


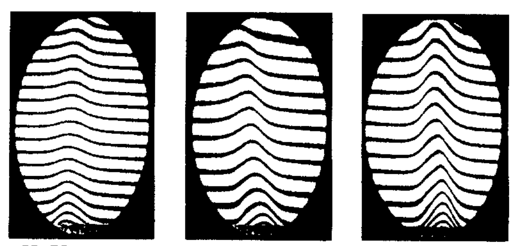
Fig. 10 Comparison of Froude numbers with partition ratio



(a) Schematic Diagram of Single Opening (b) Flow Visualization

$H_p/H_1 = 0$

Fig. 11 Flow visualization of single opening system with Mach-Zehnder interferometer



$H_p/H_1 = 0.25$ $H_p/H_1 = 0.5$ $H_p/H_1 = 1$

Fig. 12 Comparison of flow visualizations with partition ratio in partitioned opening system

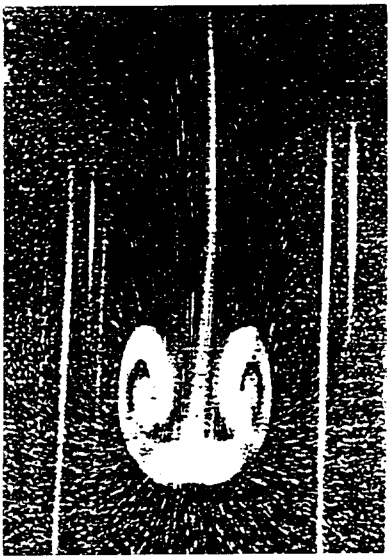


Fig. 13 Flow visualization of air flow in test cylinder[16)]

Fig. 14 Flow visualization of separated flow within partitioned opening[17)]

are larger than those of the interference fringes at H_p/H_l of 0, 0.25, 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 the air flows into the test vessel easily. Therefore, the exchange flow rate at H_p/H_l of 1 is maximum through this range as shown in Fig. 10. It indicates that the fluids interaction 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. 15. The separated flow increases the exchange flow rate and the unseparated flow leads to flow resistance. Finally, the exchange flow rate

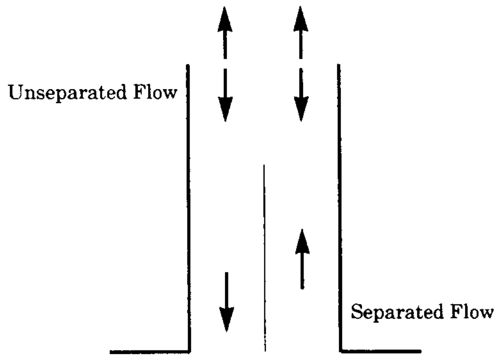


Fig. 15 Schematic diagram of flow pattern within partitioned opening

increases with increasing the separated flow zone as shown in Fig. 10.

4. Conclusions

An experimental study of the helium-air exchange flow through the opening with partition 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 partition ratio of the opening on the exchange flow rate was confirmed experimentally and discussed. Conclusions of this paper are summarized in three groups as follow :

1) The helium-air exchange flow was visualized by Mach-Zehnder interferometer.
2) The fluids interaction in the unseparated flow zone is found to be an important factor on the helium-air exchange flow.
3) The exchange flow rate increases with increasing the partition ratio.

Nomenclature

D_1	diameter of opening (m)
D_2	diameter of test cylinder (m)
D_f	effective diameter of opening (m)
Fr	Froude number

g	acceleration due to gravity (m/s^2)
H_1	height of opening (m)
H_2	height of test cylinder (m)
HP	partition length (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 $=(\rho_H+\rho_L)/2$ (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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개구부 삽입부의 길이가 헬륨 및 공기의 치환류에 미치는 영향

강 태 일

요 약

고온가스로의 STAND PIPE 파단사고시, 헬륨과 공기의 치환류가 발생한다. 본 논문은 개구부에 삽입한 수직평판 (Partition)의 길이를 변경하여, 헬륨 및 공기의 치환류량을 실험적으로 조사하였다. Test Cylinder 상부에 개구부를 설치한 용기가 실험에 이용되었으며, 치환유량을 계측하기 위하여 질량증가법이 적용되었다. 치환류를 인식하기 위하여 Mach-Zehnder 간섭기에 의한 가시화를 실시하였다. 치환류량 측정은 형상비 (수직평판길이/개구부 높이) 0에서 1까지 실시하였다. 형상비가 0인 경우 헬륨 및 공기의 유로가 분리되지 않아 개구부내에 2유체간섭이 발생하며, 미분리 흐름은 유체저항을 증가시켜 측정 형상비 중 치환류량이 가장 적다. 수직평판 길이가 증가됨에 따라 개구부내에 분리 및 미분리 흐름의 2영역이 존재한다. 개구부내에 분리흐름 영역이 증가함에 따라 치환류량은 증가하며, 따라서 형상비가 1인 경우 치환류량이 최대임이 파악되었다. 개구부내 형상비를 변화시켜 치환유량을 비교한 결과, 개구부 미분리영역의 2유체 간섭이 헬륨 및 공기의 치환류량의 중요한 인자임을 알 수 있었다.