

Study on mixing process of two component gases in a vertical fluid layer



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ABSTRACT

This study is to investigate the onset time of natural circulation through the apparatus under the stable density stratified fluid layer. The experiment has been carried out using two component gases. The experiment apparatus consists of a reverse U-shaped vertical slot and a storage tank. The left side vertical slot consists of the heated wall and the cooled wall. The right side vertical slot consists of the two cooled walls. Temperature difference between the vertical walls was set to 0, 10, 30, 50, 70, and 100 [K]. The combination of the two component gases was set to nitrogen/argon, neon/argon, helium/argon, and helium/nitrogen. The heavy gas was filled with the storage tank and light gas was filled with the reverse U-shaped vertical slot. Before the experiment starts, the localized natural convection was generated in the heated side vertical slot. After the experiment starts, the heavy gas will be transported to the slot by the molecular diffusion and natural convection. And then, natural circulation occurs abruptly through the reverse U-shaped passage. Mixing process of two component gases was affected not only by the localized natural convection but also by the molecular diffusion. The onset of natural circulation has been affected not only by molecular diffusion but also by localized natural convection in the vertical fluid layer.

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1. Introduction

A very-high-temperature reactor has currently strong interests of development worldwide. Besides its broad economical appeals resulting from unique high temperature capability, the reactor provides inherent and passive safety and aims at enhanced safety goal. Japan Atomic Energy Agency (JAEA) has successfully built and operated the 30 MWt High Temperature Engineering Test Reactor (HTTR) and is now pursuing design and development of commercial systems such as the 300 MWe gas turbine high temperature reactor GTHTR300C (Gas Turbine High Temperature Reactor 300 for Cogeneration) (Yan et al., 2003). A depressurization accident is one of the design-basis accidents of the VHTR. When the pipe rupture accident occurs, air is expected to enter the reactor core from the breach and oxidize in-core graphite structures. In order to predict or analyze the process of air ingress during the depressurization accident of the VHTR, it is very important to develop computer programs and to validate them by experiments.

Previous studies focused mostly on molecular diffusion and natural circulation of the two-component gas mixture in a reverse U-shaped tube and in a simple test model of the HTTR (Takeda and Hishida, 1992). In order to investigate the basic features of the flow behavior of the multi-component gas mixture, consisting of helium (He), nitrogen (N₂), oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), etc., experimental and numerical studies were performed on the combined phenomena of the molecular

diffusion and the natural circulation of the multi-component gas mixture with the graphite oxidation reaction in the reverse U-shaped tube (Takeda and Hishida, 1996). The numerical results were in good agreement with the experimental ones regarding the density change of the gas mixture, the mole fraction change in the gas species and the onset time of the natural circulation of air. Furthermore, the objective of these studies is to investigate the air ingress process and to develop the passive safe technology for the prevention of air ingress (Takeda and Hishida, 2000). Recently, a density-gradient driven air ingress stratified flow was analyzed using CFD code for the Next Generation Nuclear Plant (NGNP), which is the VHTR of U.S. design (Oh et al., 2009, 2010).

In general, mixing processes of two component gases in a vertical stable stratified fluid layer is often governed by molecular diffusion. When a stable stratification is formed in a vertical slot with two component gases which is different density, a rate of transportation will be different by a mutual diffusion coefficient. On the other hand, it is expected that natural convection will occur in the vertical slot when one side wall is heated and the other side wall is cooled. When the stable stratification is formed with the two component gases and the two vertical parallel walls of the slot is kept at different temperature, the transport process of the gases becomes more complex. In this case, the heavier gas diffuses into the lighter gas. In addition to that these gases will also be transported by natural convection. Both phenomena may produce at the same time during the air ingress process of the primary pipe rupture accident. According to the previous experiments (Takeda and Hishida, 1992, 1996, 2000), molecular diffusion and natural convection would have occurred simultaneously in the annular passage between the inner barrel and the water-cooled jacket. The range of

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Rayleigh number based on the width of the annular passage is about $0 < Ra_d < 3.26 \times 10^5$ (Takeda and Hishida, 1992) and $Ra_d < 1.56 \times 10^6$ (Takeda and Hishida, 2000) respectively. Rayleigh number based on the width of the annular passage of the HTTR or the GTTR-300C will be two order or bigger than that of the simulated apparatus. Therefore, it is necessary to know which phenomenon becomes dominant for the mixing processes of the two component gases in the vertical stable stratified fluid layer. It is also important to quantitatively evaluate an influence of natural convection on the mixing processes by molecular diffusion.

There are many studies regarding natural convection of the vertical slot to obtain the flow characteristics of the density stratified layer by changing of the fluid temperature. Eckert and Carlson (Eckert and Carlson, 1961) had carried out an experiment regarding natural convection of air in a vertical slot ($2.1 < \text{height/width } (H/d) < 46.7$). They have classified the flow characteristics to conduction, transition, and boundary layer regions by using Grashof number, Gr , and the aspect ratio, H/d . In addition to that, Elder (Elder, 1965a,b) had performed an experiment and analysis regarding natural convection in a vertical slot. The range of the aspect ratio is $1 < H/d < 60$ and Prandtl number, Pr , is 10^3 . If the Rayleigh number, Ra , exceed the critical number, $3.0 \times 10^5 \pm 30\%$, it is found that a unicellular convection change to a multi-cellular convection.

On the other hand, there is a double diffusive convection (Turner, 1974) as similar phenomena related with coexisting of natural convection and molecular diffusion. In this phenomenon, natural convection will occur by the buoyancy of density difference between two mediums or one medium and temperature distribution. Especially, it is called thermo-salt convection if the two elements are the temperature and salt. There are a lot of studies in the field of the ocean physics. However, the most of those are the experimental studies using liquid. Usually the density change along with transporting of medium is small in case of liquid. Then, not only the density difference but also the diffusion coefficient is also small compared with gas system.

Authors have reported the mixing process by natural convection and molecular diffusion of two-component gases in a stable stratified fluid layer (Takeda et al., 2010). According to the report, the mixing process by molecular diffusion in the vertical stratified fluid layer was affected significantly by the localized natural convection induced by the slight temperature difference between both vertical walls. Authors also have reported the transport phenomena by the molecular diffusion were affected by not only the localized natural convection but also natural circulation of the gas mixture. The localized natural convection may affect to the onset time of the natural circulation (Takeda et al., 2011).

2. Experimental apparatus and method

An experimental apparatus which consisted of two vertical slots is shown in Fig. 1. The dimension of the vertical slot was $208 \text{ mm} \times 70 \text{ mm} \times 598 \text{ mm}$. The reverse U-shaped slot was composed with the two vertical slots through the connected passage. The dimension of the connected passage was $106 \text{ mm} \times 210 \text{ mm} \times 16 \text{ mm}$. The bottom ends of the reverse U-shaped slot were connected to a gas storage tank. The dimension of the storage tank was $548 \text{ mm} \times 398 \text{ mm} \times 248 \text{ mm}$. The reverse U-shaped slot and the storage tank were separated by the partition plate. Fig. 2 shows the left side slot of the reverse U-shaped slot. The left side slot consisted of a heated wall and a cooled wall. The vertical walls of the left side slot were made of copper with thickness of 3 mm. A stainless sheath heater was attached to the heated wall and a water cooling pipe made of copper was attached to the cooled wall, respectively. These walls were covered by an

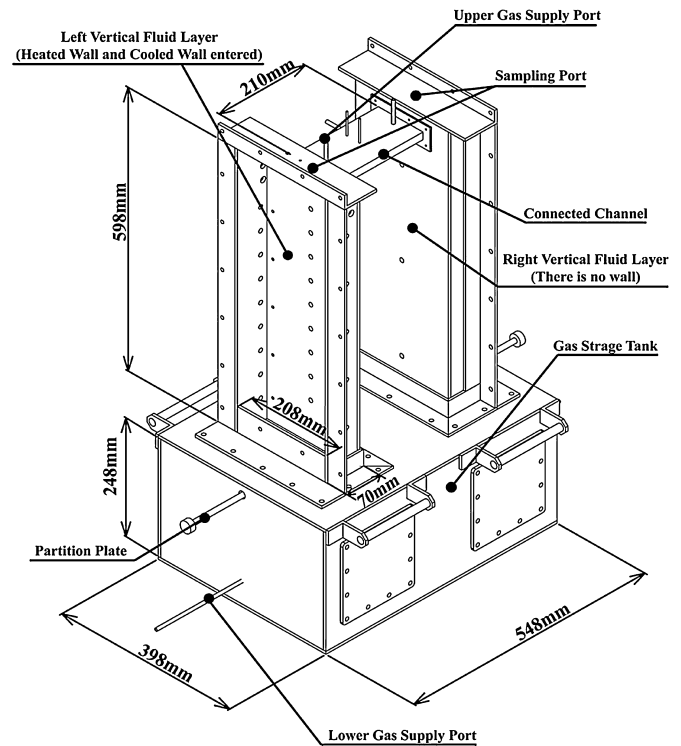


Fig. 1. Experimental apparatus

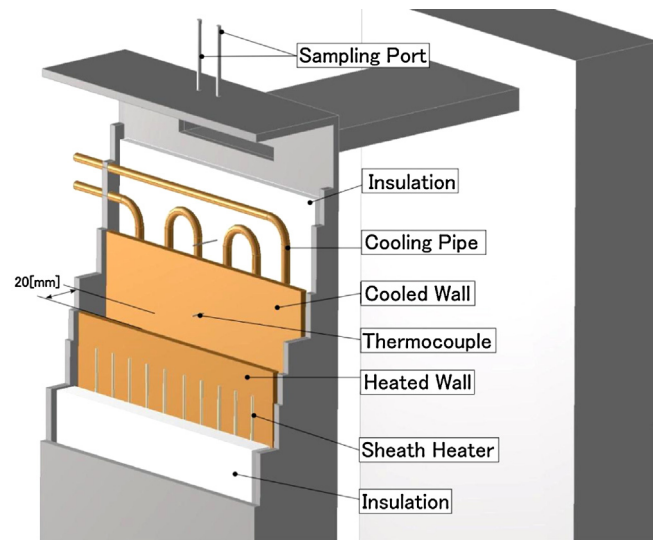


Fig. 2. Left side slot of reverse U-shaped slot

insulator which was 50 mm in thickness. The distance between the heated wall and cooled wall was set to 20 mm. The right side slot consisted of two cooled walls. The vertical walls of the right side slot were made of stainless steel. The wall and gas temperatures were measured by a K-type thermocouple. Considering the errors induced by the thermocouples, the scanner junction and the DVM accuracy, the entire accuracy of the temperature measurement was within $\pm 0.5^\circ\text{C}$. The location of the temperature measuring point is provided in Figs. 3 and 4 and Table 1.

The mole fraction of argon gas and the density of the gas mixture were obtained as follows. The two component gases and the gas mixture were assumed to the ideal gas. The velocity of sound was

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