Experiment on Density Gradient Driven Flow in Small Break Air Ingress Accident of VHTRs

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1. Introduction

A Very High Temperature Reactor (VHTR) is one of the six Gen-IV reactor concepts which is adapting carbon layered TRISO-fuel, graphite-moderator, and helium-coolant [1]. In spite of its inherent safety concept, the VHTR could be detrimental if a LOCA-type accident occurs, which is followed by a pipe break. After the break, the air in the cavity starts to ingress into the reactor by either local density-gradient driven flow or molecular diffusion. The main concern of this accident is that it could eventually lead to structural degradation or release of the toxic and explosive gasses (CO) by oxidation of graphite [2].

Previously, majority of the air-ingress studies have been focused on the large size break accident, which is called a double-ended-guillotine-break (DEGB) [3]. However, in this study, more focus in put on the small break (or leakage) accident, which is more realistic and probable in the VHTRs. According to the previous studies, the phenomena in the small break accident appear to be much more complicated than those in the DEGB, but little studies have been conducted and reported so far [3].

This study measures amount of air-ingress rates through a small hole in a circular pipe for various break conditions. The main parameters considered are (1) break orientation, (2) break size, (3) main flow velocity, and (4) density ratio. The main objectives are summarized below:

- Understanding on fundamental air-ingress phenomena in the small break accident
- Development of flow regime map for the small break air-ingress
- Development of air-ingress model for VHTR safety analysis code

2. Experiment

2.1 Description on Experimental Facility

Figures 1 and 2 show a schematic and a picture of the experimental apparatus, respectively. A main purpose of this experiment is to measure variations of oxygen concentrations in the helium flow loop using oxygen sensors. This experiment has been conducted at room temperature and ambient pressure.

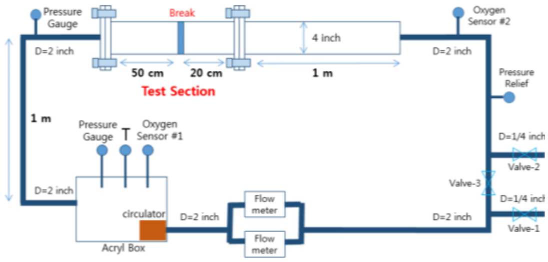


Figure 1. Schematic of Small Break Air-Ingress Experimental Facility.

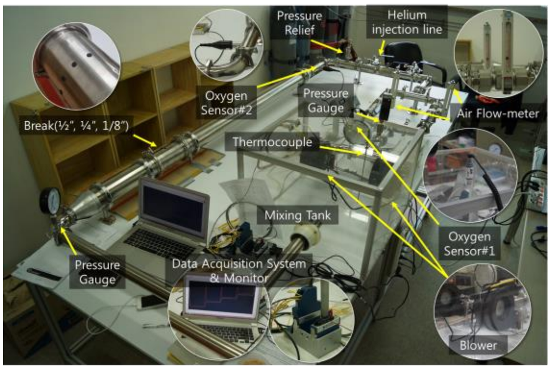


Figure 2. Small Break Air-Ingress Experimental Facility.

Design of the experimental loop is, basically, the same as the one manufactured by Kim et al. [3]. However, the facility has been improved and upgraded by adapting (1) bigger experimental unit size, (2) two oxygen sensors (one in mixing tank and one in front of test section flow-development pipe), (3) smoothing treatment on pipe internal surface, and (4) wider ranges of experimental conditions (i.e. density difference and flow-rates).

2.2 Data Analysis Method

This study measures varying oxygen concentrations and converts the raw data to more meaningful information such as air-ingress rates as follows.

$$\dot{V}_{in} = \frac{V_{total}}{(1-f_{air})} \cdot \frac{df_{air}}{dt} = \frac{V_{total}}{C_{O_2,\infty} \cdot (1-f_{air})} \cdot \frac{dC_{O_2}}{dt} \qquad (1)$$

where

$\dot{V}_{in}$ = volumetric flow rate of air into the test-section (m^3/s)
V_{total} = total volume in the test section (m^3)
f_{air} = air mole fraction in the test section
C_{O_2} = oxygen concentration in the test section (%)
$C_{O_2,\infty}$ = oxygen concentration in the environment (%)

3. Results and Discussions

Figure 3 shows the measured oxygen concentrations (%) versus time (sec) during a case of the test. In this test, change of oxygen concentrations were measured for five different oxygen concentration levels (3%, 8%, 12%, 16%, and 18%). As shown in this figure, the slope of the oxygen concentration changes are linear in the interval. Based on this raw data, time derivative of the oxygen concentration (dC_{O_2}/dt) were estimated. Figure 4 shows the oxygen concentration changes versus density ratio between the light fluid (in the test section) and the heavy fluid (in the environment).

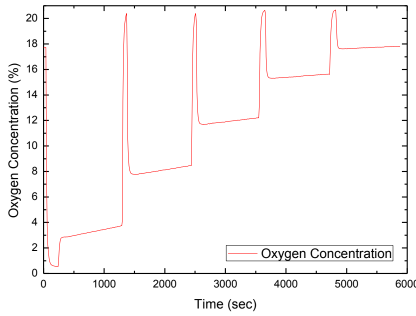
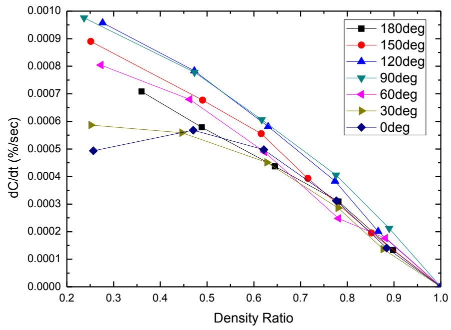
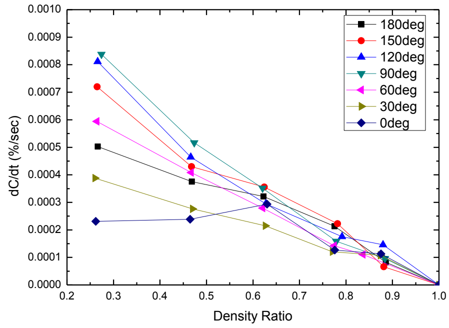


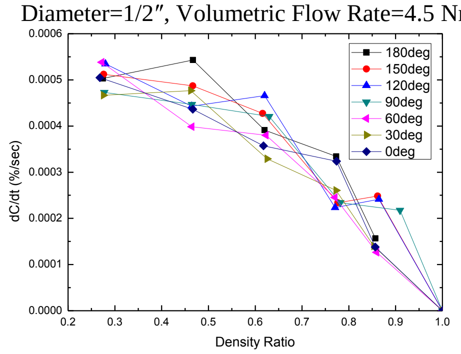
Figure 3. Collected Oxygen Concentration Data.



(a) Diameter=1/2″, Volumetric Flow Rate=7.25 Nm³/h



(b) Diameter=1/2″, Volumetric Flow Rate=4.5 Nm³/h



(c) Diameter=1/4″, Volumetric Flow Rate=7.25 Nm³/h

Figure 4. Oxygen Concentration Changes vs. Density Ratio.

The main observations from the experimental results are summarized below:

- **Effect of Density Ratio:** High density difference makes air-ingress faster. Angle effect is significant at low density ratios, but it becomes trivial at the higher density ratios because of lower driving force.
- **Effect of Hole Orientation:** Air-ingress rate increases with hole angles from 0˚ to 90~120˚ by enhanced density gradient driven flow effect. However, for higher than 120˚, the air-ingress rate starts to decrease sharply due to the flow interference by shifting the mechanisms. Orientation effects become trivial under the smaller holes (1/4″, 1/8″).
- **Effect of Hole Size:** Increase of hole size increases air-ingress rate due to the increase of flow exchange surface area and driving force (local density gradient).
- **Effect of Main Flow Velocity:** Increased flow rate in the loop increases air-ingress rate. Increased flow instability around the hole seems to be the attributes increasing of the air-ingress rate.

4. Summary and Conclusions

This study has experimentally investigated fundamental small break air-ingress phenomena for the VHTRs. Several important parameters including break orientation, break size, and main flow velocity have been considered in the experiment. From the experiment, it was observed that the air-ingress rates increase with (1) decrease of density ratio, (2) increase of hole size, and (3) increase of main flow velocity. The experiments are still on-going at Seoul National University. The collected data is expected to be used for developing a flow regime map and air-ingress models for safety analysis of small break accident in the VHTRs.

Acknowledgement

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[3] Oh, C. H., and E. S. Kim, Small Break Air Ingress Experiment, INL/EXT-11-23380, Idaho National Laboratory, September 2011.