Annals of Nuclear Energy 87 (2016) 145–156

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Experimental study on fundamental phenomena in HTGR small break air-ingress accident

Jae Soon Kim [a], Jin-Seok Hwang [a], Eung Soo Kim [a,*], Byung Jun Kim [b], Chang Ho Oh [c]

[a] Department of Nuclear Engineering, Seoul National University, Daehak-dong, Gwanak-gu, Seoul 151-742, Republic of Korea
[b] Korea Institute of Industry Technology, 618-230 Kangsu-gu, Busan, South Korea
[c] Idaho National Laboratory, 2525 N. Fremont Ave., Idaho Falls, ID 83415, USA

ARTICLE INFO

Article history:
Received 1 March 2015
Received in revised form 4 August 2015
Accepted 9 August 2015
Available online 9 September 2015

Keywords:
HTGR
Air ingress
Small break
Density gradient driven flow

ABSTRACT

This study experimentally investigates fundamental phenomena in the HTGR small break air-ingress accident. Several important parameters including density ratio, break angle, break size, and main flow velocity are considered in the measurement and the analysis. The test-section is made of a circular pipe with small holes drilled around the surface and it is installed in the helium/air flow circulation loop. Oxygen concentrations and flow rates are recorded during the tests with fixed break angles, break sizes, and flow velocities for measurement of the air-ingress rates. According to the experimental results, the higher density difference leads to the higher rates of air-ingress with large sensitivity of the break angles. It is also found that the break angle significantly affects the air-ingress rates, which is gradually increased from 0° to 120° and suddenly decreased to 180°. The minimum air ingress rate is found at 0° and the maximum, at 110°. The air-ingress rate increases with the break size due to the increased flow-exchange area. However, it is not directly proportional to the break area due to the complexity of the phenomena. The increased flow velocity in the channel inside enhances the air-ingress process. However, among all the parameters, the main flow velocity exhibits the lowest effect on this process. In this study, the Froude Number relevant to the small break air-ingress conditions are newly defined considering both heavy and light fluids, and break angles. Based on this definition, the experimental data can be well rearranged and collected. Finally, this study develops and proposes a non-dimensional parameter and a criteria for determination of the small break air-ingress flow regimes. As a result, the non-dimensional parameter higher than 0.49 indicates that the air-ingress is mainly controlled by density gradient effect. On the other hand, that lower than 0.47 indicates that the other effects such as inertia or diffusion are dominant air-ingress mechanisms.

1. Introduction

A high temperature gas cooled reactor (HTGR) is a Gen-IV reactor concept incorporating high temperature, graphite-moderated, uranium-fueled, helium-cooled features for high efficiency, safety, and usability (GA, 1996); Schultz et al., 2006; Melse and Katz, 1984). The HTGR technology has been studied and developed since the 1950s and it exhibits several advantages over light water reactors including fuel integrity, proliferation resistance, a relatively simple fuel cycle, easy refueling, and modularity to supply electricity to remote areas. Even though gas reactors have been developed in the past with limited success, the innovations of modularity and integrated state-of-the-art safety systems make the HTGR design attractive from technical and economic perspectives.

In spite of its inherent safety features, the HTGR concept could be detrimental if a loss of coolant accident (LOCA) occurs that results in depressurization and potential air-ingress issues related with various physical/chemical phenomena (ORNL (2007); Schultz, 2008; Oh et al., 2006, 2010). This LOCA could lead to oxidation of the in-core graphite structure and the fuel, which will accelerate heat-up of the reactor core and lead to the release of toxic gasses (CO and CO_2) and fission products. Therefore, without effective countermeasures, a pipe break may lead to significant fuel damage and fission product release depending on the reactor design, break locations, and break orientations.

The most recent researches on the air-ingress accident phenomena were performed and reported by Idaho National Laboratory (Oh et al., 2006, 2010). In their researches, an air-ingress scenario based on density gradient driven flow were newly proposed (Oh et al., 2010), which consists of four steps. Based on extensive CFD analyses, it was shown that the density gradient driven stratified

* Corresponding author.
E-mail address: kes7741@snu.ac.kr (E.S. Kim).

http://dx.doi.org/10.1016/j.anucene.2015.08.012
0306-4549/

flow is the dominant air-ingress mechanism regardless of the accident scenarios. Characteristics of natural circulation were also investigated by Oh and Kim (2012) in the post onset-natural-circulation (ONC). This study showed that a natural circulation pattern consists of two flow paths and a recirculation flow rapidly drives air into the reactor vessel. An estimated air-ingress rates from 3-D CFD simulations were about an order of magnitude faster than that estimated by a 1-D system code. It indicated that the air ingress modeling should be conducted on multi-dimensional basis.

Even though many researches were previously conducted for the air-ingress accident in the HTGR, they mostly focused on a double-ended guillotine break (DEGB) scenario, where the inside and the outside connecting vessels are ruptured simultaneously (Hishida et al., 1993; Xiaowei et al., 2004; INET (2006); Oh et al., 2006; KAERI, 2011). It is based on the basic assumption that the DEGB would cause highest air-ingress into the reactor and therefore it could result in the most serious consequences. However, there have been some recent discussions that a small break or leak is a much more probable accident in reality than the DEGB, and therefore this accident scenario should be also importantly considered. From this motivation, the present study is focusing on air-ingress phenomena that expected to occur under much smaller break accident like SBLOCA in a light water reactor (LWR). There is no clear definition on the small break accident in the HTGR, but it is generally considered to be an accident whose break size is less than 1/2 inch according to Next Generation Nuclear Plant Method Technical Program Plan (Schultz et al. (2006)). Currently, the detailed situations for the small-break are not well defined and identified yet in the existing Phenomena Identification and Ranking Tables (PIRTs). However, it is obvious that the probability of the small-break is much higher than the double-ended-guillotine-break (DEGB). The possible small-break locations are coolant pipes, control rod guide tubes, instrumentation lines, heat exchanger tubes, and etc. in the primary side.

Previously, few researches were carried out on the HTGR small break phenomena. Oh et al. (2010) conducted simple CFD simulations in order to understand basic phenomena. Comparing to the DEGB scenario, the most important aspect observed in the small break situation is that the flow characteristics are highly dependent on the break angles. According to their research, the flow phenomena can be divided into three regimes as shows in Fig. 1. Molecular diffusion is identified as the first flow regime. It is observed when the break is at the bottom. In this case, gravitational force keeps the air from mixing with the helium through either of the second two regimes. For this reason, only diffusion governs the exchange of helium and air. The second flow regime identified is density gradient driven stratified flow. It occurs when the break is somewhere on the side. In this case, heavier fluid flows into the lower part of the hole as a counter current manner, stratified with the lighter fluid exiting in the upper portion like shown in the DEGB scenario. An unstable gravity-driven flow, observed when the break angle of around 180°, is the last flow regime identified. In this case, the helium exit flow is counter currently chocked with the air inlet flow. The air flow rate is not constant and will be much smaller than that in the second flow regime.

Although some computational works have been previously conducted to visualize small break situations, no quantitative experimental data are now available for supporting these numerical results. From this reason, this study attempts to quantitatively measure the air-ingress rates in a small break for various flow and break conditions. Several parameters including break angle, break size, density ratio, and main flow velocity are importantly taken into account. The main objectives of this study is (1) to understand fundamental phenomena and air-ingress characteristics in the HTGR small break accident and (2) to develop a quantitative measure to determine different flow regimes.

2. Experimental loop

Fig. 2 shows a schematic of the SNU small break air-ingress experimental loop which consists of the following five parts:

- *Test section:* the test section is made of a circular pipe (4 inch) with several holes around it for mimicking a small break situation in the HTGR. During the experiment, all holes except for one are closed. The test-section is made of stainless steel, and nylon caps are used to plug the holes.
- *Circulator:* the circulator flows air/helium mixture in the test loop. The circulator speed is adjustable. The circulator is designed to provide the same volumetric flows regardless of types of mixtures.
- *Mixing tank:* the mixing tank is designed to stabilize flow and enhances mixing of it. This mixing tank also contains a circulator and various instrument devices including a thermocouple, a pressure transducer, a pressure gauge, and an oxygen sensor. The mixing tank is made of acrylic.
- *Flowmeter:* the flow meter measures the flow rates of the working fluids (mainly helium). Since the mixture concentrations are changing during the experiment, the flow velocity are also separately measured using an optical technique.
- *Oxygen sensor:* two oxygen sensors measure oxygen concentrations (0–25%) in the helium/air mixture flow. These oxygen sensors are installed in the mixing tank and at the entry of the test-section, respectively. This experiment uses zirconia based sensors commercially available.

The test-loop is initially filled with helium gas, and the flow is generated by a circulator. If the flow is stabilized and the system reaches a steady-state condition, a cap on the test-section is un-

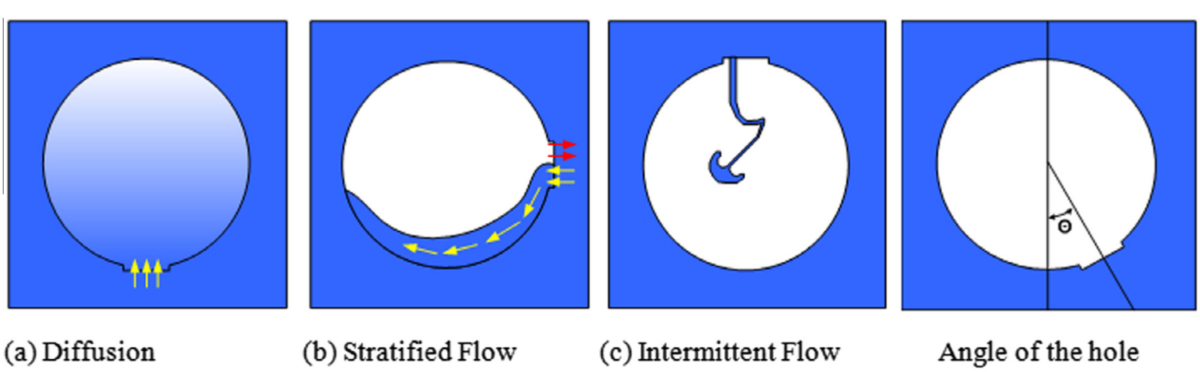

Fig. 1. Three different regimes created depending on the break angle of the hole (Oh et al., 2010).