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Numerical study of air ingress transition to natural circulation in a high temperature helium loop

Daniel Franken [a], Daniel Gould [a], Prashant K. Jain [b,1], Hitesh Bindra [a,*]

[a] *Department of Mechanical and Nuclear Engineering, Kansas State University, Manhattan, KS 66506, United States*
[b] *Oak Ridge National Laboratory, Oak Ridge, TN 37830, United States*

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ABSTRACT

The generation-IV high temperature gas cooled reactors (HTGRs) are designed with many passive safety features, one of which is the ability to passively remove heat under a loss of coolant accident (LOCA). However, several common reactor designs do not prevent against a large break in the coolant system and may therefore experience a depressurized LOCA. This would lead to air entering into the reactor system via several potential modes of ingress: diffusion, gravity currents, and natural circulation. At the onset of a LOCA, the initial rate of air ingress is expected to be very slow because it is governed by molecular diffusion. However, after several hours, natural circulation would commence, thus, bringing the air into the reactor system at a much higher rate. As a consequence, air ingress would cause the high temperature graphite matrix to oxidize, leading to its thermal degradation and decreased passive heat (decay) removal capability. Therefore, it is essential to understand the transition of air ingress from molecular diffusion to natural circulation in an HTGR system. This paper presents results from a computational fluid dynamics (CFD) model to study the air ingress transition behavior. These results are validated against an h-shaped high temperature helium loop experiment (McIlroy et al., 2010). Details are provided to quantitatively predict the transition time from molecular diffusion to natural circulation.

1. Introduction

The next generation HTGRs – such as the gas turbine modular helium reactors (GT-MHRs), pebble bed modular reactors (PBMRs) and very high temperature reactors (VHTR) – are designed with passive safety features to ensure safe shutdown under off-normal conditions without any need of active intervention. It is important to ensure that these passive safety features will perform their intended function or to be able to predict their failure possibilities. Therefore, these passive safety features must be understood and modeled with a high degree of accuracy by themselves and also when integrated with a reactor under off-normal conditions. Various modeling tools such as computational fluid dynamics, multiphysics solvers and system scale codes can assist in predicting the behavior of the passive safety systems under off-normal scenarios. However, these codes or tools must be validated before they can be qualified for design and safety analysis. Common practice for the validation of these codes is to conduct separate effect, mixed effect, and integral experiments in scaled facilities.

Design and development of HTGRs are facilitated by experimental studies of separate or mixed effect physics (Lee et al., 2005; McIlroy et al., 2010; Said et al., 2017; Valentín et al., 2016; Sun et al., 2013; Arcilesi, 2012). The High Temperature Test Facility (HTTF) at Oregon State University (Schultz et al., 2012) was built to conduct integral thermal–hydraulics experiments for the development of HTGRs. The HTTF experiments will be conducted to cover steady-state operations, pressurized conduction cooldown (PCC) and depressurized conduction cooldown (DCC) scenarios simulating inlet–outlet double header break (Schultz et al., 2010). Other HTGR related projects include bypass flow experiments, plenum-to-plenum flow experiments, and graphite irradiation experiments in the Idaho National Laboratory (INL) Advanced Test Reactor (ATR) to study irradiation-induced deformation of graphite channels. Although many of these studies have emphasized on HTGR core and plenum-to-plenum thermal–hydraulic behavior, there is limited understanding on the air ingress process upon

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* Corresponding author.
E-mail address: hbindra@ksu.edu (H. Bindra).

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depressurization, which is associated with several coupled phenomena: helium-air stratification, helium-air diffusion, and global natural circulation.

HTGR designs have effective passive heat removal systems due to the conduction and radiation heat transfer that occurs between the graphite moderator and vessel walls. This passive heat transfer system may undergo significant changes in ability to transfer heat under a LOCA scenario. One of the design-basis LOCA considers a large break in coolant headers. During such an incident, air from the reactor cavity can enter HTGR and react with the graphite, causing oxidation. This process can directly impact the passive heat removal capabilities of the reactor due to deterioration of thermal properties of graphite, geometric changes, and heat of oxidation reaction. Therefore, it is important to understand the physics of the air ingress process and be able to quantitatively predict the rate of air ingress for evaluating reactor safety characteristics.

Several flow phenomena characterize helium-air exchange between the reactor cavity and the HTGR during a LOCA. During large break conditions in the coolant headers, the reactor vessel is expected to be depressurized upon ejection of helium coolant. The helium coolant inlet–outlet headers are located near the lower head of the vessel to retain Helium inside the reactor for a long duration of several hours due to the lower density of helium. This geometric design feature is intended to delay bulk air ingress into the high temperature graphite after depressurization.

However, stratified flow allows air to enter the lower plenum of the reactor core, replacing the escaping helium. Following this, air and helium exchange between the lower plenum and the rest of the reactor geometry is governed by molecular diffusion. Due to the slow nature of the diffusion process, it takes a significant amount of time for the air fraction to reach dominant levels inside the reactor core. However, once the air fraction in the core is dominate, a sudden onset of natural convection (ONC) is expected to occur, providing a bulk flow of air into the reactor. The stages air ingress into the reactor core are depicted in Fig. 1.

Previously, several different numerical and experimental studies have been conducted to increase understanding and improve predictive capabilities of the air ingress phenomena. CFD simulation studies conducted by Oh et al. Oh and Kim (2011) predict that the bulk air ingress from the reactor cavity into the HTGR core region occurs either instantaneously or within a few seconds as driven by the stratified flow. However, other predictive modeling results obtained from a validated 2D Gamma code (Jin et al., 2011; Hyung Gon Jin, 2012) show that the onset of natural circulation within an HTGR is not anticipated to occur until several hours – rather than several seconds – after the depressurization. In a separate-effects experimental study on isothermal air ingress into a helium filled scaled-vessel (Kim et al., 2013) through horizontal ports, it was determined that it would take several minutes to fill the entire test chamber. An 'inverted U' scaled model of the HTTR was developed by JAERI (Takeda and Hishida, 1992; Takeda and Hishida, 1993; Takeda and Hishida, 1996) to conduct experimental studies. These studies also included a one-dimensional (1-D) numerical model to predict the behavior observed in experimental studies. While these studies from JAERI were conducted to understand the transition from molecular diffusion to natural circulation driven air ingress, the geometric characteristics of the 'inverted U' shape experimental setup do not capture the effect of helium present in the upper plenum of HTGRs.

A recent experimental setup was developed at KSU (Gould et al., 2017) in the shape of a lower case h to accurately simulate the geometry of a HTGR. The extended upper leg of the h models the effect that the helium within the upper plenum of the GT-MHR would have on the time duration experienced from the initial coolant pipe rupture and depressurization until the onset of natural convection (ONC).

To understand the governing physics and predict behavior, a 3-D numerical model was developed using commercial software ANSYS CFX. This paper presents the simulation results from this model and compares them with experimental data for validation purposes. Section 2 presents the qualitative understanding developed from previous experimental results. It is followed by a description and details of numerical model analogous to the experimental setup. Simulation results and discussion are presented with the validation report. The final section presents the conclusions of this study.

2. Understanding transition to natural circulation

In general, air ingress can occur in a VHTR system through three different modes: (1) molecular diffusion due to concentration gradient of a helium-air mixture, (2) convective transport of air, and (3) natural convection due to a thermally driven up-draft in the reactor core. If the molecular diffusion is the dominant mode, then the rate of air-ingress remains quite low; however, it becomes very high with the convective transport and can start air circulation within few minutes of a LOCA.

Previous studies have suggested that the transition to natural circulation time can be simulated by a simple diffusion model. However, recent experimental studies with an h-shaped test facility (Gould et al., 2017) demonstrate that diffusion may not be the dominant mass transfer process during the air ingress. Although the diffusion mechanism can describe the general qualitative trends for different temperatures of the hot legs, these results suggest that (1) the diffusion constants are not sufficient for quantitatively predicting the ONC times and (2) Pre-ONC convection currents may

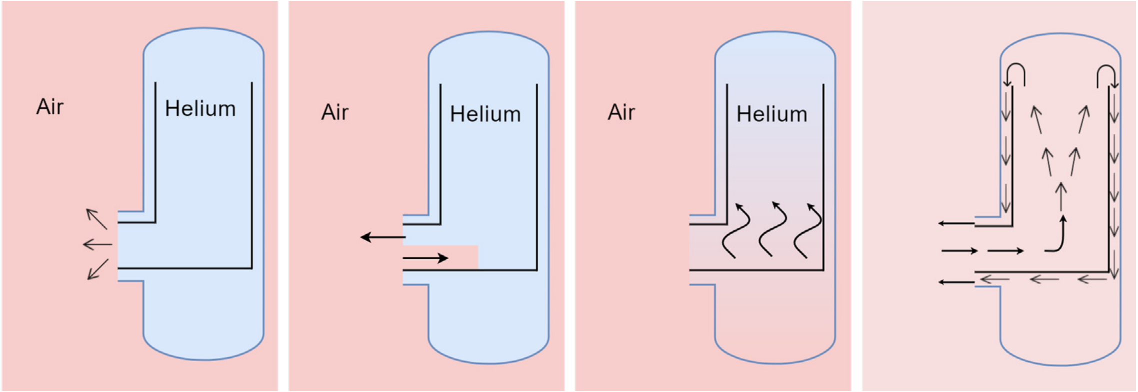

Fig. 1. Stages of flow in a LOCA scenario (Gould et al., 2017).