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Effect of helium pressure on natural convection heat transfer in a prismatic dual-channel circulation loop

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ABSTRACT

The effects of helium pressure on the convection heat transfer coefficient and temperature fields (helium and wall surface temperatures) in a unique scaled-down dual-channel natural circulation loop with upper and lower plena have been investigated in this study. Natural convection is one of the passive safety systems of the prismatic very high-temperature reactors (VHTRs) during the accident scenarios. The operating helium pressure was varied from 413.47 to 689.12 kPa in the temperature range from 6 to 196 °C. Radial and axial measurements were carried out along the flow channels using a new sophisticated flush wall-mounted heat transfer coefficient probe in conjunction with the radial adjuster for T-thermocouple that are integrated in a novel way to characterize natural convection heat transfer in terms of heat transfer coefficient, Nusselt number, helium temperature, and wall surface temperature. The obtained experimental results along the flow channels showed the dependence of natural convection on the system's pressure in which the Rayleigh number is proportional to the square of the helium pressure ($Ra \propto P^2$). Also, it was found that upon increasing the helium pressure from 413.47 to 689.12 kPa, the heat transfer coefficient and Nusselt number are increased by 30% and 35%, respectively. Moreover, the wall surface temperature along the downcomer and riser channels are decreased by 12.7% and 18% with increasing the helium pressure from 413.47 to 689.12 kPa, respectively.

1. Introduction

Investigations of natural convection heat transfer and flow dynamics in different geometries and operating conditions have been the focus of many past and current studies by several authors. Natural convection has received significant attention from researchers due to its presence in nature and engineering applications. In nuclear reactors, natural convection is being implemented as an engineered feature to achieve passive safety [1,2]. Natural convection is one of the main passive safety phenomena in the prismatic very high-temperature reactors (VHTRs) cooled by gas helium for a safeguard under the loss of flow accidents (LOFA) [3]. In the event of the failure of the gas circulator, LOFA, the driving pressure drop force across the reactor core will decrease to zero. Subsequently, the natural circulation due to density differences will be established to remove the decay heat from the core. Also, during the LOFA scenario, the coolant flows direction is reversed, and there are two different possibilities for flow direction that may occur inside the flow channels in the core due to large temperature variation. For the heated sections of the core, the coolant would flow upward, while in the relatively cooled section, the coolant would flow downward, establishing the natural circulation loop due to buoyancy force. The coolant channels with upward flow act as riser channels, while the coolant channels with downward flow act as downcomer channels. Natural convection currents by helium plumes transport the decay heat from the reactor core to the reactor cavity cooling system, and it prevents the core from possible meltdown and localized hot spots. There are many parameters affecting the rate of natural convection heat transfer, and consideration of each in a representative geometry can enhance one's knowledge about the phenomenon. Most reactor safety analyses and related natural convection studies are conducted using standard computational fluid dynamics (CFD) codes combined with heat transfer computations such as CFD-STAR-CCM+, and CFD-Fluent and thermal hydraulic codes such as RELAP5-3D that can provide crucial details of heat transfer data. There are extensive computational studies of natural circulation in the prismatic very high-temperature reactor (VHTRs) that have been reported in the open literature [1,3–8]. However, the thermal hydraulic codes used for these studies involve approximations in the obtained results because of the

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inexact nature of turbulence models that are used, assumptions used in the describing governing equations such as the Boussinesq approximation, nature of discretization required and so forth. Despite many numerical and experimental studies available on natural convection heat transfer in the open literature [9–21], little consideration is given to the effect of operating pressure variation on the flow field, heat transfer coefficient, and temperature profile [22–26]. Furthermore, the previous studies were carried out in simple geometries with limited measurement techniques and can not be extended for complex reactor geometries. Therefore, the Multiphase Reactors Engineering and Applications Laboratory (mReal) research team at Missouri S & T developed a unique scaled-down separate effect experimental facility of two flow channels [27]. The mReal research team developed a new integrated noninvasive heat flux sensors and radial temperature adjusters for the T-thermocouple sensor (1.6 mm in diameter) in a novel way to measure axially and radially heat transfer coefficient and the corresponding temperatures along the flow channels. Several experimental measurements were executed on the nature convection for a loop of two flow channels (riser and downcomer channels) with upper and lower plena under different helium pressures (413.47, 482.38, 551.29, 620.20, and 689.12 kPa). Therefore, the main objective of the current work is to experimentally investigate the phenomenon of the natural convection in terms of heat transfer coefficients, Nusselt number and temperature fields (gas and wall surface temperatures) at different operating pressures with helium as a working fluid using the newly developed facility and the novel techniques.

Under these operating conditions, the variation of natural convection coefficients and the axial and radial temperature fields along the riser and downcomer channels have been studied. The obtained knowledge and benchmarking data can be valuable for detailed validation of thermal hydraulic codes and CFD codes integrated with the heat transfer computations. Though this work only uses two channels for coolant flow, the study can be extended to multiple channels and different working fluid.

2. Experimental setup

The experimental setup is a scaled down separate effects facility fabricated using stainless steel alloy to handle high temperature and pressure. Figs. 1–2 show a physical picture and schematic diagram of the experimental setup [27]. This setup is capable of simulating accident scenarios for thermal hydraulics phenomena in prismatic very high-temperature reactors (VHTRs). It consists of two plena (i.e., upper and lower plena) with two channels for coolant flow in the reactor core. The two channels mimic the upward and downward flows inside the reactor core in the case of loss of flow accidents (LOFA). The inside diameter of the flow channels is kept constant at 16 mm, while the height of the channels was 1 m, representing five prismatic blocks. The upward flow in the riser channel, for reactor core, is simulated by electrically heating the riser channel by four heavily insulated Duo-Tape electrical heaters (50.8 × 609.6 mm) with a maximum wattage capacity of 312 W at 120 V. Each electrical heater is individually connected to a variable voltage regulator with a digital power reader to control the magnitude of wattage supplied to the riser channel. The downward flow in the downcomer channel is mimicked by executing cooling for the outer surface of the channel. A helical coil heat exchanger is implemented around the downcomer channel to cool the surface and initiate the downward flow. Also, the outer surface of the upper plenum is equipped with a cooling jacket to keep the outer surface temperature of the upper plenum at a constant value. An automatic chiller (Applied Thermal Control Ltd, K4 chiller) with temperature and pressure controllers has been used to provide chilled water at the desired temperature to the cooling jacket and helical coil heat exchanger for downcomer. The difference between the inlet and outlet of chilled water across the cooling jacket and heat exchanger always turns out to be less than 1.5 K. Hence; the constant wall surface temperature can be assumed as a thermal boundary condition for the downcomer channel and upper plenum. The lower plenum walls are maintained at adiabatic conditions by using thick ceramic fiber blanket. To reduce the heat losses to the environment, the whole setup is thermally insulated by a ceramic fiber blanket, as shown in Fig. 1. Further detailed explanation of the experimental setup in conjunction with design considerations can be found elsewhere [27].

3. Measurement technique

3.1. Radial temperature sensor adjuster

A radial temperature sensor adjuster for T-thermocouple has been designed and developed in-house to measure radial temperature variation of the coolant (helium) along the flow channels (riser and downcomer) for different axial locations. This radial temperature adjuster is used to adjust the radial location of the T-thermocouple sensor (1.6 mm in diameter with a time response of 4 s) along the flow channels (Fig. 3). Also, Fig. 4 shows a schematic diagram of the radial positions of the T-thermocouple sensor for a given axial location. Eight radial measurements of helium temperature with a step size of 1 mm have been performed. It is worth mentioning that the radial sensor adjuster is specifically designed and constructed for this application and can withstand high temperature and pressure up to 300 °C and 1.03×10^6 Pa, respectively.

3.2. Noninvasive flush wall mounted heat transfer coefficient probe

A new noninvasive heat transfer coefficient probe has been designed, developed, tested, and implemented as an integrated part of the channels.

The current probe consists of the micro-foil heat flux sensor (6.35×10^{-3} m x 1.78×10^{-2} m x 8×10^{-5} m) from RDF Corporation (model no. 27036-1). This new fast-response sensor has been used to measure reliably the heat flux and surface temperature in single and multiphase flow systems [27,28]. By measuring simultaneously the local instantaneous heat flux between the surface of the sensor and the flowing fluid, the surface temperature of the sensor, and the flowing gas temperature, the heat transfer coefficient can be obtained. The measured instantaneous heat flux (q_i), surface temperature ($T_{s,i}$), and characteristic fluid temperature ($T_{b,i}$) can be used as per Equations (1)-(2) to estimate the local instantaneous heat transfer coefficients (h_i) and the local time-averaged heat transfer coefficients (h_{avg}):

$$h_i = \frac{q_i}{(T_{s,i} - T_{b,i})} \tag{1}$$

$$h_{avg} = \frac{1}{N} \cdot \sum_{i=1}^{i=N} h_i \tag{2}$$

The sampling time is 40 s at sampling rate 50 Hz to collect 2000 data points in order to achieve a high stable value of the estimated heat transfer coefficients for the experimental conditions. The characteristic fluid temperature ($T_{b,i}$) for the riser channel is measured for a given axial location by averaging eight radial values of helium temperature ($T_{f\,i,j}$) with a step size of 1 mm (1/16 of the inside diameter):

$$T_{b,i} = \frac{1}{8} \cdot \sum_{j=1}^{j=8} T_{f\,i,j}. \tag{3}$$

For the downcomer channel, the characteristic fluid temperature ($T_{b,i}$) is the centerline's helium temperature. For the downcomer, there was only slight variation in the measured radial helium temperatures for any given axial location. Based on experiments that were conducted in the downcomer channel, only 2 K or less radial temperature variations were observed. Hence, centerline's helium temperature was used