Effect of heating configuration on plenum-to-plenum thermal hydraulics of buoyancy driven air

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Abstract – *Plenum-to-plenum thermal hydraulics in a Prismatic Modular Reactor (PMR) during loss of flow accidents (LOFA) has been of high interest for several researchers. Accordingly, this study aims to examine the effect of uniform and non-uniform heating configurations on the buoyancy driven air in a vertical plenum-to-plenum facility (P2PF) with dual channel representing the PMR core geometry. Advanced measurement techniques such as hot wire anemometry, T-type thermocouples, and micro-foil sensors are integrated to enable thermal and flow fields measurements at different axial and radial locations along the electrically heated channel. Results show that surface temperature as well as temperature and velocity of air increase from the leading edge up to a dimensionless axial position (Z/L) (0.6 < Z/L < 0.8) where a temperature reduction is observed. This reduction could be attributed to the conduction heat losses from the channel wall to the upper plenum in addition to expected flow destabilization due to reversal and back mixing at the exit of the hot channel. It is concluded that buoyancy driven air flow fields are significantly affected by the configuration and intensity of heat applied to the channel. Present findings will overcome the lack of insufficient experimental data for studying the thermal hydraulics in PMR and for validating computational fluid dynamics codes.*

Keywords: Prismatic modular reactor; Very high temperature reactor, Thermal hydraulics; Passive safety; Natural convection

I. Introduction

Natural circulation loops (NCLs) play a significant role in various heat exchange engineering applications, harnessing the inherent ability of fluids to transport heat without the need for external pumping. These systems utilize buoyancy forces induced by density differences to facilitate fluid motion between heated and cooled regions [1]. The study of natural convection phenomena is particularly relevant in the context of Very High Temperature Gas Reactors (VHTGRs) as Prismatic Modular Reactors (PMRs), where it serves as a passive safety feature for decay heat removal during loss of flow accidents (LOFAs) [2]. The interest in natural circulation thermal hydraulics in PMRs significantly intensified after the Fukushima Daiichi nuclear power plant accident in 2011, leading to extensive research on safer nuclear reactor designs [3].

A typical PMR vessel contains the reactor core, upper and lower plena, neutron control systems, core support structures, and shutdown cooling systems. The core consists of replaceable hexagonal graphite fuel and reflector blocks, with fuel blocks containing blind holes for heater rods and full-length channels for helium coolant flow. Stacked fuel and reflector blocks form fuel and reflector columns, with a three-row annulus between replaceable reflector blocks in the inner and outer regions [4].

During normal operation conditions, helium at around 260 °C is pumped into the reactor primarily through the inlet riser channels or the channels designed between the permanent layer and the reactor pressure vessel to an upper plenum (cold plenum). From there, it flows down through the channels shaped in the fuel blocks, extracting the fission heat, and exits the reactor through a lower plenum (hot plenum) at high temperatures (700-900 °C) [5]. However, during LOFA conditions such as a Pressurized Conduction Cooldown (PCC) scenario, where loss of cooling occurs while the primary pipe remains pressurized, the coolant flow reverses in the core. Helium gas, induced by density differences, flows upward in hotter coolant channels and downward in relatively colder coolant channels, forming a closed loop intra-core natural circulation. This natural circulation participates in dissipating the decay heat to the peripheral regions and prevents core meltdown. Moreover, this intra-core natural circulation results in axial and radial temperature variations within the core, further enhancing the natural circulation intensity [6].

Extensive computational and experimental research has been conducted on heat transfer and natural circulation within PMRs. Computational studies have investigated natural circulation examining coolant gas velocity variations and streamlining patterns in the upper plenum and channels and temperature distribution in the core under specific initial conditions [7-10]. Experimental investigations have focused on the effect of system pressure and different coolant gases such as helium, carbon dioxide, nitrogen, and air on natural circulation intensity, axial and radial temperature distribution, convective heat transfer coefficient, and local gas velocities [11-15]. However, these studies have primarily focused on uniform heat distribution, which leads to predictable natural circulation transients while neglecting the effect of non-uniform decay heat generation in the core. In contrast, non-uniform heating involves variations in heat input across the axial height of the core, introducing temperature gradients that significantly affect the buoyancy-driven natural circulation behavior and thermal hydraulics.

The heating configuration, whether uniform or non-uniform, is critical in determining the flow patterns, heat transfer characteristics, and overall performance of the natural circulation system. Consequently, this study investigates the effect of uniform and non-uniform heating configurations on natural circulation, temperature distribution, peak temperature location, and convective heat transfer coefficient in a dual-channel plenum-to-plenum experimental facility that mimics the core of a prismatic VHTGRs during PCC conditions. Understanding the impact of uniform and non-uniform heating on plenum-to-plenum thermal hydraulics is essential for optimizing the design and operation of VHTGRs. By investigating these two heating configurations, we aim to enhance our understanding of the flow patterns, heat transfer characteristics, and safety implications associated with buoyancy-driven natural circulation within VHTGRs. Additionally, the experimental data obtained from this research will serve as crucial benchmark data to validate thermal hydraulic codes such as STAR-CCM+ and Ansys Fluent. The insights gained from this research will contribute to a better understanding of natural circulation behavior in PMRs and aid in the development of safer and more efficient nuclear reactor designs.

II. Plenum-to-plenum dual channel facility

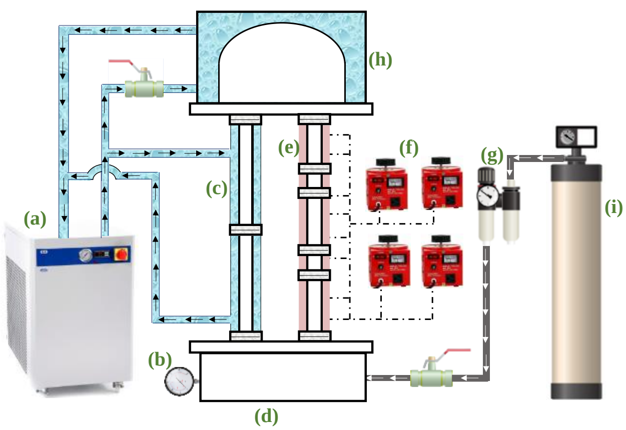
The dual channel plenum-to-plenum facility (P2PF) shown in Figure 1 was designed to experimentally investigate natural circulation thermal hydraulics under various operating conditions, such as different heating intensities, pressure levels, and coolant gases. The P2PF is composed of two plena (upper and lower) and core channels, which are the primary elements of the Prismatic Modular Reactors (PMRs). The dimensions of the P2PF plena are 1/4 of the size of the High Temperature Test Facility (HTTF) at Oregon State University, both axially and radially. This translates to a height of 0.24 meters (9.41 inches) for the upper plenum and 0.13 meters (5 inches) for the lower plenum, with a diameter of 0.30 meters (11.81 inches) for both.

The core of the facility is scaled down by half in the axial direction compared to the HTTF core channels. Consequently, the core channels in the P2PF measure 1 meter (39.37 inches) in height and have a diameter of 0.016 meters (9.41 inches), which matches the dimensions of a real Modular High-Temperature Gas Reactor (MHTGR) and the HTTF.

One channel represents the hot PMR reactor core as it is electrically heated by wrapping the entire channel length with four heavily insulated duo-taped electrical heaters, 1 × 24 inch with a maximum capacity of 312 W at 120 V. Heat flux supplied from each heater can be controlled separately by using a BTV Variac power controller with an accuracy of 0.2%. Meanwhile, the other channel represents the PMR cold section as it is cooled by using chilled water, which is supplied by an Applied Thermal Control Ltd., K4 chiller with temperature stability of around ±0.1 °C. The chilled water is pumped simultaneously into a copper coil, with a thermal conductivity of 400 W/(m.K) and a jacket surrounding the channel and the upper plenum, respectively.

To minimize interferences with the surroundings, facility components (stainless steel channels and two planes) were substantially insulated by using ceramic fiber insulation.

In this designed setup, a natural circulation loop is established due to the temperature difference between the hot and cold channels. As a result of heating, the air density in the hot channel (known as a riser channel) decreases, causing it to rise upwards against gravity towards the upper plenum, where it is cooled. Subsequently, the air flows downwards in the cold channel (known as the downcomer) towards the lower plenum and then circulates back to the upper plenum.



a	Chiller
b	Pressure gauge
c	Cold channel
d	Lower plenum
e	Hot channel
f	Electric heaters
g	Air filter
h	Cold plenum
i	Air supply

Fig. 1. Schematic diagram for the vertical dual channel P2PF.

III. Experimental procedures

To study the air thermal hydraulics in the P2PF under uniform and non-uniform heating profiles as listed in Table 1, the setup was pressurized with dehumidified air at 14.5 psi then the four heaters were adjusted at the desired value. After that, the chiller was turned on at 5 °C. The system was left for 4 hours until reaching thermal stability where the temperatures don't change more than 0.5 °C within half an hour. It is worth mentioning that the hot channel inner surface temperature as well as air temperature and velocity were measured at six axial locations (Z/L = 0.044, 0.279, 0.409, 0.591, 0.773, 0.956) along the hot channel, where Z is the axial position measured from the beginning of the channel and L is the length of the channel. Moreover, radial measurements for the air temperature and velocity from the hot channel inner surface (r/R = 1) to the hot channel centerline (r/R = 0) were recorded at each axial location by means of radial adjustors manufactured at our shop. Here, 'r' represents the radial distance measured from the channel centerline towards the wall, and 'R' is the channel radius. Sampling rate is 100 Hz for 60 seconds to get (N = 6000) datapoints to ensure temperature and velocity stability for the experiments [6, 12].

Table1. Heating profiles applied along the hot channel.

Distribution of the electrical heater tapes along the hot channel	Heating intensities (W/m^2)			
	Set 1	Set 2	Set 3	Set 4
Heater 1	100	100	300	700
Heater 2	100	300	700	700
Heater 3	100	300	700	700
Heater 4	100	100	300	700

IV. Measurement techniques and data processing

IV.A. Thermocouple radial adjustor

To locally measure the air temperature in the hot channel, a T-type thermocouple probe with a diameter of 1.6 mm was fixed to a radial adjustor shown in Figure 2. The radial adjustor was attached at the six axial locations along the hot channel. This adjustor facilitated nine different radial measurements, capturing data from the center of the channel all the way to the inner wall surface with 1 mm intervals at each axial location. The characteristic air bulk temperature ($T_{b,i}$) at each axial location was calculated using the following procedure:

1. The instantaneous air temperature ($T_{f,i,j}$) was recorded, and these values were then averaged to obtain the time-averaged temperature

($\bar{T}_{f,i,j}$). The calculation can be expressed as follows:

$$\bar{T}_{f,i,j} = \frac{1}{N}\sum_{N=1}^{N=6000} T_{f,i,j} \quad (1)$$

2. The nine time-averaged air temperatures were averaged together to obtain the characteristic air bulk temperature ($T_{b,i}$). The calculation is given by:

$$T_{b,i} = \frac{1}{9}\sum_{j=1}^{j=9} \bar{T}_{f,i,j} \quad (2)$$

Fig. 2. Thermocouple probe radial adjustor.

IV.B. Flush mounted micro-foil sensors

To accurately measure the surface temperature along the heated channel, a new and innovative method utilizing micro-foil sensors has been implemented. These fast response sensors are from RDF Corporation (model no. 27036-1) and provide precise surface temperature detection and possess the capability to determine the direction of heat transfer, whether it is from the channel surface to the air (indicated by positive signals of heat flux) or from the air to the channel surface (indicated by negative signals of heat flux). By averaging the time instantaneous surface temperature readings ($T_{s,i}$), the hot channel surface temperature at any given axial position ($\bar{T}_s$) can be accurately calculated.

$$\bar{T}_s = \frac{1}{N}\sum_{N=1}^{N=6000} T_{s,i} \quad (3)$$

IV.C. Hot wire anemometer probe

To assess the air velocity within the riser channel, an advanced and sophisticated hot wire anemometer probe, provided by Dantec Dynamics Company, was utilized. The hot wire anemometer incorporates a remarkably small sensor wire, typically just a few microns in diameter and a couple of millimeters in length. As a result, it has the capability to measure the instantaneous air velocity at any point in the flow with minimal disruption to the flow itself. This instrument boasts exceptional spatial and temporal resolution, enabling the acquisition of thousands of velocity measurements per second. It accurately measures gases velocities across a wide range, spanning from a few centimeters to well over a hundred meters per second.

The operating principle revolves around the behavior of the wire sensor, which naturally cools as it loses heat to the surrounding flowing air. However, precise electronic controls are employed to maintain the sensor at a constant temperature by adjusting the electric current, achieved through voltage variation, as required. The rate of heat transfer from the sensor increases with higher air velocities, necessitating a larger voltage across the sensor to sustain its temperature at a constant level. A close correlation exists between the air velocity and the voltage, allowing the determination of air velocity by measuring the applied voltage using an amplifier or monitoring the electric current passing through the sensor [16].

For the current study the hot wire anemometer probe was attached to a radial adjustor to measure the air velocity at nine different radial positions from the hot channel center line to the channel inner wall at the six axial positions defined earlier. The local air bulk velocity ($U_{b,i}$) at a given axial location is calculated by:

(a) at each radial position, the instantaneous fluid (air) velocity ($U_{f,i,j}$) is averaged to obtain the time-averaged velocity ($\bar{U}_{f,i,j}$).

$$\bar{U}_{f,i,j} = \frac{1}{N}\sum_{N=1}^{N=6000} U_{f,i,j} \quad (4)$$

(b) The nine-radial time-averaged air velocities are then averaged together to determine the local air bulk velocity.

$$U_{b,i} = \frac{1}{9}\sum_{i=1}^{i=9} \bar{U}_{f,i,j} \quad (5)$$

V. Results and discussion

V.A. Hot/riser channel surface temperature distribution

Figure 3 illustrates that the temperature distribution along the surface of the riser channel remains consistent across all heating profiles. When heat is continuously applied along the entire length of the channel, the surface temperature increases as we move along the channel until reaching an axial position of Z/L = 0.591. Beyond this point, the temperature starts to decrease. This trend in temperature distribution aligns with previous research on convection heat transfer and natural circulation. Notably, there is no consensus among researchers regarding the specific axial position where the highest temperature occurs in the heated channels. For example, Lau et al. [17], Sanvincente et al. [18, 19], Webb and Hill [20], and Manca et al. [21], conducted numerical and experimental investigations on natural convection in uniformly and non-uniformly heated vertical open channels, and they reported the presence of temperature inflection at the channel outlet. These studies attributed the temperature reduction to heat losses from the outlet section of the channel to the surroundings. However, previous studies within the P2PF explained this inflection in terms of axial heat losses due to conduction through the flange that connects the riser channel to the cold upper plenum [11-15]. These findings emphasize the significant influence of geometric configuration, heating intensities and profiles, as well as the surrounding environment, on the variation of surface temperatures in heated channels and walls.

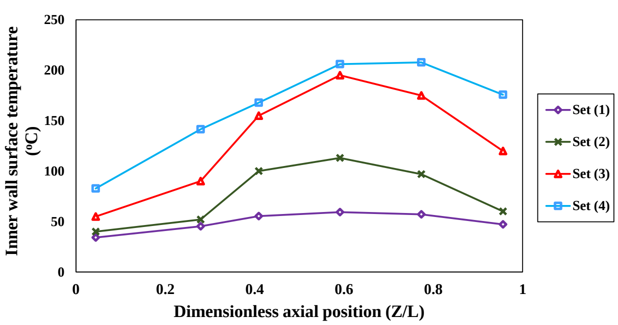


Fig. 3. Inner wall surface distribution along the hot/riser channel.

V.B. Air temperature distribution along the hot/riser channel

Figure 4 illustrates the distribution of air temperature along the riser channel. It is evident that the air temperature profiles for different heating intensities exhibit similarities and are influenced by the temperature of the riser channel surface.

The initial rise in air temperature is due to the continuous heat transfer from the hot inner surface of the riser channel to the air. Conversely, the decrease in temperature is a result of the decrease in channel surface temperature due to the conduction heat losses as mentioned previously. Additionally, the decrease in air temperature at the outlet section of the riser channel can be attributed to the phenomenon of flow reversal, which has been reported in previous studies [11-15]. This reversal phenomenon occurs when the heated buoyant air flowing upward encounters cold air from the upper plenum flowing downward due to its higher density compared to the hot air. Therefore, flow instability, high turbulence, and the formation of vortices and eddies at the outlet section of the riser channel occur showing the intricate nature of buoyancy-driven flow.

Furthermore, the intensity of heating applied at the riser channel surface outlet affects the flow reversal and back-mixing phenomenon. Among the different sets and at the channel outlet (Z/L = 0.956), set (1) displays the lowest distribution of heat along the riser channel, resulting in a radial temperature drop of 4.3 °C, in comparison to set (4) with the highest heating intensity profile, experiences a radial temperature drop of 11 °C.

Moreover, it should be noted that the flow reversal of cold air entering the riser channel from the outlet section affects the thermal behavior of the hot air flowing upward in the riser channel. Consequently, the air temperature at the center of the riser channel at the channel outlet (Z/L = 0.956) is higher than that near the wall, as shown in Figure 5. This causes the air to flow as a high-velocity jet from the riser channel outlet toward the upper plenum which will be discussed in the following section.

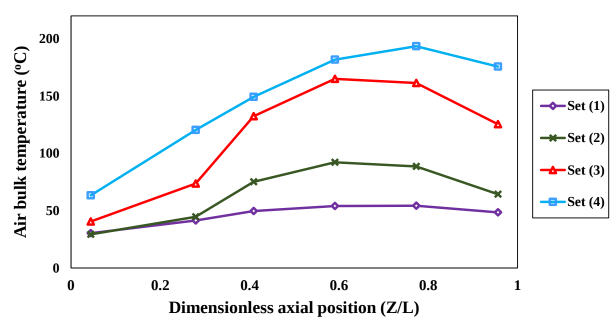


Fig. 4. Air temperature distribution along the hot/riser channel.

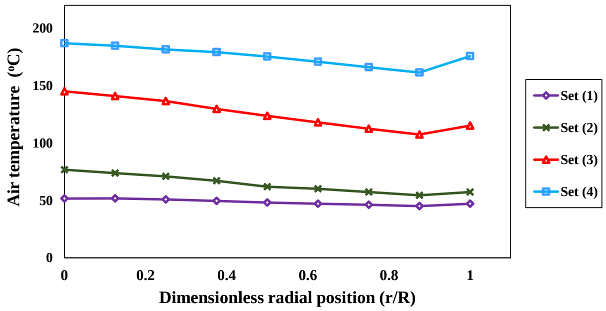


Fig. 5. Radial air temperature variation at the axial position Z/L= 0.956 of the hot/riser channel.

V.C. Air velocity along the hot/riser channel

The normalized velocity contours depicted in Figure 6 reveal the axial and radial variations in air velocity within the hot channel. The axial distribution of velocity demonstrates a noticeable increase from the channel inlet to the midsection (0.4 < Z/L < 0.591). This increase can be attributed to the decrease in air density and simultaneous temperature rise, which, according to mass conservation, results in an augmented air velocity. However, as we proceed along the upper section (Z/L > 0.591), temperatures decrease, leading to an increase in density. Consequently, the movement of air molecules is affected, causing a reduction in air velocities.

Studying the variation of air radial velocity requires examining three approximately axial locations: (i) 0 < Z/L < 0.3, where the velocity peak is near the channel wall. This is attributed to the start of building of boundary layers and the sharp entry edge which leads to vortices and turbulence near the channel wall. (ii) 0.3 < Z/L < 0.591, where the velocity peak is shifted near the channel centerline as the heating intense is severe and lesser wall (boundary) effect [22]. (iii) 0.591 < Z/L < 1 where the velocity peak is at the channel centerline, aligning with the temperature profile where the maximum air temperature at the channel outlet is also centered. This observation supports the existence of flow reversal at the channel exit, which impacts the flow dynamics within the channel. Consequently, the upward flow of air, propelled by buoyancy, is influenced by the reversal flow, causing a change in direction and an accelerated flow through the central region of the channel, ultimately exiting as a jet [6, 14, 23].

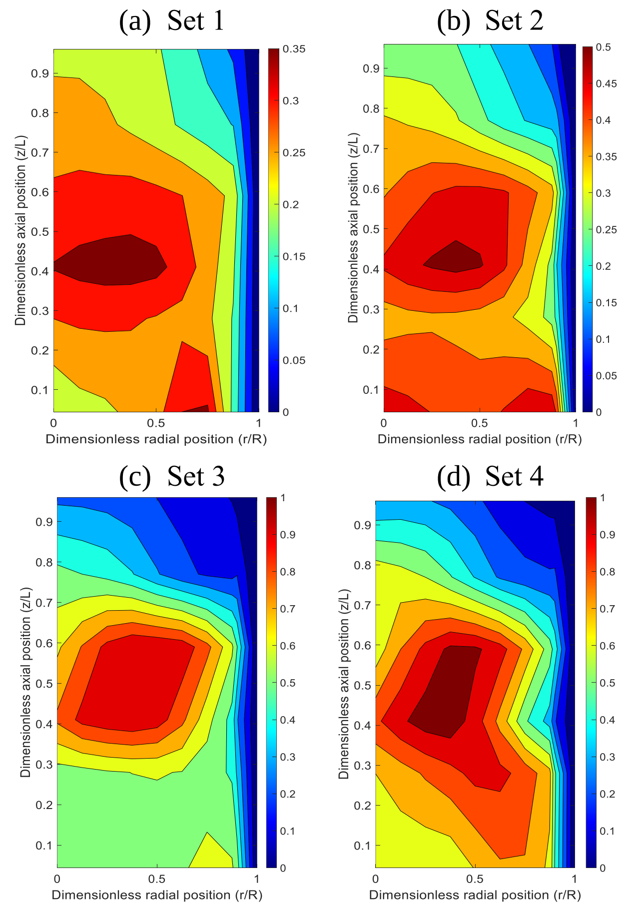


Fig. 6. Normalized air velocity contours along the hot/riser channel for different heating profiles.

VI. Conclusions

The present study investigates the air thermal hydraulics in a vertical dual channel plenum-to-plenum facility representing the core of a prismatic modular reactor (PMR). The key findings for the current study are summarized as follows:

- A decrease in the hot channel outlet temperature due to the conduction heat losses through the flange connecting the channel to the upper plenum.
- Air temperature distribution is affected by the hot channel surface temperature showing the delicacy of natural convection heat transfer.
- Air temperature decreases at the channel outlet due to the flow reversal and back mixing with the cold air in the cold plenum.
- The axial air velocity is consistent with the air temperature profile and affected by the heating intensity applied to the hot channel.

- The air leaves the hot channel as a jet where the velocity peak is at the centerline of the channel outlet.

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Nomenclature

Abbreviations	
LOFA	Loss of Flow Accidents
NCLs	Natural Circulation Loops
VHTRs	Very High Temperature Gas Reactors
PCC	Pressurized Conduction Cooldown
PMRs	Prismatic Modular Reactors
P2PF	Plenum-to-Plenum Facility
HTTF	High Temperature Test Facility
MHTGR	Modular High Temperature Gas Reactor
Dimensionless groups	
Z/L	Dimensionless axial position
r/R	Dimensionless radial position
Symbols	
L	Channel length
N	Number of data points
$T_{b,i}$	Characteristic air bulk temperature
$T_{f,i,j}$	Instantaneous air temperature
$\bar{T}_{f,i,j}$	Time-averaged air temperature
$T_{s,i}$	Time-instantaneous surface temperature
$\bar{T}_s$	Hot channel surface temperature
$U_{b,i}$	Local air bulk velocity
$U_{f,i,j}$	Instantaneous air velocity
$\bar{U}_{f,i,j}$	Time-averaged air velocity

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