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EXPERIMENTAL INVESTIGATION ON HEAT TRANSFER IN A PRISMATIC MODULAR REACTOR UNDER COSINE HEAT FLUX

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ABSTRACT

The current study has investigated natural convection heat during pressurized conduction cooldown (PCC) accident scenario to understand the passive safety features of prismatic modular reactors (PMR) under different intensities of nonuniform center peaking step heat flux distributions (approximating cosine shape) using an advanced fast-response heat transfer technique. A scaled-down PMR module was designed and developed at Missouri S&T by the research team of the Multiphase Reactors Engineering and Applications Laboratory (mReal). The module consists of upper and lower plena connected by heated and cooled channels. Nonuniform heat flux distribution was applied to the heated channel under nonuniform heating center peaking step (approximating cosine shape), simulating nonuniform heat distribution within the core of PMR. Air was used as the coolant to study the effect of nonuniform heating under a range of heat flux intensity (four sets of nonuniform heat flux and one set of uniform heat flux were tested) at 413.7 kPa (60 psi). At an axial position of Z/L = 0.409 along the heated channel, the heat transfer coefficient is increased by 35% for nonuniform heat flux distributions of set 1 (0.25*2.579 kW.m^{-2}+0.50*3.152 kW.m^{-2}+0.25*2.579 kW.m^{-2}) and set 2 (0.25*2.292 kW.m^{-2}+0.50*2.865 kW.m^{-2}+0.25*2.292 kW.m^{-2}) with respect to the the uniform heat flux set 5(2.865 kW.m^{-2}), and it is decreased by 56% for nonuniform heat flux distributions of set 3 (0.25*2.006 kW.m^{-2}+0.50*2.579 kW.m^{-2}+0.25*2.006 kW.m^{-2}) and set 4 (0.25*1.719 kW.m^{-2}+0.50*2.292 kW.m^{-2}+0.25*1.719 kW.m^{-2}) with respect to the uniform heat flux set (set 5). There is a significant reorder in the heat transfer coefficients distribution curves in descending order along the heated channel after the inflection point (after Z/L =0.773).

KEYWORDS

Natural convection; pressurized conduction cooldown accidents; prismatic modular reactors; nonuniform heat flux; heat transfer technique.

1. INTRODUCTION

Among the promising candidates for the next generation nuclear plant (NGNP) is the prismatic modular reactor (PMR). Reactor core of PMR is made up of hexagonal graphite blocks with channels for fuel rods and coolant flow. The removal of the post-shutdown decay heat relies on natural circulation. Under off-normal shutdown and accidental scenarios such as loss of forced cooling accident (LOFA), adequacy of natural convection must be evaluated to ensure passive safety. Pressurized conduction cooldown accidents (PCC) is a loss of flow accident, meaning the forced flow of working fluid to the reactor is suspended. During PCC, high working fluid pressure is maintained. In contrast to depressurized conduction cooldown (DCC) where working fluid pressure drops down immediately. Understanding how reactor properties affect natural convection during PCC is crucial to passive safety. It is important to understand how the coolant circulates to design reactors that safely shut down in the event of a loss of coolant flow accident. When pressurized conduction cooldown (PCC) accident takes place, the heat transfer characterization in the PMR is addressed by numerous computational studies in the open literature [1, 2, 3, 4, 5]. Recent experimental studies used some sophisticated measurement techniques to advance the current knowledge of the PMR under natural circulation in a unique dual-channel facility [6, 7, 8, 9, 10, 11, 12, 13]. However, the focus of the initial studies was on uniform heat flux conditions, which is not a typical scenario of the PMR during the LOFA scenarios. Due to the cosine nature power distribution of a typical cylindrical reactor, one would expect the decay heat to follow the same cosine shape. Therefore, additional emphasis is placed on generated heat transfer data, in terms of field temperatures and heat transfer coefficients, for nonuniform heating center peaking step (approximating cosine shape). There is a real need to extend this investigation to include more realistic conditions of nonuniform axial heat flux distributions. In this study, experimental results and analysis are provided for natural circulation with air (working fluid) using advanced instrumentation detailing heat transfer data in terms of temperature fields (centerline air and inner wall surface temperatures) and heat transfer coefficients under natural circulation. The effect of the intensity of nonuniform heat flux at steady state is investigated for air at 413.685 kPa. The collected data in this study can provide the necessary benchmark to validate thermal-hydraulic codes such as; RELAP5-3D, CFD-STAR-CCM1, CFD-Fluent, and so forth.

2. EXPERIMENTAL WORK

Multiphase Reactors Engineering and Applications Laboratory (mReal) at Missouri S&T developed a dual-channel facility to imitate the coolant flow in PMR [7, 8, 9, 10]. The current facility is constructed with reference to OSU-HTTF with a scale ratio of ¼ axially and radially [4]. The development of the constant diameter’s (0.016 m) dual channel is for the upward and downward flows of the coolant at the center block and at an outer block, respectively, with the upper and lower plena as shown in Figure 1, and Table 1 shows the physical dimension of our facility with HTTF. A cooling jacket around the upper plenum and helical coil heat exchanger around the cooled channel were connected to an automatic high capacity chiller (Applied Thermal Control Ltd, K4 chiller) to keep the outer surface temperature at the desired value (5 °C). A variable voltage regulator with a span of 0-130 volts and a digital power reader (0.2% precision) was attached to each of four electrical heaters to regulate and monitor the intensity of the power supplied to the heated channel. Each heater covers 25% of the length of the heated channel, and each heater is connected with a separate controller and power reader as shown in Figure 1. The heated channel external surface has been carefully insulated using a ceramic fiber blanket of 0.05m in thickness with a low thermal conductivity of 0.07 W/m K in order to reduce heat loss to the environment. The stimulation of the natural circulation takes place within the current setup by heating the heated channel and cooling the upper plenum and cooled channel. In this study, a nonuniform heating center peaking step (approximating cosine shape as shown in Figure 2 and Table 2) heat flux was applied to investigate the effect of heat flux nonuniformity (sets 1-4) and uniform heat flux equal to 2.865 kW/m^2 for the entire length of the heated channel (set 5). The current experiments have been performed using air as the coolant at 413.7 kPa (60 psi). An advanced heat transfer technique consisting of heat transfer foil sensor (with an uncertainty of 2.5% of the sensor reading) and T-thermocouples (with an uncertainty of 2.2 °C or 0.75% of the reading) is adapted and implemented along the channels. Simultaneous measurements of the inner local heat flux (q_i) and the inner surface temperature ($T_{s,i}$) were carried out by utilizing the heat flux foil sensor. The implemented heat flux foil sensor can detect the direction of heat transfer between the surface sensor and the adjacent flowing air based on the sign of heat flux. Negative heat flux signals mean that heat transfers from the air to the surface, while positive heat flux signals imply that heat transfers from the surface of the foil sensor to the air. Centerline air temperature ($T_{b,i}$) in front of the sensor was measured using a T-thermocouple (1.6 mm in diameter). With this technique, instantaneous heat transfer coefficient (h_i) and local time-averaged heat transfer coefficient (h_{avg}) can be calculated [14, 15]:

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

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

where N is the total data points; N= 2000 was selected to attain stable values. Data was measured for six non-dimensional axial positions along the heated channel (Z/L = 0.044, 0.279, 0.409, 0.591, 0.773, and 0.956) and three non-dimensional axial positions along the cooled channel (Z/L = 0.044, 0.5, and 0.956). The present study calls for the measurement of the heat transfer coefficients along the heated channel for various flux distributions.

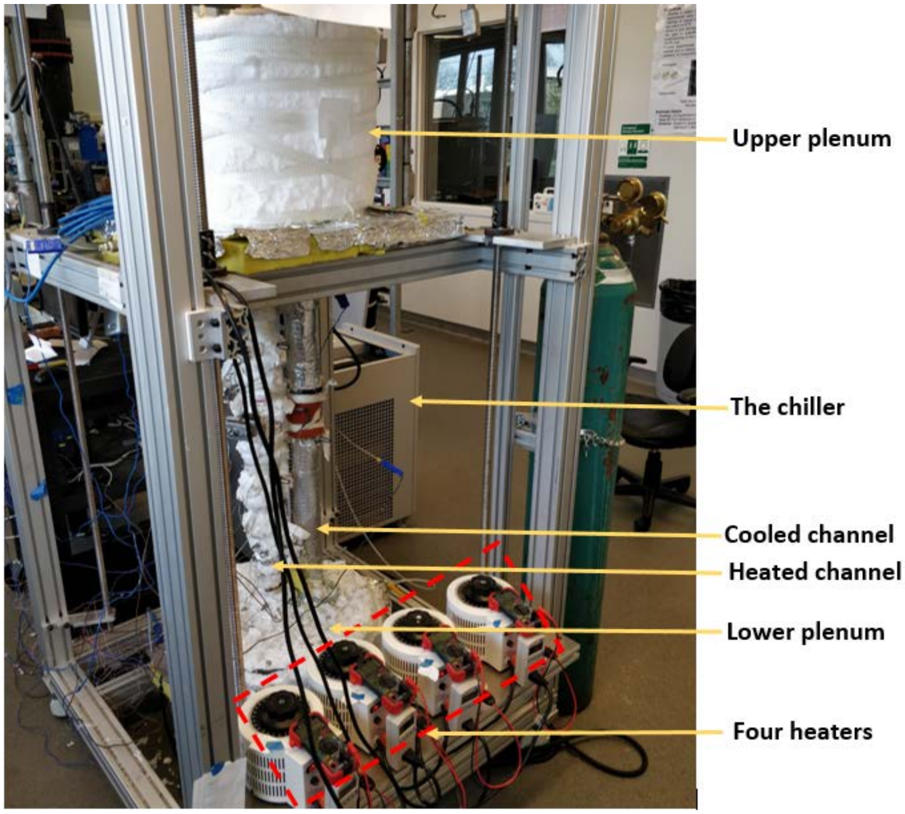

Figure 1. The dual-channel facility.

Table.1 Dimensions of the current facility with reference to OSU-HTTF

Parameter	Current facility	OSU-HTTF
Tube diameter (m)	0.016	0.016
Coolant channel length inside block (m)	1	2
Core diameter (m)	0.3	1.2
Upper plenum height (m)	0.239	0.956
Outer vessel diameter (m)	0.381	1.524
Number of channels	Two channels (one upward flow and other downward flow)	516 coolant channel 210 Heater Rod Six inner gap channel 36 outer gap channel

The current study focused only on measuring the heat transfer coefficients along the heated channel due to the small temperature gradient along the cooled channel [9]. The steady-state condition was achieved when temperature readings did not vary by more than 0.5 K and the local heat transfer coefficient was within ±0.8 W/m^2 K for a 30-minute observation. Each experiment is repeated three times with ±1.5% reproducibility

3. RESULTS AND DISCUSSION

The reversal of heat direction and reduction in temperature fields was earlier observed within the heated channel close to the exit (end effect) [6, 7, 8]. Similar thermal behavior was observed in the current study. At two different axial positions along the heated channel (Z/L = 0.773 and 0.956), negative heat fluxes were observed for uniform (Set 5, 50 W) as well as for all cases of nonuniform heating center peaking step (approximating cosine shape) .

Table.2 Heat flux distribution around the heat channel.

	Axial division			
	0 - 0.25 (m)	0.25 - 0.50 (m)	0.50 - 0.75 (m)	0.75 - 1 (m)
Set 1	2.579 kW/m^2	3.152 kW/m^2	3.152 kW/m^2	2.579 kW/m^2
Set 2	2.292 kW/m^2	2.865 kW/m^2	2.865 kW/m^2	2.292 kW/m^2
Set 3	2.006 kW/m^2	2.579 kW/m^2	2.579 kW/m^2	2.006 kW/m^2
Set 4	1.719 kW/m^2	2.292 kW/m^2	2.292 kW/m^2	1.719 kW/m^2
Set 5	2.865 kW/m^2	2.865 kW/m^2	2.865 kW/m^2	2.865 kW/m^2

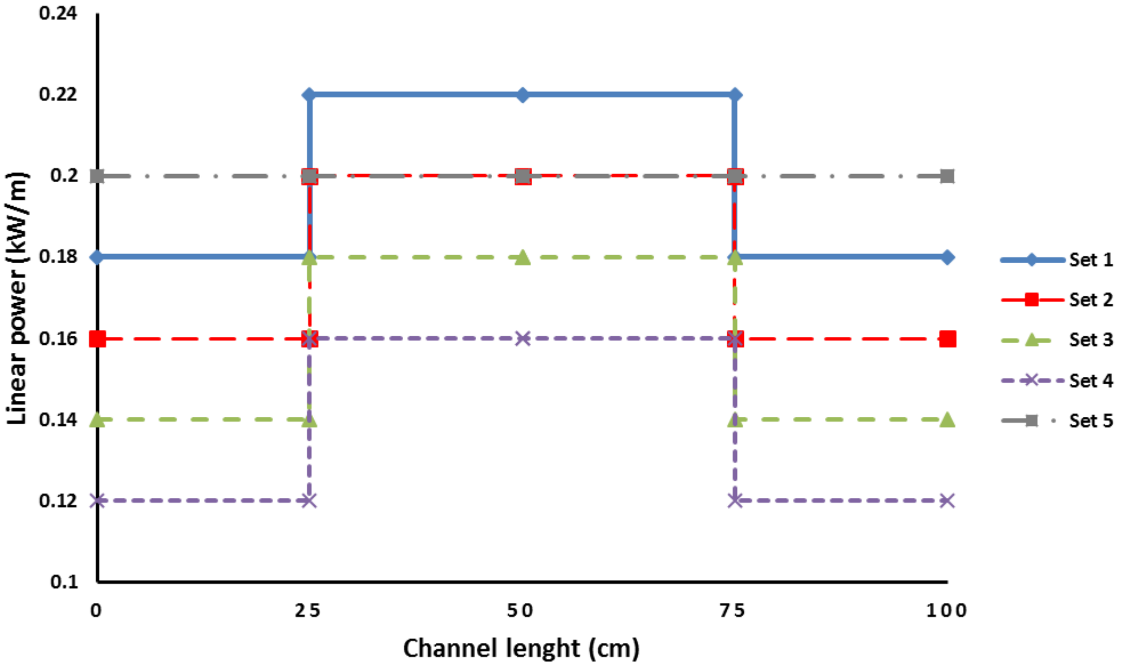

Figure 2. Power distribution (nonuniform heating center peaking step (approximating cosine shape)) around the heated channel.

This behavior could be attributed to nonuniform heating in terms of secondary flow [16], and the heat conduction between the two channels through the upper flange, which results in temperature variation along the heated channel. These negative heat flux signals confirm that there is a reversal in the direction of heat transfer from the flowing air to the inner surface of the heated channel. The heat flow reversal can be caused by axial cooling conduction through the solid wall of the heated channel (conjugate heat transfer) and the presence of the upper plenum as an adiabatic extension with large expansion ratio at the outlet. Figures 3 and 4 show the reversal in the heat direction (negative signals of heat fluxes) from the adjacent air to the inner wall for Z/L = 0.773 and 0.956. The negative signals of heat fluxes in Figures 3 and 4 showed that the heat was transferred from air to the inner wall of the heated channel, while positive heat fluxes are observed for the remaining axial locations. Figure 5 shows all positive heat fluxes for Z/L =0.591. Negative heat fluxes are observed along the cooled channel for all operating conditions. This confirms the downward flow and establishment of natural circulation between upper and lower plena. It is interesting to see the order of the negative heat flux. For the highest heating case, the negative heat flux is also highest.

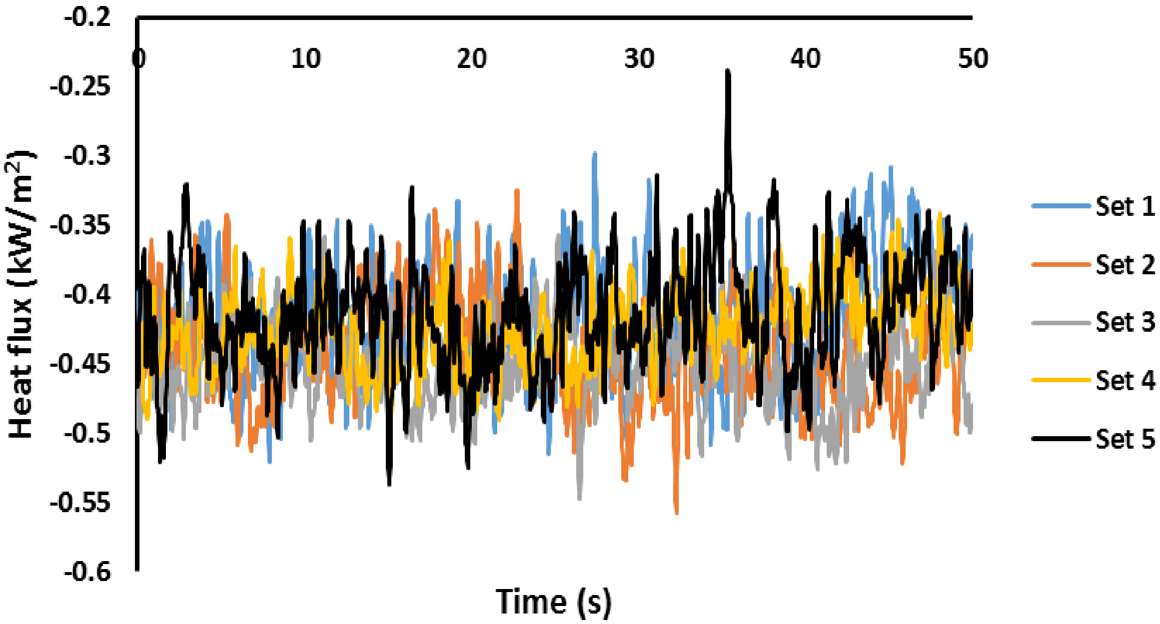

Figure 3. End effect at heated channel position Z/L = 0.773.

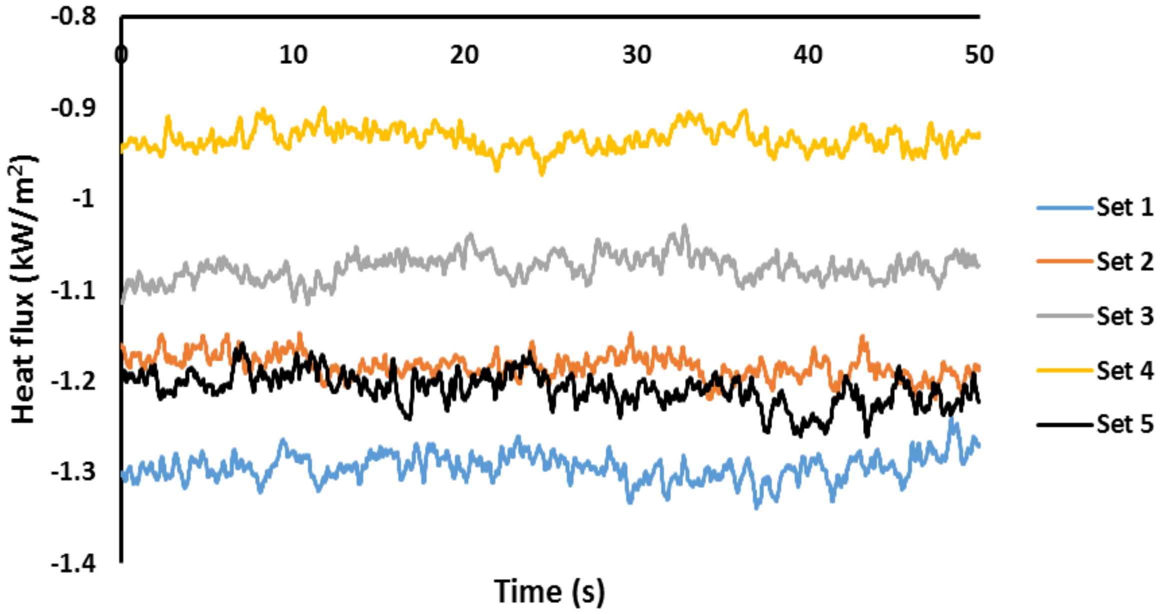

Figure 4. End effect at heated channel position Z/L = 0.956.

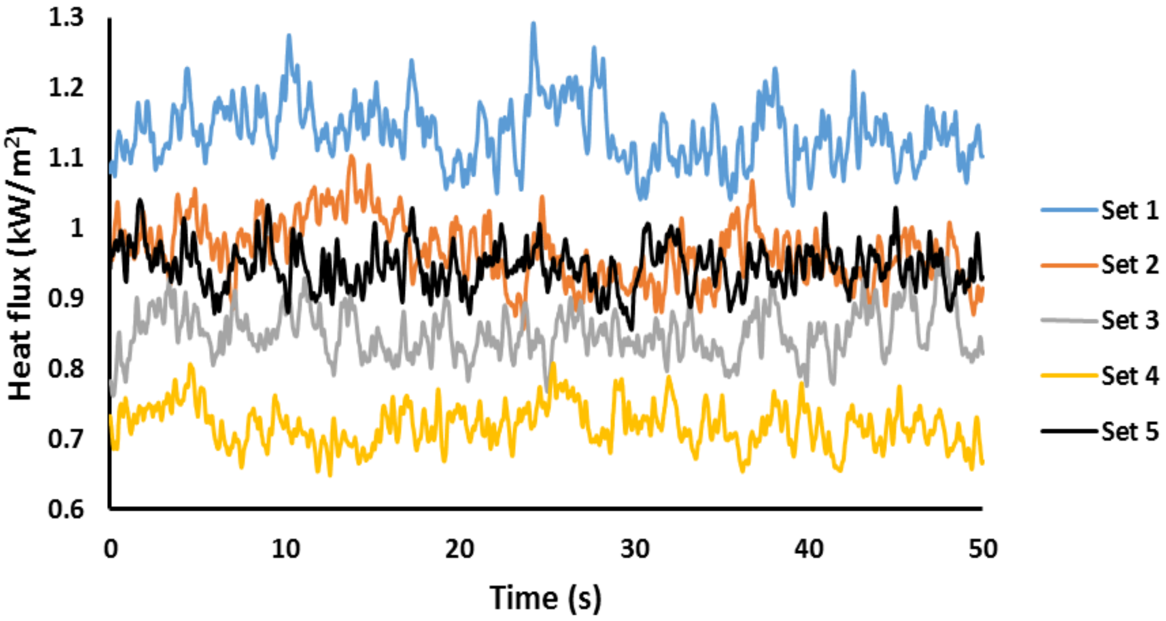

Figure 5. End effect at heated channel position Z/L = 0.591.

Figures 6 and 7 show the axial temperature profiles for the inner wall surface and air centerline temperatures along the heated channel. The maximum surface temperature is observed for uniform heat flux (set 5) at Z/L =0.773 and at Z/L =0.591 for all nonuniform heating center peaking step sets. A sharp reduction is observed for uniform heat flux (set 5) after Z/L = 0.773, but for nonuniform heating center peaking step cases from Z/L = 0.591 to Z/L = 0.773, there is a plateau for sets 1, 2, 3, and 4. This plateau is not seen for set 5 (uniform heating), where the temperature is still increasing after position Z/L = 0.591. For air centerline temperature, the temperature profile is slightly different from inner wall surface temperature profile: 1) The maximum temperature is observed at Z/L = 0.773 for all sets; 2) The plateau that exists in the inner wall surface temperature is not observed in the air centerline temperature profile. This thermal performance in terms of field temperatures could be attributed to an increase in the air thermal conductivity, which leads to lower resistance and an increase in the viscosity, causing the radial flow of the hotter layers of air to move nearer to the surface toward the tube center. Figure 8 shows the heat transfer coefficient along the heated channel, and the heat transfers from the adjacent air layer to the inner wall started after Z/L = 0.591. This heat transfer reversal could be attributed to the downward axial cooling conduction inside the solid wall of the heated channel from the upper plenum and co-circulation at the top section of the heated channel, as reported in the literature [7, 8, 9, 17, 18]. The heat transfer coefficients decrease from the inlet Z/L = 0.044 to Z/L = 0.279. This could be attributed to the developing of hydrodynamic and thermal boundary layers. Again in the values of the heat transfer coefficients is observed after Z/L = 0.279 to Z/L = 0.591 due to the laminarization effects [19, 20, 21]. At Z/L = 0.409, the heat transfer coefficient increases by 35% for nonuniform heating center peaking step (sets 1and 2) with respect to the uniform heating (set 5), and it decreases by 56% for nonuniform heating center peaking step (sets 3 and 4) with respect to the uniform heating (set 5).

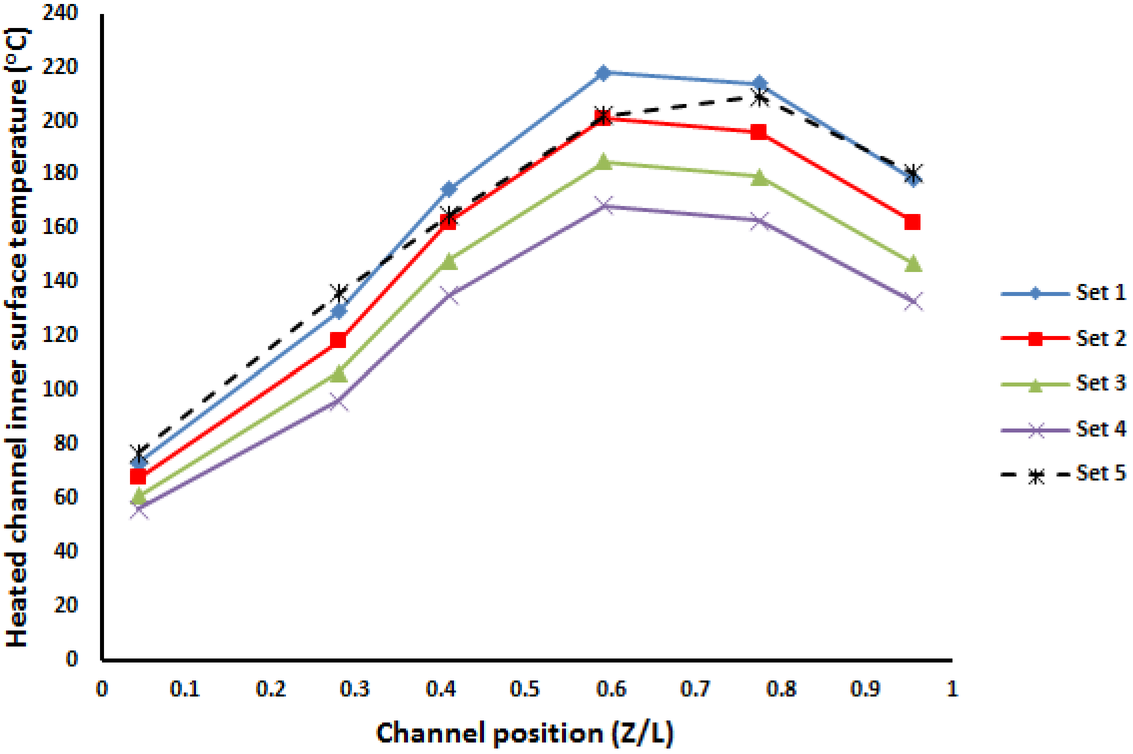

Figure 6. Heated channel inner surface temperature.

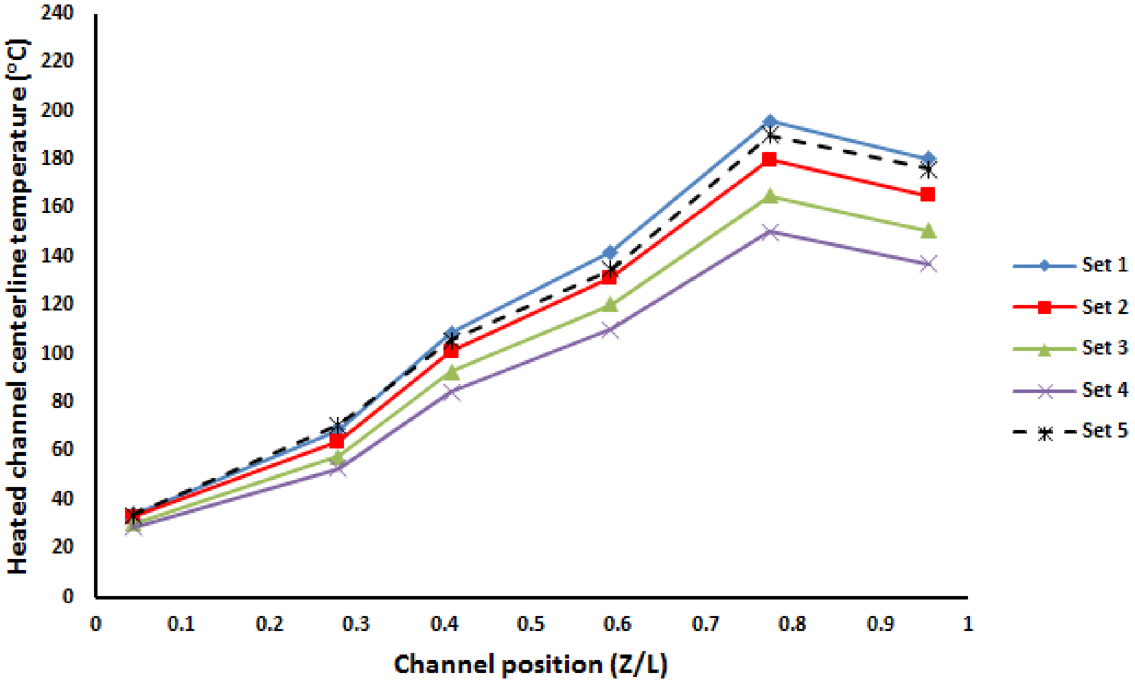

Figure 7. Heated channel centerline temperature.

It is very clear in Figure 8; there is reorder in the distributions of the local heat transfer coefficients in descending order after the inflection point (after Z/L = 0.773). This could be attributed to the end effect

[6,7,8]. The influence of the end effect on values of the local heat transfer coefficients is very clear after Z/L = 0.591 in terms of a decreasing trend.

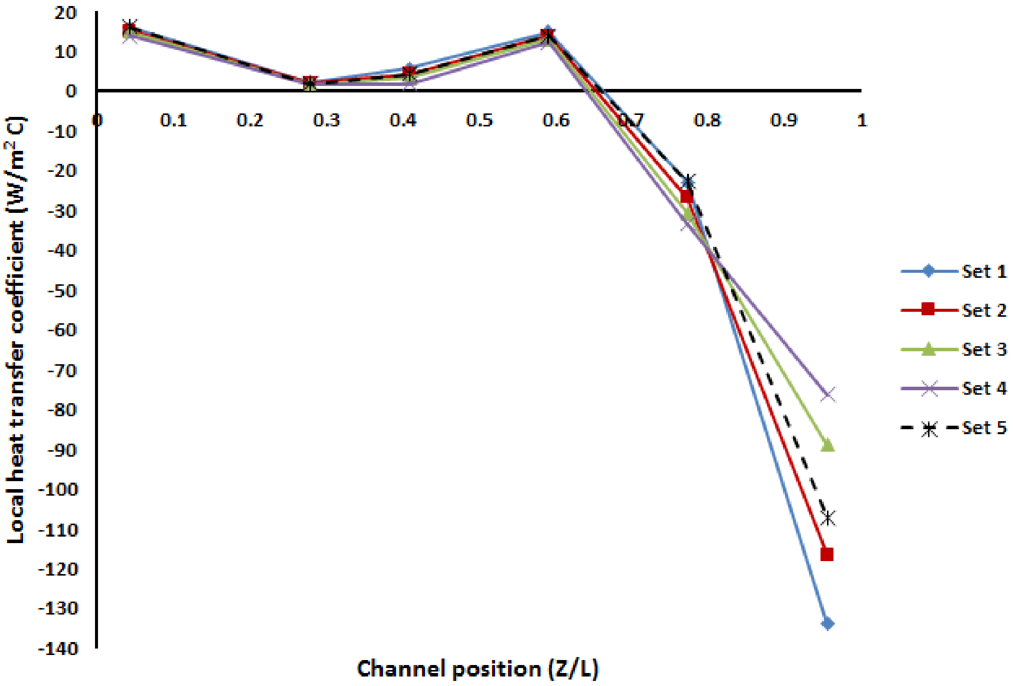

Figure 8. Local heat transfer coefficient along the heated channel.

Figures 9 and 10 show the temperature variations along the inner wall surface and air centerline of the cooled channel. A decreasing trend in the field temperatures from Z/L = 0.956 (inlet) to Z/L = 0.044 (outlet) is observed, which confirms the establishment of natural circulation and downward flow.

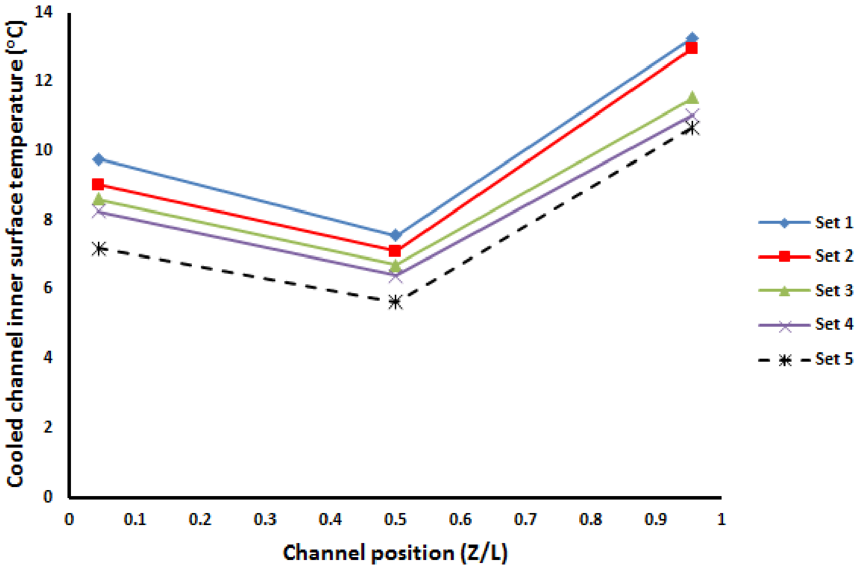

Figure 9. Temperature along the inner wall surface of the cooled channel

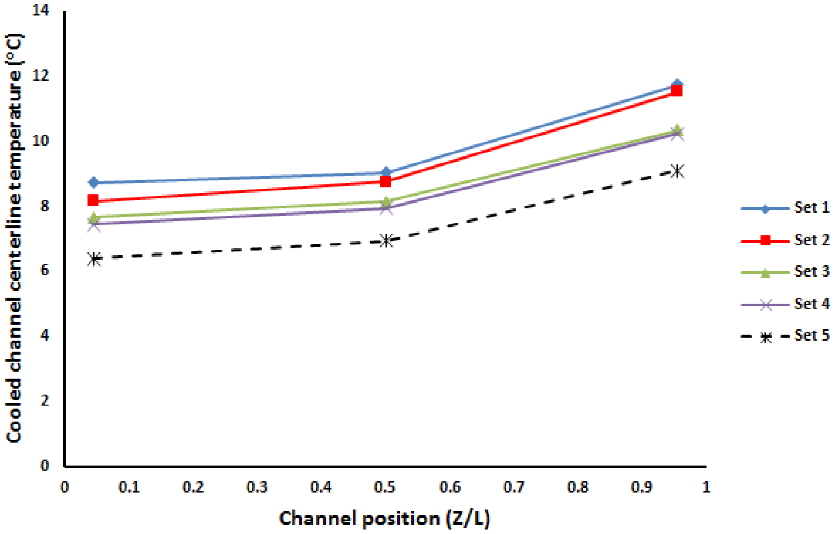

Figure 10. Temperature along air centerline of the cooled channel

4. CONCLUSIONS

Nonuniform heating center peaking step (approximating cosine shape) within a dual-channel circulation loop of upper and lower plena have been designed and developed to investigate the natural circulation heat transfer within the prismatic block nuclear reactor (PMR) under the PCC accident scenario. The most significant study variable is the nonuniform heating distribution along the heated channel that comes in the form of nonuniform heating center peaking step cases along the heated channel in dual-channel circulation by using an advanced fast-response heat transfer technique of flush-mounted heat flux foil sensors in conjunction with a series of T-thermocouples to measure the local heat transfer coefficients, inner wall surface temperature, and air centerline temperature along the flow channels simultaneously. Air is used as a coolant (working fluid) at a higher operating pressure of 413.7 kPa (60 psi). The impact of flux shape was observed. In figure 7, one can notice that case 1 (center peaking case) and case 5 with uniform heat flux with the same total heat input produce different results, The exit temperature of the center peaking case is higher than the uniform heating case. Therefore, the heat flux profile is expected to play a significant role in the overall heating of the coolant. Moreover, a reversal of heat direction and reduction in temperature fields is observed at two different axial positions along the heated channel (Z/L = 0.773 and 0.956). The maximum surface temperature is observed for uniform heat flux (set 5) at Z/L = 0.773 and at Z/L = 0.591 for all nonuniform heating center peaking step sets. Negative heat transfer coefficients were observed for all experimental conditions from Z/L = 0.773 to Z/L = 0.956, and there is reorder in the curves in the descending order after the inflection point (after Z/L = 0.773).

NOMENCLATURE

h_{avg} = Time-averaged local heat-transfer coefficient (W/m^2 K).
h_i = Local instantaneous heat-transfer coefficient (W/m^2 K).
N = Number of data points sampled.
q_i = Local instantaneous heat flux (W/m^2).
$T_{s,i}$ = Instantaneous inner surface temperature (°C).
$T_{b,i}$ = Instantaneous gas centerline temperature (°C).
Z/L = Dimensionless axial position.

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