ROLE OF RADIATION HEAT TRANSFER IN COOLING OF A SCALED MODEL OF A PRISMATIC GRAPHITE CORE IN A VHTR

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ABSTRACT

A thermal hydraulic analysis has been carried out for a scaled model of a Very High Temperature Reactor (VHTR) consisting of a prismatic graphite core. This study presents the role of multidimensional conduction, forced and natural convection, and radiative heat transfer in overall heat dissipation from a VHTR core under various accident scenarios. The geometry considered is a prismatic graphite block surrounded on six sides by other prismatic blocks whose outer boundaries are kept at a constant temperature of 773 K. The situations considered include accident scenarios leading to pressurized conduction cooling, depressurized conduction cooling, and forced convection cooling. A multi-physics code, COMSOL Multiphysics v4.3b, was used to model this heat transfer problem and investigate the fundamental role of radiative heat transfer between the central and adjacent graphite blocks. The predicted temperature gradients in the graphite blocks were compared for stagnant gas, forced convection, or natural circulation flows in the bypass gap. From the simulation results, radiative heat transfer is seen to be essential in dissipating heat from the central graphite block when the graphite's thermal conductivity becomes substantially low; which could occur due to prolonged exposures to neutron radiation and elevated temperatures. Even under normal operating conditions, radiation heat transfer across the bypass flow gaps could account for 20% - 30% of the total heat removal rate from the central block. Under accident situations, the core temperature could rise further to above 1,373K and radiation could become the primary heat transport mode. Thus, the present work suggests that radiative heat transfer needs to be considered in cooling of a VHTR core under accident conditions, especially when the coolant flow rates through the flow channels and bypass flow gaps decrease substantially.

KEYWORDS
VHTR, Radiation Heat Transfer, By-pass flow

1. BACKGROUND

Very High Temperature Reactors (VHTRs) are one of the new generation gas-cooled reactors designs which have been proposed for Gen-IV reactor designs demonstrating various design and performance advantages including higher thermodynamic efficiencies and passive safety features. The VHTRs can passively remove decay heat through intracore natural circulation and natural convection from the reactor vessel surface during accident scenarios. This feature will enable long term cooling of these reactors even in the absence of forced coolant circulation. Such capability is attributed to high thermal conductivity of graphite and natural circulation of the coolant transporting the decay heat from the fuel zone to the surface of the reactor vessel.[1, 2] Effective cooling of the reactor vessel by radiative heat transfer and natural convection to the ambient air in the containment would provide the heat dissipation mechanism.

In prismatic reactor designs, such as VHTR models, the prismatic graphite blocks might not be perfectly aligned during the initial reactor assembly and operation. During the initial assembly, gaps may exist between adjacent graphite blocks due to human error or manufacturing tolerances. In addition, during reactor operation, different materials will experience thermal expansion, which will not be uniform due to temperature gradients existing inside the reactor core. Thermal cycling could also cause material creep. These factors could lead to different gap widths between the adjacent graphite blocks in which the coolant could flow. As a result, the flow through the normal coolant channels could be partially diverted through the new passages which are referred to as by-pass flow gaps. These gaps can be as large as 3-5 mm in width, in which case as much as 25% of the total mass flow could be potentially diverted away from the normal coolant channels. [3, 4] Additionally, externally initiated events such as earthquakes could cause the by-pass flow gaps to widen. Therefore, the VHTR's capability to dissipate decay heat during accident scenarios needs to be investigated in reactor safety analyses.

The fundamental understanding of the influence of by-pass gap widths on core outlet temperatures and temperature gradients in graphite blocks was investigated numerically by Sato et al. (2010) using a commercial CFD code, Fluent.[5, 6] They discussed the apparent relationship between the by-pass flow gaps and the occurrence of hot spots in the core. Kim and Lim[7] discussed the effect of neutron fluence and core temperature profile on bypass flow gap widths. The possibility of cross flow between bypass and core flow channels was indicated as well through numerical studies using a commercial code, STAR-CCM. [8] Laminar flows were predicted for gap widths up to 2 mm based on the Reynolds number and velocity profiles.

As could be observed in any of the above cited references, numerical analyses of VHTRs and other high temperature gas reactors tend to neglect radiative heat transfer within the reactor core including the wall to wall radiation between the prismatic blocks and possibly within cooling channels. Many widely used codes which study accident scenarios in reactor systems, such as RELAP5, disregard surface to surface radiation, or radiation in the participating media.[9] An argument in favor of neglecting radiative heat transfer is that, this would make the calculations conservative from a safety point of view. Actual scenarios, in which radiative heat transfer is significant, would lead to lower temperature gradients across by-pass flow gaps since overall heat dissipation is enhanced as opposed to a conduction only case.

Under Pressurized Conduction Cool-down (PCC), Depressurized Conduction Cool-down (DCC) or natural circulation flow of the coolant between the upper and lower plenums, a large radial temperature gradient could exist between the fuel and outer reflector regions of a VHTR core. The thermal conductivity of the graphite core in an operating VHTR is expected to decrease substantially to 20 - 40 W/mK due to neutron irradiation and elevated temperatures. The contribution of radiative heat transfer to the overall radial heat transport in the VHTR core would increase relative to the conduction heat transfer.

This work quantifies radiative heat transfer rates in by-pass flow gaps between neighboring prismatic blocks. It is not the intention of this paper to accurately predict heat transfer in a proposed VHTR core geometry, but rather to provide a comparative analysis of the fractional role of all heat transport modes in the by-pass flow areas. An investigation of the significance of all heat transport modes would be useful for design and safety analyses of accident scenarios. This work complements a study on the effects of oxidation on nuclear grade graphite and its thermal conductivity being conducted at Kansas State University. [10]

2. DESCRIPTION OF WORK

This work presents a three dimensional thermal study of a simplified prism geometry used in a VHTR core. The individual roles of heat transfer modes, i.e., conduction, convection, radiation, are examined for dissipation of decay heat from the core with or without helium flow at high temperatures under PCC and DCC scenarios. Assessment of radiative heat transfer in core cooling is provided at different coolant gas temperatures and pressures and different thermal conductivities and surface emissivities of the graphite prisms. More specifically, the importance of radiative heat transfer in the by-pass flow gaps between adjacent prismatic blocks is evaluated relative to multi-dimensional conduction as predicted by CFD models. Based on the current numerical results, improved models will be developed for the prismatic core including the by-pass flow gaps.

3. PHYSICAL MODEL

This model simulates the conjugate heat transfer problem involving non-isothermal flow of helium gas through by-pass flow gaps in a simplified prismatic geometry used in a VHTR core. The sample geometry and boundary conditions for the problem investigated are shown in Fig. 1. It consists of seven hexagonal graphite blocks, 1.0-m tall and with 20 cm (8”) length on each side. The neighboring blocks are separated by a 1 mm gap and the center block contains a 1.27 mm (0.5”) diameter cylinder which generates heat. Coolant channels are not included in any of the graphite blocks, as the main aim of this work is to study the heat transport across the by-pass gaps between adjacent graphite blocks by conduction, convection and radiation.

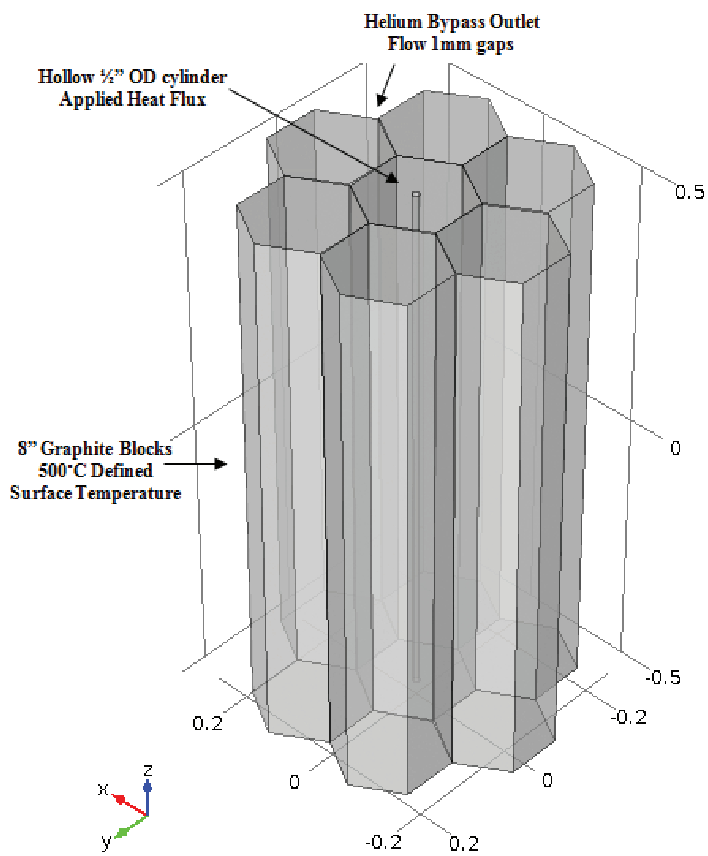

Figure 1 Physical model consisting of 7 hexagonal prisms and a central prism containing a hollow cylinder with a uniform surface heat flux defined on its inner surface.

All three modes of heat transfer are taken into account. First, when the central graphite block is heated by a heater rod placed at the center, heat is conducted to the outer surfaces of the central prismatic block and transferred to adjacent graphite blocks by convection to the coolant flowing through the by-pass gaps. However, convective heat transfer is expected to be less important at low coolant velocities and low pressures. Additionally, there is radiative heat transfer between the graphite block surfaces facing each other, while helium is assumed to be transparent to the radiative heat transfer.

The governing equations are partial differential equations expressing conservation of mass and momentum in the fluid domain at steady state:

$$\nabla \cdot \left(\rho \bar{u}\right) = 0 \tag{1}$$

$$\rho\left(\bar{u} \cdot \nabla\right)\bar{u} = \nabla \cdot \begin{bmatrix} -p\bar{I} + \left(\mu + \mu_T\right)\left(\nabla \bar{u} + \left(\nabla \bar{u}\right)^T\right) \\ -\frac{2}{3}\left(\mu + \mu_T\right)\left(\nabla \cdot \bar{u}\right)\bar{I} \end{bmatrix} + \bar{F} \tag{2}$$

where $\bar{u}$ represents the velocity vector of the fluid, ρ is the fluid density, p is the pressure and $\bar{F}$ refers to the body force due to gravity defined as $\bar{F}_z = -\rho\bar{g}$. This is important for low Reynolds number flows experiencing large temperature and density changes along the flow direction. In the present model, helium is treated as a real gas.

Convection and conduction heat transfer is governed by:

$$\rho c_p \bar{u} \cdot \nabla T = \nabla \cdot \left(k \nabla T\right) \tag{3}$$

where c_p , k , and T are heat capacity, thermal conductivity and temperature of the fluid, respectively.

At the graphite block surfaces, radiative heat transfer is described by surface-to-surface radiation and the mutual irradiation from the surfaces that can be seen from a particular surface is accounted for. Equations (4) through (6) are used to calculate radiative heat transfer in the present model.

$$-\bar{n} \cdot \left(-k\nabla T\right) = \varepsilon(G - \sigma T^4) \tag{4}$$

$$G = G_m(J) + F_{amb}\sigma T_{amb}^4 + G_{ext} \tag{5}$$

$$\left(1-\varepsilon\right)G = J - \varepsilon\sigma T^4 \tag{6}$$

In these equations, ε is the surface emissivity, G is the incoming radiative heat flux, or irradiation heat flux (W/m^2), σ is the Stefan-Boltzmann constant (equal to 5.6704×10^{-8} W/m^2K^4), and J (W/m^2) is radiosity which represents the exiting radiation and is a function of the incident radiation at every other point of view. Equations (4) - (6) describe radiation interaction with convective and conductive heat transfer as a heat flux boundary condition. By definition, this heat flux must be the difference between incident radiation and radiation leaving the surface.

The irradiation, G, at a point can be written as,

$$G = G_m + F_{amb}\sigma T^4 \tag{7}$$

where G_m is the mutual irradiation, coming in from other surfaces, and F_{amb} is an *ambient view factor* whose value is equal to the fraction of the field of view that is not covered by other surfaces.[11]

3.1. Assumptions and Boundary Conditions

A conjugate heat transfer model was constructed based on the following assumptions: (1) the fluid is a Newtonian gas treated as a real gas, (2) graphite material properties are assumed constant except for c_p which is computed as a function of temperature[12,13], (3) the fluid is considered to be transparent to radiation, (4) solid domains are considered opaque; thus graphite is considered to have zero transmissivity, and (5) graphite thermal emissivity, thermal conductivity and density are considered constant.

A high radial heat flux of 1.5 MW/m^2 is uniformly applied along the outer surface of the heated cylinder in the central prism. The top and bottom surfaces of all graphite prisms are thermally insulated while the temperature of the outer surfaces of the outer graphite prisms is set at 773 K (500 ºC). The temperatures on the surfaces facing the by-pass gaps are calculated as part of the solution. Helium is the working fluid and fills the by-pass flow gaps.

Fluid velocity, temperature and pressure are specified at the inlet, thus allowing for the calculations of density and the inlet Reynolds number. At the outlet the temperature gradient in the normal direction is zero and radiative heat transport is neglected. This is usually a good approximation of the conditions at an outlet boundary in a heat transfer model with fluid flow. [11] Working pressure is established by defining the pressure at the outlet. No-slip boundary condition is applied at the walls of the by-pass flow gaps.

The inlet velocity for simulations intended to study the natural circulation effect was assumed to be 0.2 m/s. The inlet gas velocity could have been determined based on the gas temperature at this location if upper and lower plena had been added to the geometry. However, the chosen value is characteristic of natural circulation flows of helium at these temperatures. [14]

4. NUMERICAL PROCEDURE

A 3D model was constructed and analyzed using a COMSOL Multiphysics code. Benchmark solutions demonstrating COMSOL's capability to solve natural circulation problems, as well as forced convection problems have been published by the present authors elsewhere.[14, 15] COMSOL Multiphysics code has been widely used at Oak Ridge National Laboratory to model their High Flux Isotope Reactor (HFIR). Numerical predictions of their models, as well as benchmark validation have been produced.[16, 17] A non-isothermal fluid flow module was used to provide coupling between momentum and energy equations. The heat transfer module coupled to the fluid flow module, contains the radiation equations described in Eqs. (4) - (6); there is a continuity of temperature boundary condition and continuous heat flux at the solid-fluid interface. The fluid was modeled to be in laminar flow which is valid considering the low velocities used and small by-pass gap width. The laminar nature of the flow is presented in Table 1. Wang et al.[8] also detected laminar flows in their numerical studies for by-pass flow gap widths of ≤ 2 mm. In the present model, the fluid velocity components and temperature, surface radiosity, and pressure are the dependent variables. In the steady transport model, direct solvers are used with a convergence criterion of 1×10^{-3}. The numerical solution involves the calculation of six dependent variables with higher computational intensities than standard fluid flow models.

4.1. Mesh Selection

The computational mesh used in this work is shown in Fig. 2. A structured mesh was created in the upper plane and this meshed face was repeated every 20 cm over the total 1 m length. The fluid domain contained six rectangular elements across the 1mm gap. Attained solutions in this problem appear to be mesh independent, corroborating the efficiency of the extruded mesh. In order to solve the governing equations, direct solvers were used which were found to be more efficient than iterative solvers, although computationally more expensive for this type of problems. As the number of mesh elements was increased from 300,000 to 600,000, the average graphite temperatures across the gap and gas bulk temperatures varied by less than 0.5%. Similar percentage differences were obtained for the average Reynolds numbers in the by-pass channels. Triangular extruded meshes were also used in this study. The top faces of the graphite blocks were meshed with triangular elements and extruded through the rest of the geometry, while maintaining a similar number of elements as the ones used for the final results (513,850). In this case, differences in the graphite wall temperatures and average fluid Reynolds numbers were less than 0.005%.

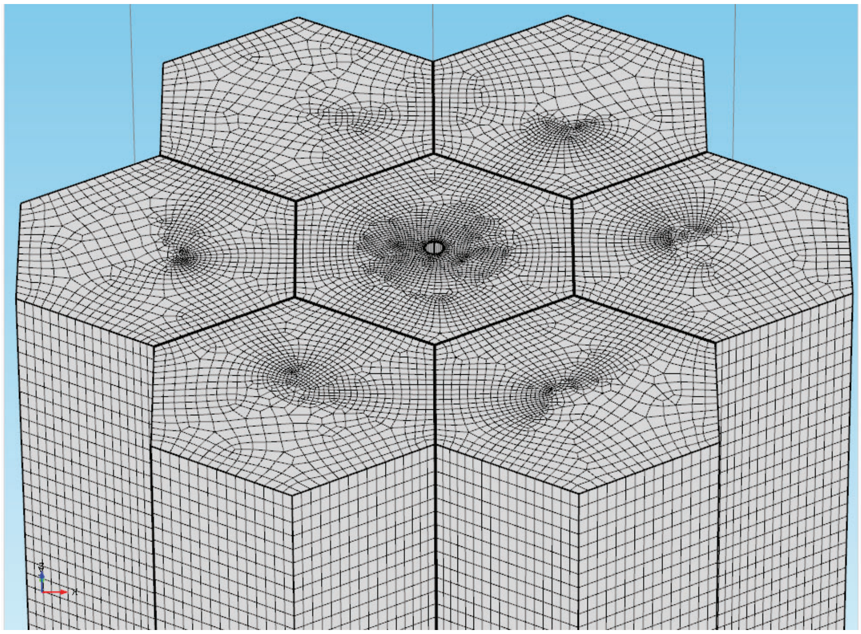

Figure 2 Mesh consisting of 513,850 mostly hexahedral elements

5. DISCUSSION & RESULTS

Table 1 presents a list of 30 studied cases, including a study of independent heat transfer modes as well as coupled heat transfer modes. The last four cases were parametric studies in which the graphite thermal conductivity, emissivity, outer wall temperature and total input power were varied one at a time.

Table 1 Summary of cases studied

Case #	Heat transfer mode	Q_{in} [kW]	$T_{outer\ wall}$ [K]	P_{out} [bar]	Re_{in} [-]	$k_{graphite}$ [W/mK]	$\varepsilon_{graphite}$ [-]
1	Conduction	26.5	500	5	N/A	62.8	0.675
2	Conduction	26.6	500	70	N/A	62.8	0.675
3	Radiation	16	500	10	N/A	62.8	0.675
4	Radiation	28	500	10	N/A	62.8	0.80
5	Cond. + Conv.	27	500	10	3, 15, 76	62.8	0.675
7	All	30	500	5	1.53	62.8	0.675
8	All	30	500	70	21.38	62.8	0.675
9	All	30	500	30	45.82	62.8	0.675
10	All	30	500	70	534.64	62.8	0.675
11	All	10	200-1600	5	1.52	62.8	0.675
12	All	10	500	5	1.52	10-150	0.675
13	All	10	500	5	1.52	62.8	0.2-1
14	All	10-40	500	5	1.52	62.8	0.675

5.1 Single Heat Transport Mode Results

Simulations were carried out to first evaluate the individual contributions of each heat transport mode in the prescribed geometry. The amount of power dissipated while maintaining a maximum graphite temperature of 1,176 K was compared for each heat transport mode.

Simulations involving conduction heat transfer were carried out with a stagnant gas in the by-pass gaps (PCC and DCC conditions involving no natural circulation). The simulations were then repeated with only radiation as the heat transport mode. In this case, there was vacuum in the by-pass gaps and heat transport across the by-pass gaps was only by radiation. Additional combinations were also carried out, by removing radiation heat transport (RHT) and having only conduction and convection. The last of these simulations paired conduction, convection and radiation heat transport.

Predicted temperature profiles from two of these simulations are displayed in Figs. 3 and 4. They show the temperature profiles in the graphite blocks, where the vertical axis is scaled according to the temperature. The arrows indicate the heat flow direction. Figure 3 shows the temperature profiles obtained for the radiation only case. The simulation results display a temperature jump across the bypass gap between the central and surrounding graphite block surfaces, confirming the effectiveness of radiative heat transport even in the absence of a gas in the by-pass gaps. Figure 4 displays the results for the case of a stagnant gas present in the by-pass gaps where heat is transported across the gas by conduction.

A summary of these results is presented in Fig. 5, which displays the heat dissipation rates for different heat transport modes and their combinations. These are, however, general results under the conditions studied and there are certain variables which affect each heat transport mode. For instance, conduction dominates the slow flow case as opposed to convection. Convection will dominate at higher gas flow rates and with a large heat transfer area. Radiative heat transfer is more important when the wall temperatures and wall-to-wall temperature differences are high. Radiation also becomes more significant for high emissivity and low thermal conductivity of graphite.

Figure 5 shows the heat dissipating capabilities of each transport mode. For the conditions studied, in which input power was varied and a maximum graphite temperature was kept the same, conduction heat transport would dissipate 44% more heat than radiation heat transport alone. Convection and conduction combined would dissipate 50% more than radiation alone. As discussed before, and will later be demonstrated in the results, the fractional role of each transport mode will vary depending on the simulation conditions. At higher temperatures and surface emissivities, or lower thermal conductivities, radiative heat transfer will become dominant.

The individual contribution of each heat transport mode will be further discussed in a later section. Simulations involving the coupling of all three heat transport methods were carried out and variables affecting them were studied.

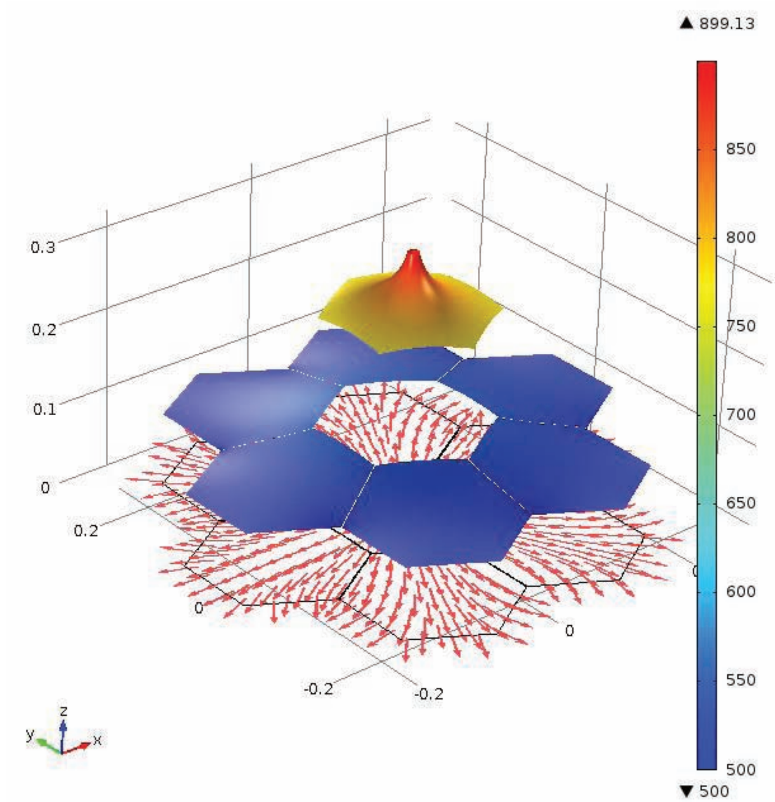

Figure 3 Temperature profile (°C) at middle of graphite section (*z* = 0.5m): Radiation only case, Pressure = 10 bar, Input Power = 16,000 W.

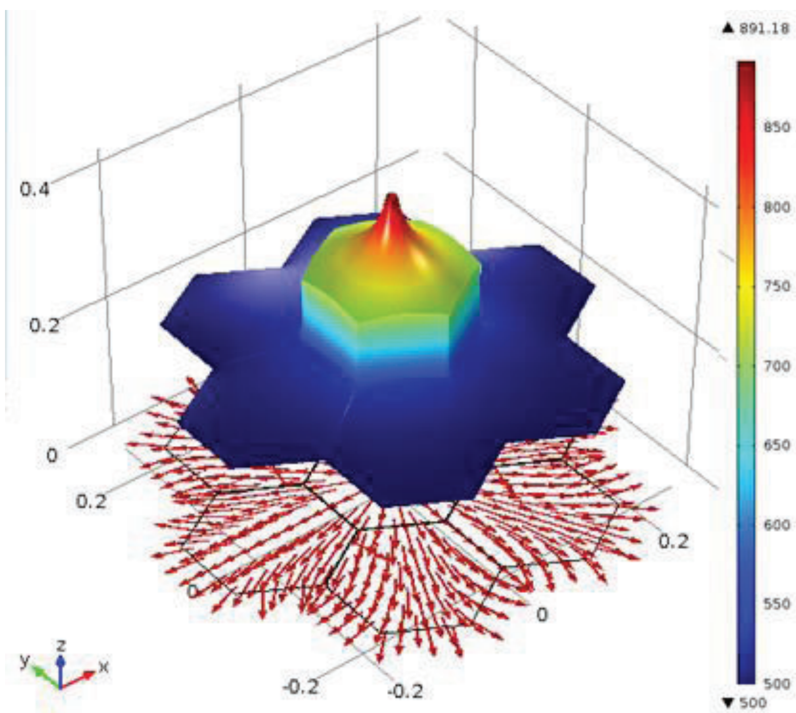

Figure 4 Temperature Profile (°C) at middle of graphite section (*z* = 0.5m): Stagnant gas case, Pressure = 10 bar, Input Power = 26,000W.

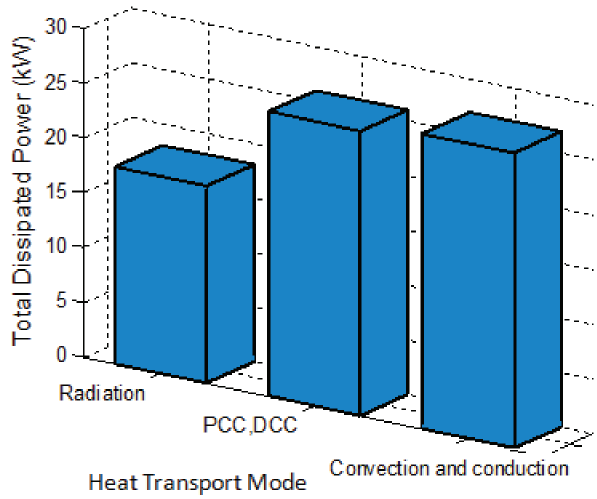

Figure 5 Heat dissipation rates for different heat transport modes when the maximum graphite temperature is kept at 1,176 K and outer wall temperature at 773 K.

5.2 Convection Dominated Heat Transport

A study was carried out to assess the importance of each heat transfer mode in overall heat dissipation. Simulations were carried out at low, average and high inlet gas velocities (0.2, 1.0 and 5 m/s) and different pressures for DCC (5 bar) and PCC (70 bar). All flows are laminar due to the small gap width. Under the conditions studied, the inlet Reynolds number based on the gap width varied from 10 to 100. The contribution of convection heat transfer was determined by calculating the rate of energy carried off by the gas flowing through and out of the by-pass gaps as given by Eq. (8).

$$Q_{convection} = \dot{m}c_p\left(T_{b,in} - T_{b,out}\right) \tag{8}$$

On the other hand, the heat transferred across the by-pass gap by the flowing gas was considered to be part of the radial conduction heat transport. This is a reasonable assumption, since under the boundary layer approximation for laminar flow in wide rectangular channels, stream-wise conduction can be neglected so radial heat conduction is possible across the gap with small heating of the gas involved. The conduction heat transfer rate was obtained using Fourier's Law evaluated with the average wall and bulk temperature differences and thermal conductivity of the gas at the average temperature. Radiative heat transfer involved the Stefan-Boltzmann law, evaluated using the temperatures of the opposing graphite surfaces.

As shown in Figure 6, the essential role of heat conduction in heat transport across solid (graphite) and gas phases can be observed, accounting for an average of 70% of the total heat input (30 kW). Nevertheless, the essential contribution of radiative heat transfer can also be observed accounting for an average of 26% of the total energy dissipated.

DCC and PCC conditions are characterized by the dominance of conduction. Though the thermal conductivity of gas is generally much lower than that of graphite, helium's thermal conductivity is approximately 5 times larger than that of air. So, the steep temperature gradients that exist in the small by-pass gaps give rise to large conduction heat fluxes. Observe an example of the wall-to-wall temperature difference existing across a 1 mm gap for two of the flow conditions studied (Fig. 7). Convection heat transfer is almost non-existent, or relatively low compared to other heat transfer modes, due to the laminar nature of the flow thus leading to low heat transfer coefficients.

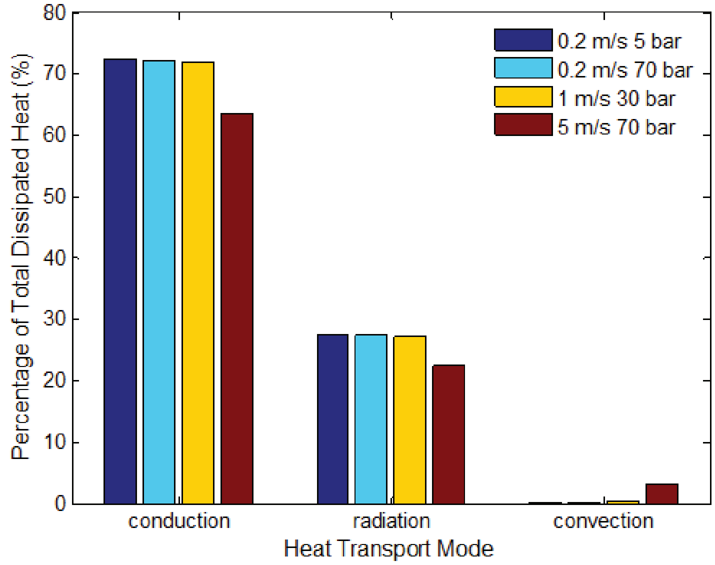

Figure 6 Fractional contributions of individual heat transport modes for various helium flow conditions.

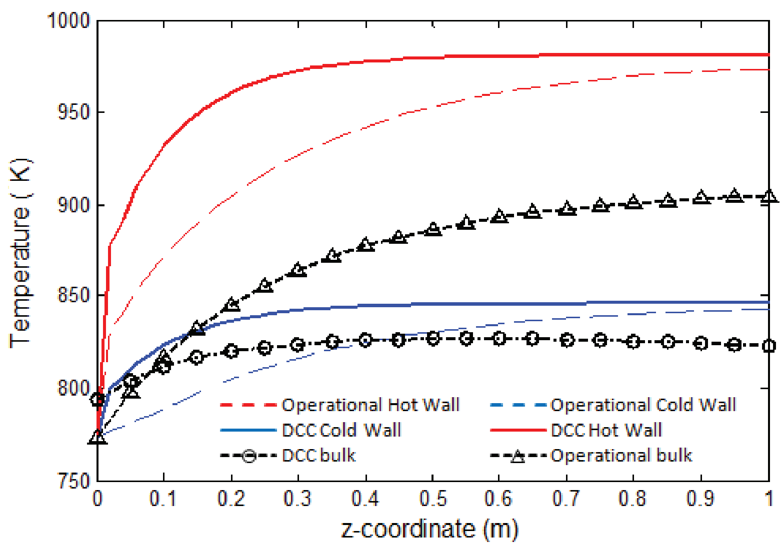

Figure 7 Centerline graphite temperature for DCC conditions (5 bar, 0.2 m/s (solid line)) and operational conditions (70 bar, 5 m/s (dashed line)) for parallel graphite walls; also gas bulk temperatures shown with symbols for both conditions.

5.3 Material properties affecting conduction and radiation heat transfer behavior

Having observed the significant contributions of conduction and radiative heat transfer for the cases studied, the impact of material properties on the role of each heat transport mode on overall heat dissipation is next evaluated. A parametric study was carried out by varying the graphite thermal conductivity and surface emissivity. The effects of temperature and other variables such as neutron fluence on these graphite properties over time have been studied in the past, however, to our knowledge little data at operational conditions is yet available. In addition to the uncertain effects of neutron fluence, knowledge gaps still exist concerning the effects of air and steam ingress and subsequent graphite oxidation, and material properties including graphite thermal conductivity and surface emissivity. These are still the subject of current research. [5, 10]

For all the simulation results shown so far, the thermal conductivity of graphite was assumed to be constant at $k = 62.8$ (W/mK). Then, a parametric study was carried out by varying k from 150 (W/mK) for a fresh graphite to 10 (W/mK) for a neutron-irradiated graphite. The surface emissivity was varied from 1 to 0.2, where an average value of 0.675 had been used for previously discussed results. Figure 8 displays the percentage contribution of each heat transport mode to the overall heat dissipation. As expected, heat conduction continues to be the dominant heat transport mode. As a result, the average graphite temperature is more sensitive to changes in thermal conductivity than the surface emissivity. Reducing the thermal conductivity to 30 (W/mK) increased the maximum graphite temperature by almost 573 K.

It can be seen, however, that in all cases radiative heat transfer accounts for at least 20% of the overall heat dissipation. For even lower thermal conductivities of aged graphite, radiative heat transfer could account for more than 35% of the total heat dissipation.

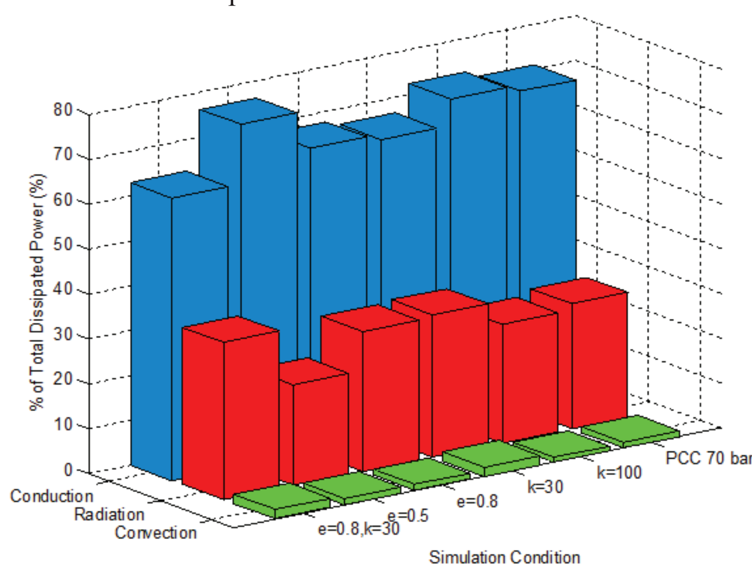

Figure 8 Fractional contributions of different heat transport modes for various coolant flow conditions.

5.4 Assessment of radiation heat transfer in by-pass cooling at different gas temperatures

Numerical simulations were carried out to assess the increasing importance of radiative heat transfer in reducing the graphite temperatures as the average graphite temperature increases. Figure 9 displays surface radiation heat fluxes of the hot graphite block at the center and the irradiation of the colder surfaces of the surrounding blocks. As can be clearly observed in Fig. 9, radiosity and irradiation profiles exist. These heat flux distributions are influenced mainly by geometry and surface cooling. Although a detailed analysis of these quantities and their profiles is beyond the scope of this study, it is believed that these quantities play crucial roles in the creation of localized hot spots in a full reactor core due to degraded heat transfer. [1, 2] The role played by radiative heat transfer in abnormal heat transfer phenomena, such as localized hot spots, becomes more important as average wall temperatures increase. Increments in wall temperatures are expected to occur in some accident scenarios such as Loss of Coolant Accidents (LOCA) and Loss of Flow Accidents (LOFA). Understanding and obtaining data for this type of phenomena is essential in the construction of Phenomena Identification and Ranking Tables (PIRT).

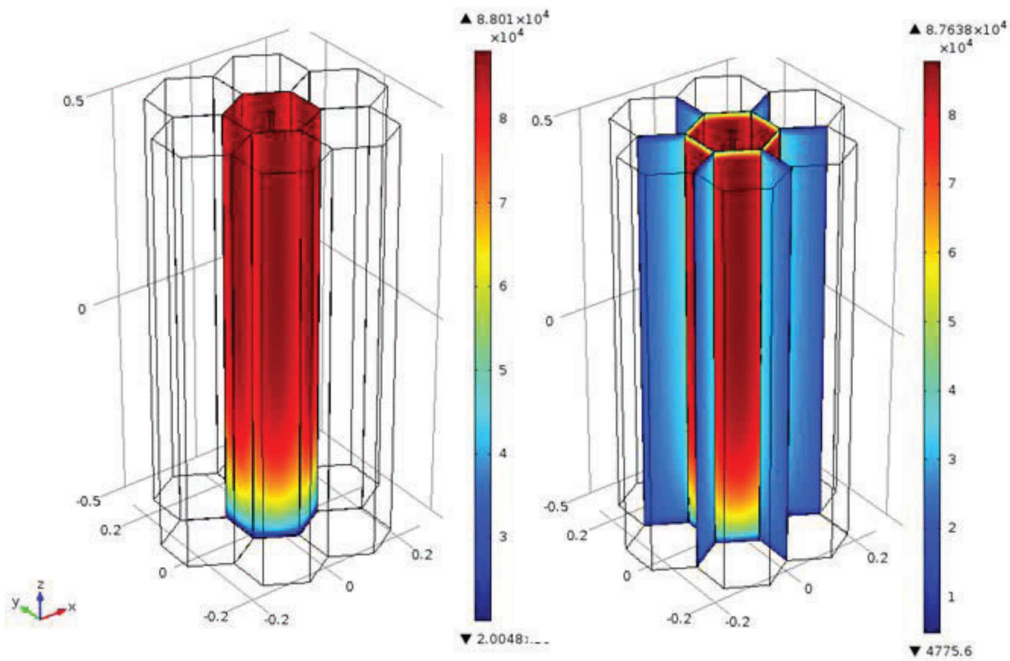

Figure 9 Surface radiosity (W/m^2) (left) and surface irradiation (W/m^2) (right).

Numerical simulation results highlight the essential role played by radiative heat transport in heat dissipation from the core in possible accident scenarios where convection heat transport through the main cooling channels is brought to a halt or partially obstructed. Figure 10 displays the percentages of the total heat dissipated by conduction and radiation as a function of the maximum graphite wall temperature under PCC conditions. As expected we can observe increasing contributions of radiative heat transport for higher graphite temperatures. At the graphite temperature of 1,223 K, which is a realistic temperature expected in actual designs of VHTR reactors, radiative heat transport could account for 42% of the total heat dissipation. The results presented in Fig. 10 took into account a possible decrease in graphite's thermal conductivity to 62.8 W/mK and an average graphite surface emissivity of 0.675. These percentage contributions would increase for fresh graphite which has a surface emissivity of at least 0.8.

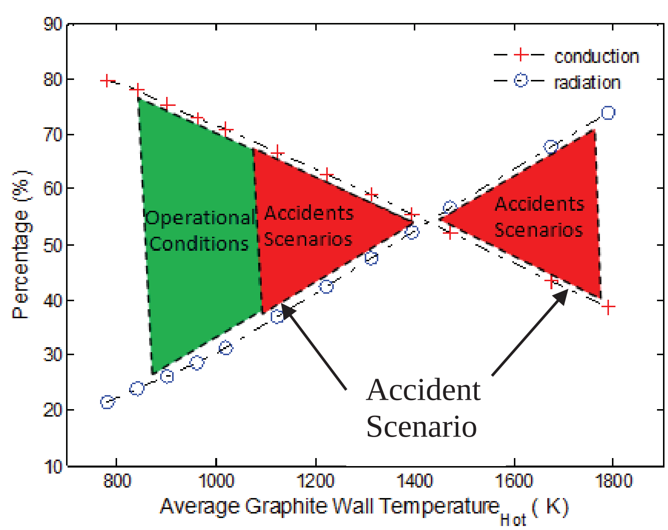

Figure 10 Conduction and radiative heat transfer contributions in total heat dissipation under PCC conditions as a function of average graphite wall temperature.

5.2 Radiation Dominated Heat Transport

Throughout this study, both the outer surface temperature and ambient temperature were set at 773 K. This value is well within the parameters of VHTR operational temperatures, which are proposed to be about 1,773 K. A sensitivity study was carried out by varying the outer wall temperature and ambient temperature. Both were increased systematically from 473 K to 1,873 K. Once again the results displayed in Fig. 11 highlight the growing importance of radiative heat transfer at higher temperatures. Graphite temperatures of ~1,873 K are expected in accident scenarios such as Loss of Flow Accidents (LOFA). At these temperatures, due to the existence of bypass flow gaps, radiative heat transfer will be the predominant heat transport mode. Thus, it is essential to further understand the impact of material properties affecting radiative heat transfer under accident scenarios.

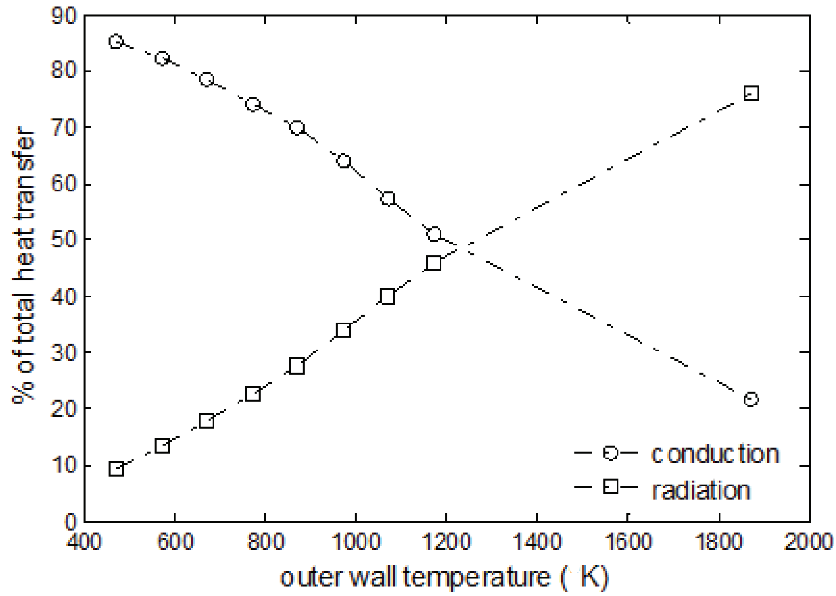

Figure 11 Sensitivity study on outer wall temperature: input power 10kW

6. CONCLUSIONS

Three-dimensional conjugate heat transfer and fluid flow calculations were performed on a simplified geometry of a VHTR prismatic core design with one heated graphite block using a multiphysics code, COMSOL, in order to investigate the importance of radiative heat transfer in overall heat dissipation for various coolant flow rates including DCC and PCC conditions. Parametric studies for various inlet Reynolds numbers, graphite temperatures and thermal properties of graphite were carried out. The results of the CFD calculations show significant contributions of radiative heat transport amounting to as much as 42% of the total heat dissipated in the modeled geometry. Radiative heat transport has been shown to increase in importance with decreasing graphite thermal conductivity (increasing thermal resistance), which occurs as a result of neutron irradiation among others, and higher surface emissivities typical for fresh graphite.[17]

The present numerical simulation work points to the importance of including radiative heat transfer in by-pass gap areas. Most models which evaluate accident scenarios such as PCC and DCC, focus on conduction and convective heat transport, however, realistic analyses should take into account radiative heat transfer as well. The accident analyses which ignore radiative heat transfer can be considered to be more conservative since better heat dissipation could be achieved with radiative heat transfer included.

Further assessments of radiative heat transfer will be carried out considering the coolant gas as a gray medium capable of absorbing radiation and re-irradiating it.

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