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Analysis of Fluid Flow and Heat Transfer Model for the Pebble Bed High Temperature Gas Cooled Reactor

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Abstract: The pebble bed type high temperature gas cooled nuclear reactor is a promising option for next generation reactor technology and has the potential to provide high efficiency and cost effective electricity generation. The reactor unit heat transfer poses a challenge due to the complexity associated with the thermal-flow design. Therefore to reliably simulate the flow and heat transport of the pebble bed modular reactor necessitates a heat transfer model that deals with radiation as well as thermal convection and conduction. In this study, a model with the capability to simulate fluid flow and heat transfer in the pebble bed modular reactor core has been developed. The developed model was implemented on a personal computer using FORTRAN 95 programming language. Several important fluid flow and heat transfer parameters have been examined: including the pressure drop over the reactor core, the heat transfer coefficient, the Nusselt number and the effective thermal conductivity of the fuel pebbles. Results obtained from the simulation experiments show a uniform pressure in the radial direction for a core to fuel element diameter (D/d) ratio>20 and the heat transfer coefficient increases with increasing temperature and coolant mass flow rate. The model can adequately account for the flow and heat transfer phenomenon and the loss of pressure through friction in the pebble bed type high temperature nuclear reactor.

Key words: Fluid flow, heat transfer, HTGR, packed bed, PBMR, pressure drop

INTRODUCTION

The reliable simulation of flow and heat transport is fundamental for the analysis of Nuclear Power Plants (NPPs) as nuclear reactor is (virtually) capable of producing all the wanted power provided it can be removed from the core. Therefore a complete analysis of the reactor energy balance is always mandatory (Lomonaco *et al*., 2009). The pebble bed modular reactor (PBMR) is among the Gen IV reactor projects which must meet Gen IV criteria (Lomonaco *et al*., 2009; htpp//www.gen-4.org/Index.html), namely:

- Sustainability
- Economics
- Proliferation-resistance
- Safety and Reliability

The capability of removing the heat produced in the core (both in normal operation and under accident conditions) is a key point of criterion four. Some studies have been conducted on the thermal analysis of the pebble bed modular reactor (Becker and Laurien, 2003).

The pebble bed reactor can be considered as a fixed or packed bed reactor (Du Toit, 2002). Packed bed reactor design is based upon the mechanisms of heat and mass transfer and the flow and pressure drop of the fluid through the bed of solids.

The pebble bed reactor unit heat transfer poses a challenge in that it includes a complex three dimensional geometry and various materials. This necessitates a heat transfer model that deals with radiation as well as thermal convection and conduction using a variety of analysis techniques and simulation tools.

E. Achenbach (Achenbach, 1995) investigated heat and flow characteristics of packed beds and recommends equations for the prediction of convective heat transfer, pressure drop, effective thermal conductivity and wall heat transfer.

The purpose of this study is to develop a model with the capability to simulate flow and heat transfer in the PBMR. The model examines laminar and turbulent flow in the vicinity of a single spherical fuel pebble near the centre of the core. Several important fluid flow and heat transfer parameters are examined, including the pressure drop over the reactor core, the heat transfer coefficient,

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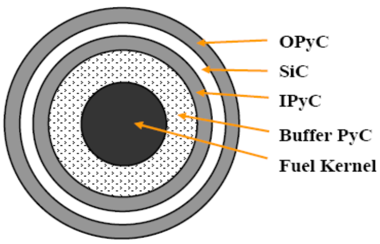

Fig. 1: Layers of the pebble bed reactor fuel

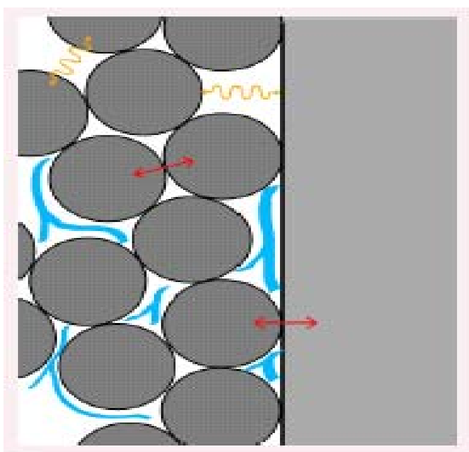

Fig. 2: Heat transfer details

the Nusselt number and the effective thermal conductivity of the fuel pebbles.

The pebble bed modular reactor: The design of the Pebble Bed Modular Reactor (PBMR) is based on the High Temperature Gas Cooled Nuclear Reactor (HTGR) technology which was originally developed in Germany (Pieter and Mark, 2007). The HTGR is a graphite-moderated, helium cooled reactor using a direct or indirect gas cycle to convert the heat generated by nuclear fission into electrical energy by means of a helium Brayton cycle.

The PBMR is considered as inherently safe because of the choices of materials used, the confinement of fuel in multiple layers, the thermal inertia of the graphite moderator, the high thermal efficiency features as well as a flexible fuel cycle with the capability to achieve high burnup levels. The fuel design together with the use of gas coolant and non-metallic core structures allows high operating temperatures.

The PBMR fuel is based on a proven, high quality German fuel design consisting of Low Enriched Uranium Triple-Coated Isotropic (LEU-TRISO) particles contained in a molded graphite sphere. The coated particles comprise a kernel of uranium dioxide surrounded by four coating layers (Fig. 1) to form the fuel sphere or pebbles with a diameter of 6 cm.

The core flow and heat transfer details in the PBMR is shown in Fig. 2. To transfer the heat generated by nuclear fission reaction, the helium coolant enters the reactor core at the top and flows down through the voids between the hot fuel spheres, after which it leave the core at the bottom having been heated to a higher temperature. In the PBMR the overall heat transfer (Fig. 2) consists of:

- Conduction heat transfer in both the radial and axial directions (pebble-pebble, pebble-reflector, all solids)
- Convection heat transfer between the bed particles and the flowing gas (helium-coolant)
- Radiation heat transfer (pebble-pebble, pebble-reflector walls, core barrel-RPV walls)

Simulation of flow and heat transport of the pebble bed modular reactor: For the PBMR, the coolant flows downwards through the voids between the hot fuel spheres. Therefore suitable physical models designed for such a system were used through research of available scientific literature. In particular, models suitable to evaluate helium pressure drop over the core and the heat transfer between the fuel pebbles and the helium coolant as well as the effective thermal conductivity of the fuel pebbles were researched.

Pressure drop over the pebble bed: The pressure drop over the pebble bed due to friction is an important phenomenon that ultimately affects the heat transfer effectiveness. The importance of the pressure drop is such that it enables proper sizing of the turbo-machines and also determine the flow distribution through the core structures consisting mainly of graphite blocks (Achenbach, 1981). Although the leakage or bypass flow through the core structures is minimised by design, large pressure drop over the pebble bed will cause leakage or bypass flow to occur.

In order to model and evaluate the pressure drop over the pebble bed due to friction, the following relation was used (KTA, 1978, 1981, 1983):

$$\Delta P = \psi \frac{H}{d} \frac{1-\varepsilon}{\varepsilon^3} \frac{1}{2\rho} \left(\frac{\dot{m}}{A} \right)^2 \quad (1)$$

where ψ is the pressure drop coefficient, ρ is the density of fluid, ε is the porosity of the bed, *d* is the fuel pebble diameter, *A* is the cross sectional area of the core, *H* is the height of the core and *m* is the fluid mass flow rate. For application to pebble bed reactor, the following empirical formula was used to derive the pressure drop coefficient (KTA, 1978, 1981, 1983);

$$\psi = \frac{320}{\frac{\mathrm{Re}}{1-\varepsilon}} + \frac{6}{\left(\frac{\mathrm{Re}}{1-\varepsilon}\right)^{0.1}} \tag{2}$$

The Reynolds number Re, is derived from the following equation in terms of the dynamic viscosity η of the gas:

$$\mathrm{Re} = \frac{\dot{m}d}{\eta A} = \frac{\rho v A d}{\eta A} = \frac{\rho v d}{\eta} \tag{3}$$

where v is the velocity of flow, with $10^{o} < \mathrm{Re}/(1-\varepsilon) < 10^{5}$ and $0.36 < \varepsilon < 0.42$.

The severe departures of experimental pressure drop results can be due to the effect of bypass flow (Achenbach, 1995). For the pebble bed type high temperature nuclear reactor, the core diameter to fuel element diameter ratio (D/d) is very large (Achenbach, 1981). The higher the ratio of core to fuel element diameter, the stronger is the influence on the pressure drop (Achenbach, 1981). Thus, to investigate the effect of the D/d ratio on pressure drop, it was assumed for rough estimation, that the bed is subdivided into a near-wall region (index w), a central region (index c) and an average region (index t).

From the experimental results of Carman and Barthels as quoted by (Achenbach, 1981, 1995), the corresponding porosities required for the calculation of the pressure drop was estimated to be:

$$\varepsilon_t = 0.78\left(\frac{d}{D}\right)^2 + 0.375 \tag{4}$$

$$\varepsilon_w = 63.6\left(\frac{D}{d} + 15\right)^{-2} + 0.43 \tag{5}$$

$$\varepsilon_c = \varepsilon_w - \frac{\varepsilon_w - \varepsilon_t}{\left(1 - \frac{d}{D}\right)^2} \tag{6}$$

Substitution of Eq. (4), (5) and (6) into (2) enables us to compare the pressure drop at the various regions of the bed for different D/d ratio.

Heat transfer relations: To correctly describe the heat transfer in the pebble bed, relations must be defined for the heat transfer by forced convection and for the transport by conductance and radiation. For the heat transfer by forced convection, a relationship between Nusselt number, Reynolds number, Prandtl number and porosity of the pebble bed must be defined.

The heat transfer Q from a fuel pebble to the working fluid is a function of the mass flow rate of coolant and the temperature difference and is calculated by means of the following equation:

$$Q = \alpha A_p (T_p - T_g) \tag{7}$$

where α is the convective heat transfer coefficient, A_p is the surface area of a fuel pebble in the bed, T_p and T_g are the fuel pebble surface and gas temperatures respectively. The convective heat transfer coefficient is given by Eq (8):

$$\alpha = \frac{Nu \lambda_g}{d} \tag{8}$$

where Nu is the Nusselt number, λ_g is the thermal conductivity of the gas and d is the fuel pebble diameter.

To establish the relationship between Nusselt number, Reynolds number, Prandtl number and porosity of the pebble bed, Gnielinski evaluated experimental results of about 20 authors (Achenbach, 1981, 1995). The theory is based on the assumption that the heat transfer of spheres in a pebble bed can be related to the heat transfer from a single sphere by introducing an arrangement factor is f_ε, which depends on the porosity of the pebble bed. From the evaluation study and assumption, the following relations were established (Achenbach, 1981):

$$Nu = f_\varepsilon \times Nus \tag{9}$$

where

$$f_\varepsilon = 1 + 1.5(1 - \varepsilon) \tag{10}$$

and Nus the Nusselt number of a single sphere expressed as:

$$Nus = 2 + \sqrt{nu_l^2 + Nu_t^2} \tag{11}$$

with the Nusselt number for laminar flow given by:

$$Nu_l = 0.664\left(\frac{\mathrm{Re}}{\varepsilon}\right)^{1/2} \mathrm{Pr}^{1/3} \tag{12}$$

and the Nusselt number for turbulent flow given by:

$$Nu_t = \frac{0.037\left(\frac{\mathrm{Re}}{\varepsilon}\right)^{0.8} \mathrm{Pr}}{1 + 2.443\left(\frac{\mathrm{Re}}{\varepsilon}\right)^{-0.1}\left(\mathrm{Pr}^{2/3} - 1\right)} \tag{13}$$

where Pr is the Prandtl number.

The set of Eq. (9) to (13) is valid for the ranges $100 < \mathrm{Re} < 10^5$, $\mathrm{Pr} > 0.6$ and $0.36 < \varepsilon < 0.42$.

The Nusselt number as quoted by (KTA, 1978, 1981, 1983) can also be determined on the basis of the following relationship:

$$Nu = 1.27\frac{\Pr^{1/3}}{\varepsilon^{1.18}}\mathrm{Re}^{0.36} + 0.033\frac{\Pr^{1/2}}{\varepsilon^{1.07}}\mathrm{Re}^{0.86} \tag{14}$$

Effective thermal conductivity: To account for all non-convective modes of heat transfer within the solid-phase structure, the effective thermal conductivity was evaluated. The specific form of the effective thermal conductivity applied to the homogeneous (i.e., portion outside the near-wall region) section of the pebble bed as detailed by IAEA (IAEA TECDOD-1163, 2000) is based on the Zehner-Bauer-Schlunder (ZBS) correlation. The effective thermal conductivity of a pebble bed does not only depend on the material property of the particles, but also depends on the flow and heat transfer conditions and on the size and shape of the particles (Achenbach, 1995). The effective thermal conductivity is considered to consist of three parts, namely:

- Conduction through the solid phase and radiation between pebbles (λ^r_e)
- Conduction through the solid phase and across the stationary fluid phase filling the interstitial voids between the pebbles (λ^g_e)
- Conduction through the solid phase and across the contact interface between pebbles (λ^c_e)

Conduction through the solid phase and radiation between pebbles: The Zehner and Schluender model with modification by Breitbach and Barthels (1980) was used to evaluate the component of the effective thermal conductivity accounting for interstitial void radiation and solid conduction. The model is expressed as:

$$\lambda_e^r = \left\{\left[1-(1-\varepsilon)^{1/2}\right]\varepsilon + \frac{(1-\varepsilon)^{1/2}}{\frac{2}{\xi_r}-1} \times \frac{B+1}{B} \times \frac{1}{1+\frac{1}{\left(\frac{2}{\xi_r}-1\right)\Lambda}}\right\} 4\sigma T^3 d \tag{15}$$

where λ^r_e is the void radiation plus solid conduction effective thermal conductivity, ξ_r is the pebble emissivity, σ is the Stefan-Boltzmann constant, T is temperature, B is the deformation factor as expressed in Eq. (16) and Λ forms part of Damkohler equivalent thermal conductivity (Bauer and Schluender, 1978) which describes the radiative heat transfer and its expressed as in Eq. (17):

$$B = 1.25\left(\frac{1-\varepsilon}{\varepsilon}\right)^{10/9} \tag{16}$$

$$\Lambda = \frac{\lambda_f}{4\sigma T^3 d} \tag{17}$$

Where λ_f is the thermal conductivity of the fuel particle.

Conduction through the solid phase and across the stationary fluid phase filling the interstitial voids between the pebbles: The component of effective thermal conductivity accounting for thermal conduction through the solid phase and across the stationary fluid phase filling the interstitial voids between the pebbles is given by:

$$\frac{\lambda_e^g}{\lambda_g} = 1 - \sqrt{1-\varepsilon} + \frac{2\sqrt{1-\varepsilon}}{1-\lambda B}\left[\frac{(1-\lambda)B}{(1-\lambda B)^2} In\left(\frac{1}{\lambda B}\right) - \frac{B+1}{2} - \frac{B-1}{1-\lambda B}\right] \tag{18}$$

where B is the same as in Eq. (16), λ^g_e is the gas conductivity plus solid conduction effective thermal conductivity and $\lambda = \lambda_g/\lambda_f$ is the conductivity ratio. The model is based on a one dimensional heat flow for conduction through packed beds of spherical particles as defined by Zehner and Schluender (IAEA TECDOD-1163, 2000).

Solid conduction-contact area conduction-solid conduction model: The final component of effective thermal conductivity which accounts for conduction through the pebbles and across the contact between pebbles was predicted by this model as defined by Tien (IAEA TECDOD-1163, 2000). The model is expressed as:

$$\frac{\lambda_e^c}{\lambda_f} = \left[\frac{3(1-\mu_p^2)}{4E_s} fR\right]^{1/3} \frac{1}{0.531S}\left(\frac{N_A}{N_L}\right) \tag{19}$$

where λ^c_e is the contact plus solid conduction effective thermal conductivity, μ_p is the Poisson ratio, E_s is the Young's modulus, R is sphere radiusand S is a constant related to volumetric arrangement of the pebbles, *f* is force as expressed by Eq. (20):

$$f = P_s\frac{S_F}{N_A} \tag{20}$$

where P_s is external pressure as a result of the stacked pebbles, S_F is constant related to the volumetric arrangement of the pebblesand $N_A = 1/d^2$ and $N_L = 1/d$ are the number of particles per unit area and length respectively.

The total effective thermal conductivity is therefore the sum of all three conductivities:

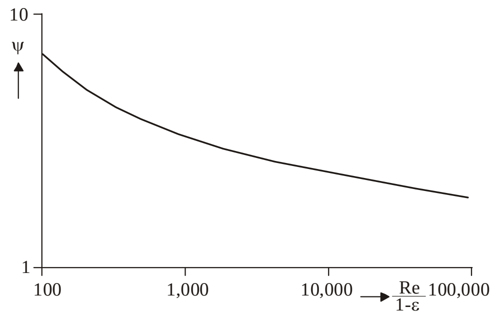

Fig. 3: Pressure drop coefficient of pebble bed

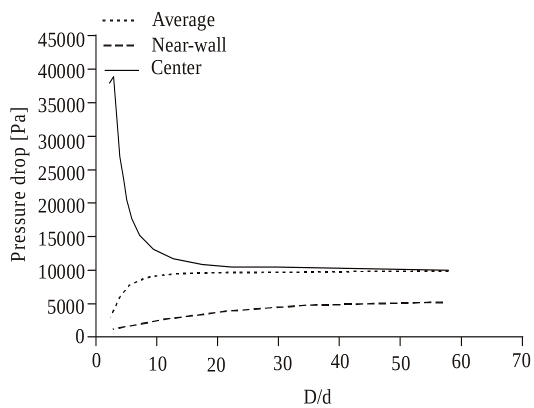

Fig. 4: Pressure drop at various regions of the pebble bed for different D/d ratio

$$\lambda_e^t = \lambda_e^r + \lambda_e^g + \lambda_e^c \tag{21}$$

The effect of gas convection on heat transfer is not included in Eq. (21). A separate function has been developed to simulate the process of forced convection for the pebble bed core in order to take the influence of forced convection heat transfer into account. Thus, the heat transported by forced convection can be evaluated according to the models presented under heat transfer relation section.

Correlations of material properties: The thermal properties of the pebble bed modular reactor materials are very important and thus, require proper representation. Thus, established safety standards were therefore used to calculate the thermal properties of the pebble bed modular reactor materials. The thermal conductivities of the helium coolant and the fuel pebble were determined using the following relations.

Helium thermal properties: The temperature dependent material properties for helium are as prescribed by the nuclear safety standards commission (KTA, 1978, 1981, 1983) and were used to calculate the material properties of helium-density, dynamic viscosity, specific heat capacity, thermal conductivity-in the ranges:

$$0.1 \text{ MPa} \le P \le 10 \text{ MPa and } 293 \text{ K} \le T \le 1773 \text{ K}$$

The helium density ρ (kg/m^3) is:

$$\rho = 48.14\frac{P}{T}\left(1 + 0.4446\frac{P}{T^{1.2}}\right)^{-1} \tag{22}$$

The dynamic viscosity η (Pa s) is:

$$\eta = 3.674 \times 10^{-7}\, T^{0.7} \tag{23}$$

The heat conductivity λ_g (W/m/K) is:

$$\lambda_g = 2.682\times10^{-3}(1+1.123\times10^{-3}\times P)\, T^{0.71\left(1-2.0\times10^{-4} P\right)} \tag{24}$$

The constant-pressure specific heat capacity is:

$$C_p = 5195 \text{ (J/kg K)}$$

The constant-volume specific heat capacity is:

$$C_v = 3117 \text{ (J/kg K)}$$

Fuel pebble thermal conductivity: The thermal conductivity of the fuel pebble λ_f (W/m/K) was derived using the empirical relationship of the German fuel (Yanhua *et al*., 2009) as:

$$\lambda_f = 1.2768 \times \left(\frac{0.06829 - 0.3906\times10^{-4}T}{DOSIS + 0.1931\times10^{-4}T + 0.105} + 1.228\times10^{-4}T + 0.042\; 450 \le T \le 300^o C\right) \tag{25}$$

DOSIS is the fast neutron radiation dose (10^{21}), (IAEA TECDOD-1163, 2000; Yanhua *et al*., 2009)

RESULTS AND DISCUSSION

Pressure drop: The pressure drop coefficient across the pebble bed is shown in Fig. 3. The increase in coolant flow rate reduces the fluid friction between the pebble surface and the fluid (coolant), induced as a result of the fluid viscosity. The pressure drop coefficient consequently reduces with increasing coolant flow rate as can be seen in Fig. 3.

The pressure drop created by the resistance to flow in the pebble bed can be varied by varying the coolant flow

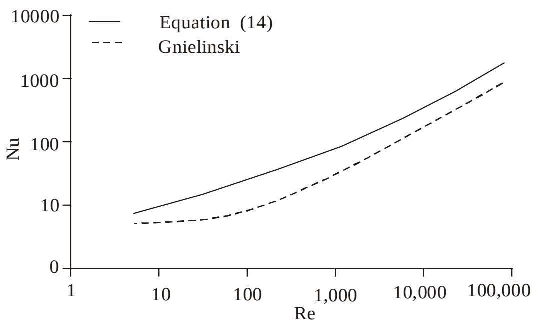

Fig. 5: Nusselt number as a function of Reynolds number for convective particle-to-fluid heat transfer for pebble bed core in helium. Pr = 0.7, ε = 0.39

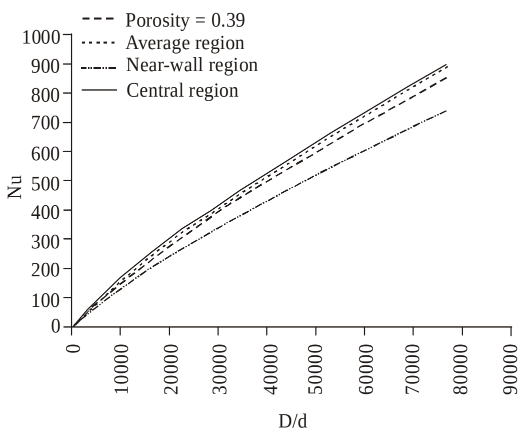

Fig. 6: Nusselt number as a function of Reynolds number for convective particle-to-fluid heat transfer for different regions of the pebble bed core

rate as all other parameters are fixed either by the reactor geometry or coolant choice. Figure 4 shows the comparison of pressure drop versus core to fuel element diameter ratio (D/d) at various regions of the pebble bed.

For fully developed flow, the pressure in the radial direction will be uniform and only vary in the axial direction. The variation in the porosity in the radial direction is accounted for by the corresponding variation in the axial velocity to maintain a uniform pressure in the radial direction.

The flow of coolant causes pressure drop which should not be too high since high pressure drop across the bed requires high pumping power to pump the coolant. The coolant mass flow rate is however limited by both the minimum and maximum allowable temperatures in the core.

Convective heat transfer: Figure 5 shows the plot of Nusselt number as a function of Reynolds number for convective particle-to-fluid heat transfer for pebble bed core.

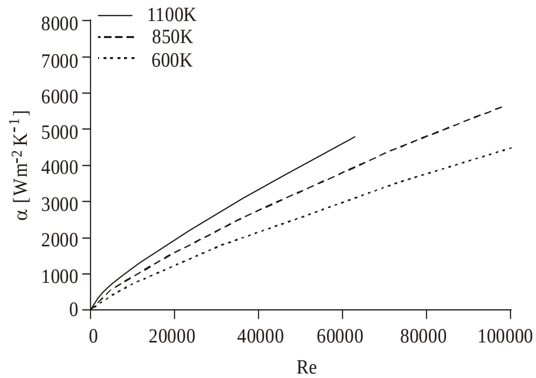

Fig. 7: The convective heat transfer coefficient α for the pebble bed core as a function of Reynolds number

The Nusselt number gives the ratio of convective to conductive heat transfer and measures the enhancement of heat transfer from a surface that occurs in real situation, compared to the heat transfer if just conduction occurred. Referring to Eq. (7), the heat transfer is influenced by either increasing the convective heat transfer coefficient, the heated surface area or the temperature difference between the pebble surface and the bulk coolant.

From Fig. 5, the heat transfer coefficient increases (because the Nusselt number increases) with increasing Reynolds number which is a function of mass flow rate. That is the increase in the mass flow rate of coolant causes a higher heat transfer due to a higher heat transfer coefficient, which leads to cooler core.

Figure 6 shows the Nusselt number as a function of Reynolds number for convective particle-to-fluid heat transfer for different regions of the pebble bed core. The result indicates that the heat transfer is larger in the centre region of the core and lower in the near-wall region of the core.

The quantity of heat that the coolant can transfer from the core depends on the coolant inlet temperature and pressure. The magnitude of the heat transfer coefficient affects the heat transfer process and is influenced by a number of parameters such as the geometry, the coolant flow rate and temperature, the flow condition and the fluid type.

Figure 7 shows the temperature dependence of the convective heat transfer coefficient for different mass flow rates. From the results, it is observed that the heat transfer coefficient increases with increasing temperature and coolant mass flow rate and at higher flow rates (higher Reynolds numbers) the differences in the heat transfer coefficient becomes larger.

Effective thermal conductivity: The effective thermal conductivity of pebble bed calculated by Eq. (15), (18), (19) and (21) is shown in Fig. 8. As depicted in Fig. 8, the

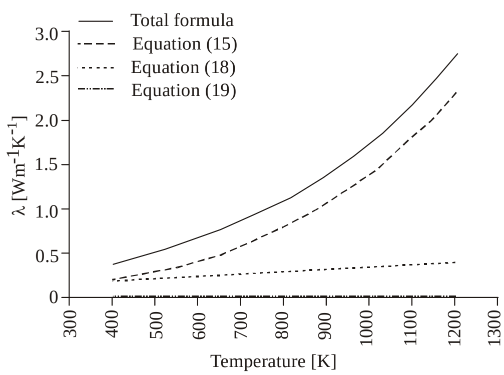

Fig. 8: Effective thermal conductivity of the pebble bed for helium condition

strong dependence of the effective thermal conductivity of the pebble bed on temperature can be observed. The comparison of the effective thermal conductivity among the correlations shows that the heat transfer resulting from interstitial void radiation and solid conduction is the most significant as the others have very little effect on the total effective thermal conductivity.

The effective thermal conductivity of pebble bed is influenced by many parameters with varying degrees. Parameters such as the thermal conductivity of the fuel pebbles and the gas (helium), the gas pressure, the bed packing fraction and fast neutron radiation dose have significant impact on the thermal conductivity of the pebble bed. Other parameters such as the pebble size and surface roughness have less impact on the thermal conductivity of the pebble bed.

NOMENCLATURE

- ΔP Pressure drop (Pa)
- P_s External pressure (Pa)
- d Fuel pebble diameter (m)
- D Core diameter (m)
- A Cross sectional area of core (m^2)
- H Core height
- R Sphere radius
- m Fluid mass flow rate (kg/s)
- Re Reynolds number (dimensionless)
- Q Heat transfer (W)
- T Temperature (K)
- Nu Nusselt number (dimensionless)
- Nus Nusselt number of single sphere (dimensionless)
- f_ϵ Arrangement factor (dimensionless)
- Pr Prandlt number (dimensionless)
- B Deformation factor = $1.25\left(\frac{1-\varepsilon}{\varepsilon}\right)^{10/9}$
- Λ Dimensionless parameter = $\lambda_f/4\sigma T^3 d$
- Es Yonng's modulus (N/m^2)

Subscripts

- p pebble
- g gas
- f fuel
- l laminar
- t turbulent

- f Force = $P\left(\frac{S_F}{N_A}\right)(N)$
- S Constant
- S_F Constant
- N_A Number of particles per unit area
- N_L Number of particles per unit length
- C_p Constant pressure specific heat (J/kg.K)
- C_v Constant volume specific heat (J/kg.K)

Greek symbols

- Ψ Pressure drop coefficient (dimensionless)
- ρ Density of fluid (kg/m^3)
- ϵ Porosity (dimensionless)
- η Dynamic viscosity (kg/s.m)
- α Convective heat transfer coefficient ($W/m^2.K$)
- λ Thermal conductivity (W/m.K)
- σ Stefan-Boltzmann constant ($W/m^2.K^4$)
- λ^r_e Void radiation plus solid conduction thermal conductivity (W/m.K)
- λ^g_e Gas conductivity plus solid conduction thermal conductivity (W/m.K)
- λ^c_e Contact plus solid conduction thermal conductivity (W/m.K)
- λ^t_e Total effective thermal conductivity (W/m.K)
- ξ_r emissivity
- μ_p Poisson ratio

CONCLUSION

A mathematical model of the pebble bed modular reactor heat transfer and loss of pressure through friction have been developed to analyse the convective heat transfer, the effective thermal conductivity and the pressure drop over the core due to friction in the pebble bed. The set of equations (mathematical model) for the prediction of the related phenomena have been presented. The developed model have been implemented on a personal computer using FORTRAN 95 programming language. The model provides understanding of the fluid flow and heat transfer as well as the pressure drop of the pebble bed high temperature gas cooled nuclear reactor.

Several important fluid flow and heat transfer parameters have been examined, including the pressure drop over the reactor core, the heat transfer coefficient, the Nusselt number and the effective thermal conductivity of the fuel pebble. Results obtained from simulation experiments is well represented by experimental results as reported in literature (Achenbach, 1981; KTA, 1978, 1981, 1983). Various experimental and theoretical models have been performed with good correlation between experimental results and that predicted by the Zehner-Schluender correlation (Achenbach, 1981, 1995). Thus the effective thermal conductivity of the pebble bed modular reactor is most reliably predicted by the models of (Achenbach, 1981, 1995). The pressure drop coefficient and hence the pressure drop can be correlated according to (Haipeng *et al*., 2008) over the entire Reynolds number range of interest.

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