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EFFECTS OF POROSITY ON THERMAL-FLUID PHENOMENA IN PBMR CORE

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ABSTRACT

This paper discusses about the effect of the porosity on the heat transfer and fluid flow phenomena in Pebble Bed Modular Reactors (PBMR) core. Computational fluid dynamics (CFD) code has been employed to simulate the unsteady state thermal – fluid phenomena in the PBMR core, in which helium is used as the coolant. In this work, the ratio of coolant mass flow rate to the fuel volume was assumed constant. The outer wall of the core was kept at a constant temperature, while the top and bottom walls were assumed to be adiabatic. In this paper, the effects of porosity on the thermo-fluid-dynamic phenomena in the PBMR core has been investigated. Results show that porosity has a significant influence on the pressure drop, the reactor power, the coolant mass flow rate, the coolant temperature and the normalized power.

INTRODUCTION

Pebble Bed Modular Reactors (PBMRs) are a type of nuclear reactors that use helium as a coolant and graphite as a moderator. The PBMR technology has been developed based on very high-temperature gas-cooled reactor (VHTR) concept by using spherical fuel element, called pebble, as its fuel configuration [1- 4]. The PBMR uses a direct Brayton cycle to convert the heat into electrical energy through a helium turbo generator [5]. At the center of the reactor is the core, which contains approximately 452000 fuel pebbles in an annular geometry with an inner diameter of 2 meters and outer diameter of 3.7 meters. The inner and outer reflectors of the annular core are made up of graphite blocks that provide the geometrical boundary of the core. The PBMR has two operating modes; normal and abnormal. In this paper, the simulation has been just performed for normal conditions.

Since the experimental measurements are so expensive as well as not easy to execute due to the limitations in the measurement technique, the reliable simulation of heat transfer and fluid flow inside the reactor can act as a helpful tool for designs and further developments.

Several numerical simulations have been conducted to analyze thermal-fluid phenomena in the PBMR core. Hossain et al [6] developed a three- dimensional thermal-hydraulic code called TH3D, aiming at providing a tool to analyze design and safety- related issues in high temperature reactors. Nelson [7] studied on scaling analysis for the pebble bed core configuration by focusing on heat transfer phenomenon. Since the pebble bed- reflector heat transfer is important in this type of reactors, van der Merwe et al [8] studied the heat transfer correlation limitations at the interface between the pebble bed and the reflector. Coert Johannes Visser [9] developed a numerical modelling to simulate flow and heat transfer through packed pebble beds. G.J. Auwerda et al [10] developed the pebFoam code, capable of evaluating thermo-hydraulics of the pebble bed including non-uniform distributions of porosity for arbitrary geometries. They also studied the influence of non-uniform porosity distributions on velocity, pressure drop, and helium and pebble temperatures. Latifi et al [11] presented a numerical investigation of thermal-fluid phenomena in a pebble bed high-temperature gas-cooled reactor (HTGR) core under steady state and transient conditions using computational fluid dynamic (CFD) to study the influence of porosity on the core performance after reactor shutdown.

A lack of access to a comprehensive experimental data due to technical obstacles, prompts the researchers to use simulation by employing CFD methods for designing PBMR or optimizing its performance. The PBMR core region is filled with thousands of fuel spheres, so it can be assumed as a porous medium. Thus, the porosity plays a key role in the transport phenomena of heat and momentum and so porosity plays an important role in reactor operations and safety. In this work, by developing CFD method and by considering the Navier-Stokes equation, energy equation and k –ε two-equation turbulence model, we have focused on the effects of the porosity on the thermal-fluid phenomena in PBMR core.

First, the thermal-hydraulic phenomena have been simulated in the PBMR core in the transient conditions; then the effects of changes in the PBMR core operating parameters, particularly the reactor power, the coolant temperature, the mass flow rate and the pressure drop due to porosity have been studied.

MATHEMATICAL MODEL

The mathematical model, which includes the continuity equation, the momentum equation, the energy equation and the k- ε two- equation turbulence model, has been developed to simulate the thermal -hydraulic characteristic of the PBMR core under the unsteady state condition. The Mach number was less than 0.3 so the coolant gas was considered as an incompressible fluid and the ideal gas law was used for the constitutive relation. The incompressible ideal gas law is:

$$\rho = \frac{P_{op}}{\frac{R}{M_w} T} \tag{1}$$

where P_{op} is the operating pressure (9 MPa), M_w is the molecular weight of the helium, and R is the universal gas constant (8.31 J / Kmol) [12].Since the PBMR core contains a large number of pebbles (in the range of 330000 to 452000), it can be assumed as a porous medium by using the governing equations as follows [13, 14, 30]:

Governing equations

Continuity equation

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla\cdot(\varepsilon\rho\vec{v}) = 0 \tag{2}$$

Momentum equation

$$\frac{\partial(\varepsilon\rho\vec{v})}{\partial t} + \nabla\cdot(\varepsilon\rho\vec{v}\vec{v}) = -\varepsilon\nabla P + \nabla\cdot(\varepsilon\vec{\tau}) + \varepsilon\rho\vec{g} - \nabla P_{Porous} \tag{3}$$

where $-\nabla P_{porous}$ is pressure drop as a result of fuel spheres presence in the core, expressed by modified Ergun correlation as follows [15-17].

$$\nabla P_{porous} = -180\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu\vec{u}}{d^2} - 1.8\frac{1-\varepsilon}{\varepsilon^3}\rho\frac{|\vec{u}|\,\vec{u}}{d} \tag{4}$$

ε is bed porosity , *d* is the diameter of the pebble (spherical fuel), u is superficial mean exit velocity, μ is dynamic viscosity and ρ is fluid density.

$$\left[(\rho C_P)_s(1-\varepsilon) + (\rho C_P)_f\,\varepsilon\right]\left(\frac{\partial T}{\partial t} + \nabla.(uT)\right) = \nabla.\left(k_{eff}\nabla T\right) + S_h \tag{5}$$

In Eq.5, the first term on the right hand side represents the conduction heat transfer, in which k_{eff} is the effective thermal conductivity and is a function of some packed bed characteristics such as, materials, structure and temperature. By assuming all the gas and all the solids are conducting in parallel, following equation can be derived for k_{eff} [18]

$$k_{eff} = \varepsilon k_f + (1-\varepsilon)k_s \tag{6}$$

k_f is the fluid thermal conductivity (i.e. helium thermal conductivity) calculated in the steady state as follows [19].

$$k_f = 2.682\times10^{-3}(1+1.123\times10^{-3}P)\times T^{(0.71\times(1-2\times10^{-4}P))} \tag{7}$$

At 90bar (operating pressure of the core), Eq.7 can be rewritten as

$$k_f = 2.953\times10^{-3}T^{0.7} \tag{8}$$

Finally, the last term in Eq. (5), S_h, stands for the heat source in the reactor generated by a chain of nuclear reactions.

Although there is no enough data about the real profile of vertical power distribution, as an approximation, chopped cosine was adopted.

k-ε Turbulence equation

The turbulence kinetic energy, *k,* and energy dissipation rate, ε, can be calculated by using the following transport equations [20].

$$\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho\vec{u}k) = \nabla.\left((\mu + \frac{\mu_t}{\sigma_k})\nabla k\right) + G_k - \rho\varepsilon \tag{9}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla.(\rho\vec{u}\varepsilon) = \nabla.\left((\mu + \frac{\mu_t}{\sigma_\varepsilon})\nabla\varepsilon\right) + \frac{\varepsilon}{k}(C_{\varepsilon1}G_K - C_{\varepsilon2}\rho\varepsilon) \tag{10}$$

where G_K is turbulence generation term and C_μ , $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_k , σ_ε are empirical constants for turbulent models and their values are 0.09, 1.44, 1.92, 1 and 1.3, respectively.

Porosity

In all equations mentioned above it can be seen that the porosity acts as the key parameter in the heat and the momentum transport phenomena. In a randomly packed bed of spheres the average porosity, outside of the wall affected region, varies between 0.36 to 0.43 [17]. It should be noted that some correlations have been developed to take into account the wall effects on the porosity in the region near the wall [21]. For this reason, it is important to employ an appropriate correlation to predict the porosity in any place in the bed.

Du Toit [22] stated that the correlations used to predict the porosity variations can be classified in to two categories, i.e. those that consider the oscillatory behavior for the variation of the porosity and those that use an exponential expression for it. Here, the porosity was assumed to be uniform in the tangential direction whereas it was considered to be exponential in the radial direction. The core is an annular space filled with the fuel spheres and is limited from two sides in radial direction, so that the effect of the core walls should be considered from two sides. The following equations express the radial porosity distribution near the walls [23].

$$\varepsilon(r) = \varepsilon_b \left[1 + C \ \exp(-N \ \frac{r - R_i}{d_p}) \right], Ri \leq r \leq \frac{R_o + R_i}{2} \qquad (11)$$

$$\varepsilon(r) = \varepsilon_b \left[1 + C \ \exp(-N \ \frac{R_o - r}{d_p}) \right], \frac{R_i + R_o}{2} \leq r \leq R_o \qquad (12)$$

where, ε_b is the volumetric porosity obtained from the ratio of the void volume to the total volume. Fig.1 depicts the porosity variation with changing the distance from the wall for various bulk porosities.

CFD SIMULATION

Finite volume method was used to solve the governing equations of the system by using Semi Implicit Method for Pressure Linked Equations (SIMPLE) algorithm [24, 25]. The equations were discretized by using first order upwind scheme. The calculation domain was divided into a finite number of control volumes. Density and turbulence kinetic energy were stored at the main grid points that were placed at the center of each control volume. A staggered grid arrangement was used and the velocity components were solved at the control volume surfaces [24, 25].

PBMR core consists of an annulus filled with 6cm fuel spheres. A simplified geometrical representation of the core is shown in Fig.3 in which helium gas enters from the top of the core and after receiving heat from the pebbles, exits the reactor core from the bottom. Since three-dimensional simulation of the core demands a large volume of computations, in this work the two-dimensional modeling with a symmetrical axis has been employed, in which the boundary conditions were defined in symmetry axis [26]. Commonly, a PBMR core with 452000 pebbles is able to generate 400MW of power [1]. As a result the power density of each fuel sphere would be 7.8 MW/m^3. The thermal power of the core can be obtained from the energy balance around the core as follows

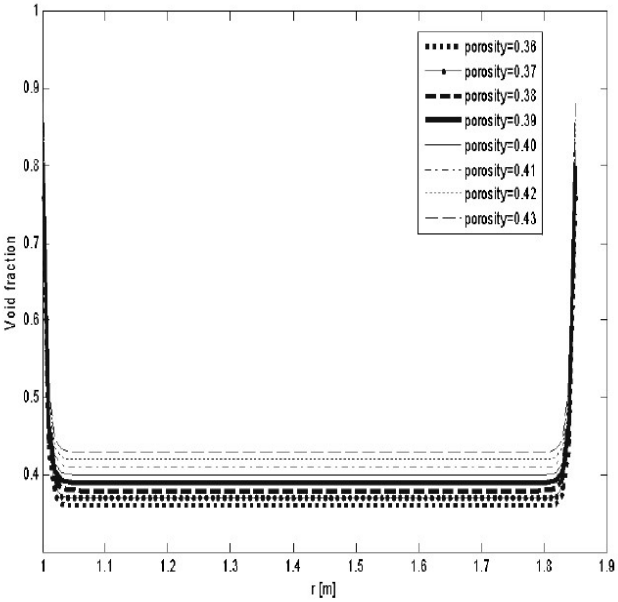

Figure 1 The porosity variation as a function of distance from wall

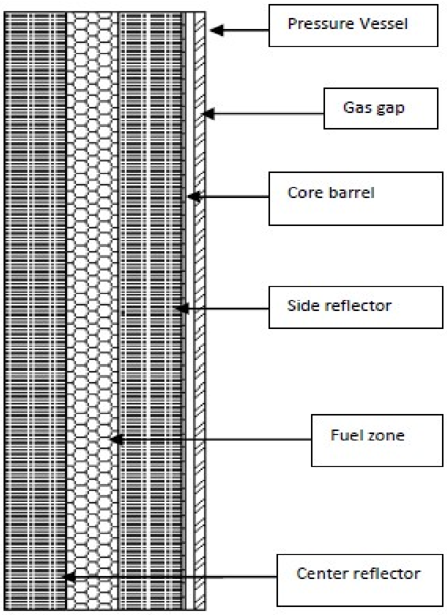

Figure 2 Axisymetric geometry of the core

$$P = V_{fuel} \times \rho_{fuel} = \dot{m}_{He} \times C_p \times \Delta T \quad (13)$$

where $\dot{m}_{He}$ is helium mass flow rate, ΔT is the inlet- outlet temperature difference, ρ_{fuel} is the power density of each fuel sphere and V_{fuel} is the fuel volume expressed as

$$V_{fuel} = (1-\varepsilon)V_{total} \quad (14)$$

According to Eqs.13 and 14 and by assuming a constant value for the ratio of the mass flow rate to the fuel volume, mass flow rate, thermal power and other core parameters change with the variation of the porosity. The porosity- independent and dependent parameters of the core are given in Table 1 and Table 2, respectively.

Table 1 Constant core parameters

Power density of fuel sphere	7.8MW/m^3
Coolant	Helium
Core inlet temperature	773K
System operating pressure	9MPa
Pressure vessel	Steel
Coolant flow direction	Down wards
Core outlet diameter	3.7m
Core inner diameter	2m
Core height	11m

Table 2 Porosity- dependent parameters of the core

porosity	0.36	0.37	0.38	0.39	0.4	0.41	0.42	0.43
Hydraulic diameter (m)	0.0225	0.0234	0.0245	0.0255	0.0266	0.0278	0.0289	0.0301
Fuel volume(m^3)	53.76	52.92	52.08	51.24	50.4	49.56	48.72	47.88
Mas flow rate (kg/s)	201.72	198.6	195.44	192.27	189.13	185.98	182.82	179.66

To simplify the computational geometry, the gas gap shown in Fig.2 is eliminated. The simplified representation of the core is shown in Fig.3, in which the fuel spheres are located between wall 2 and 3. The boundary condition of the core barrel (wall 1) was specified as constant temperature. The upper and lower surfaces were insulated so the adiabatic boundary condition can be considered for them. The inlet mass flow rate of the helium was provided with a temperature of 773K. A zero gauge pressure was set zero at the outlet boundary. A no-slip boundary condition was assumed at the solid wall. A two dimensional CFD code was used to model and simulate the heat transfer through the core and the other demanded parameters are brought in Table1 and Table 2. PBMR core was filled with thousands of fuel spheres and so it was considered as a randomly packed bed core. In a randomly packed bed of spheres, the porosity of 0.36 and 0.43 correspond to the dense packing and loose packing porosities. Thus, in order to study the effect of the porosity on the flow and heat transfer in the core, various volumetric porosities were selected between 0.36 to 0.43[17].

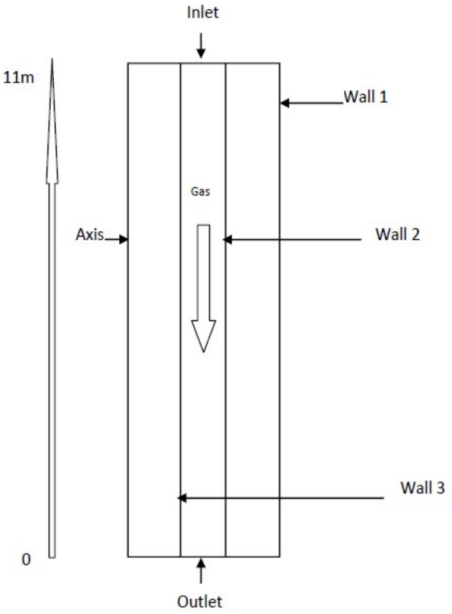

Figure 3 A simplified geometry used in the computations

To investigate mesh independency on simulation results, various meshes were employed and finally, considering both the accuracy and the computational time, whole the computations were done with 110 × 110 grid size.

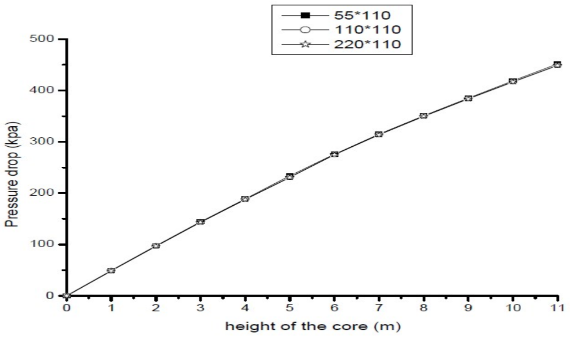

Figure 4 Mesh Independence Study

RESULTS AND DISCUSSION

All of the simulations presented in this work have been done using CFD codes that have been written in C language. The convergence criterion for relative residuals of the momentum, pressure, enthalpy, and energy equations was set to 10^{-5}.

Effect of the Porosity on Pressure Drop

The pressure drop across the core was analyzed using the semi-empirical Ergun equation and the Navier-Stokes equations. By using numerical solution, the pressure drop variations across the core as a function of the porosity were calculated and the results are shown in Fig.5. As expected, Fig. 5 shows that the pressure drop decreases along the axial position of the core with increasing the porosity. It is obvious that the porosity has a significant effect on the pressure drop since with decreasing the porosity from 0.43 to 0.36 the value of the pressure drop becomes more than two times. Fig.6. shows the pressure drop against time for different porosities. As expected, the pressure drop increases with decreasing the porosity. The pressure drop decreases steeply after a certain time, tends to reach a constant value. Its behavior is the same for different porosities approximately. However, for lower porosities especially for porosities of 0.36, 0.37 and 0.38, the slope of the pressure drop decline is more than others' markedly. It should be noted that according to Ergun equation, the pressure drop depends on the fluid density and fluid velocity, so the pressure drop is proportional to the square of the flow rate. For different porosities, the time- dependent mass flow rates on the outlet are shown in Fig.7. The transient mass flow rate decreases to the steady state in a certain time. In this work, the ratio of coolant mass flow rate to the fuel volume was assumed constant. Thus, with increasing the porosity the mass flow rate decreases and then with decreasing the mass flow rate the pressure drop decreases.

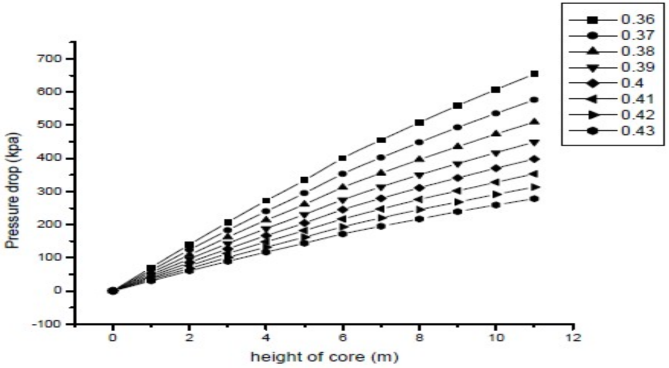

Figure 5 The influence of the porosity on pressure drop along the axial position of the core

It is clear that the decreasing of the pressure drop can receive attention due to decreasing energy loss and its economic aspects. On the other hand, for a given pebble bed core, increasing the porosity means that the number of the fuel spheres used to fill the core goes down, which leads to decreasing the power generation. Therefore, apart from the fluid energy loss, the thermal power generation should be considered.

Effect of the Porosity on Fluid Temperature

Transient behavior of inlet temperature for different porosities is shown in Fig.8. As it is observed the variation of the inlet temperature over time for all of the porosities is negligible so that the inlet temperature can be considered constant regardless the change in porosity. Fig.9, 10 and 11 depict that increasing the porosity results in rising temperature markedly. This is due to the fact that with increasing the porosity the void fraction of the bed goes up, which leads to an increases in the mixing incidence inside the coolant. Thus, the fluid turbulence rises and results in increasing Reynolds number or in the better word improving heat transfer coefficient between the fuel spheres and the coolant. It should be noted that increasing porosity raises the Reynolds number not only because of the fluid turbulence, but also because of increasing the hydraulic diameter. As shown in Fig.11, at the beginning, at lower porosities, the temperature is higher

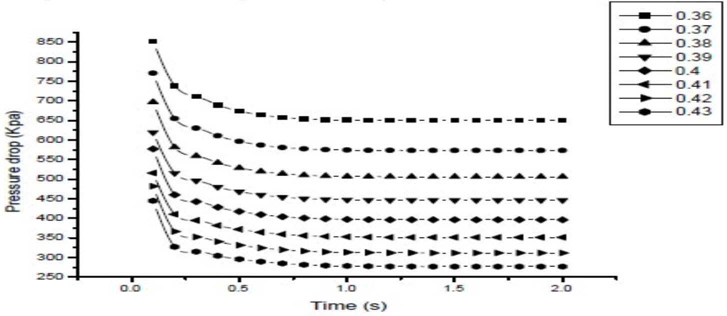

Figure 6 Transient behaviors of pressure drops in different porosities

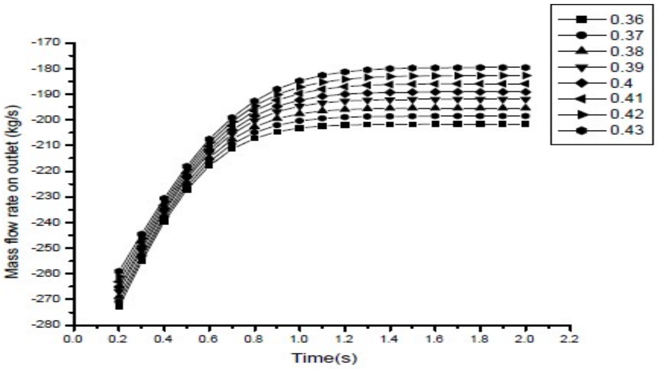

Figure 7 Transient behaviors of mass flow rates at outlet in different porosities

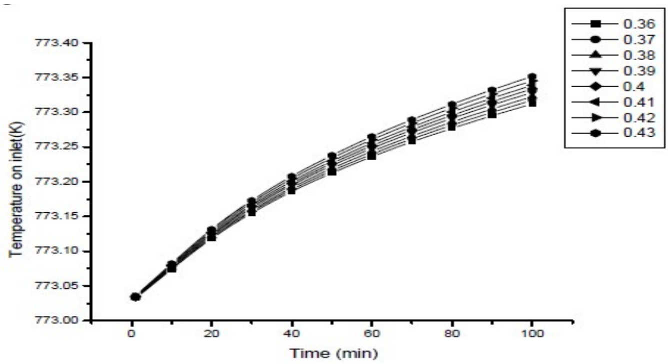

Figure 8 Transient behavior of inlet temperature in different porosities

but after a certain time, the temperature increases with increasing porosity. It is obvious that with increasing the porosity, the space in which the coolant goes through increases, which leads to better mixing and improving the heat transfer coefficient, *h* that results in increasing temperature.

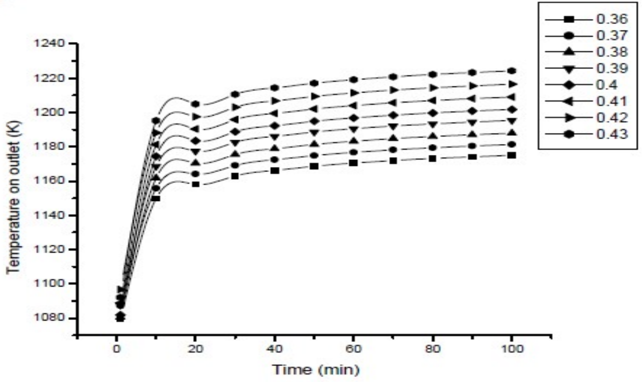

Figure 9 Transient behavior of outlet temperature in different porosities

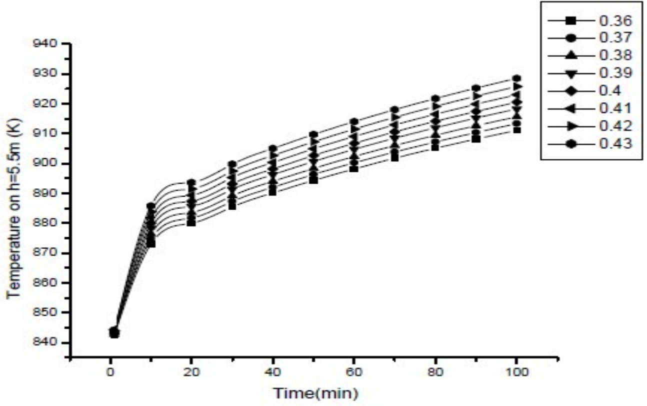

Figure 10 Transient behavior of temperature at height of 5.5m in different porosities

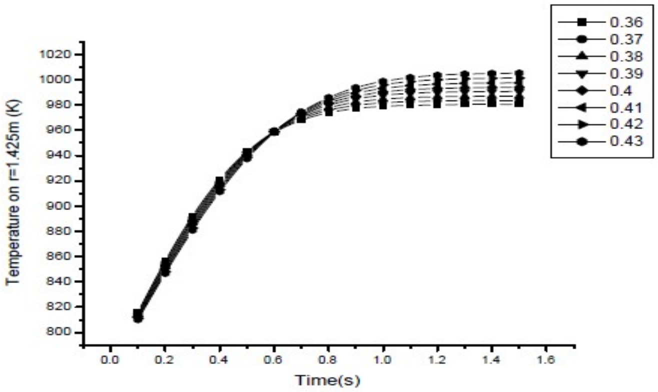

Figure 11 Transient behavior of temperature at the radius of 1.425m in different porosities

Effect of the Porosity on Thermal Reactor Power

Fig.12 shows reactor power against time in different porosities. Many parameters have effects on the reactor power profile directly or indirectly. The porosity variation in the reactor core impacts the reactor power profile. As can be seen clearly in Fig.13, with increasing the porosity the reactor power decreases. It is clear that the decreasing of the pressure drop can receive attention due to decreasing energy loss and its economic aspects. On the other hand, for a given pebble bed core, increasing the porosity means that the number of the fuel spheres used to fill the core goes down, which leads to decreasing the power generation. However, as can be seen in Fig.13 the effect of the power generation is more powerful than the effect of the pressure drop since the reactor power increases with decreasing the porosity. However, as shown in Fig.14, the behaviour of normalized reactor power variation is totally unlike the reactor power i.e. with increasing the porosity the normalized reactor power increases. To justify this observing, this fact should be noticed that with increasing the porosity the void fraction of the bed goes up, which makes less resistance to the fluid flow and allows the fluid flow to develop better.

Investigations show that there is no enough experimental data about thermal-hydraulic characteristics of PBMR core, especially for various porosities. It should be noted that the verification of this study was qualitative, since no benchmarked calculation was available for the effects of various porosities on thermal-fluid phenomena in PBMR core under unsteady state condition. The existing data just report the inlet and outlet of some thermal-hydraulic quantities for the porosity of 0.39[1, 2, 24- 26], which were employed as the boundary conditions in this simulation.

Comparing the simulation results with experimental data indicates that the outlet average temperature is calculated 1168.83K whereas according to experimental data its value is 1173K, which shows a difference of 0.35% between simulation results and experimental data.

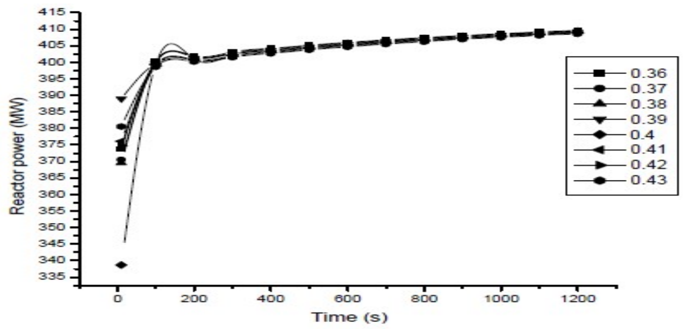

Figure 12 Transient behavior of reactor power in different porosities (0<t<1200s)

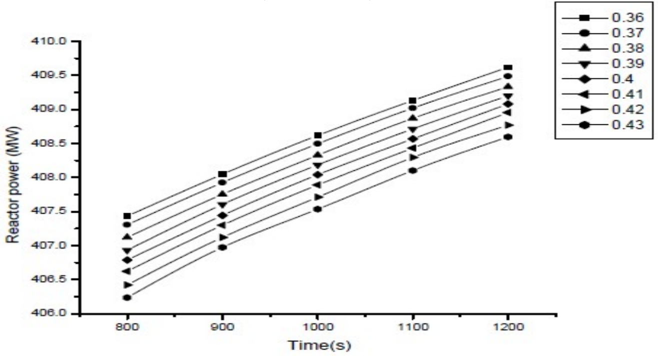

Figure 13 Transient behavior of reactor power in different porosities(800s<t<1200s)

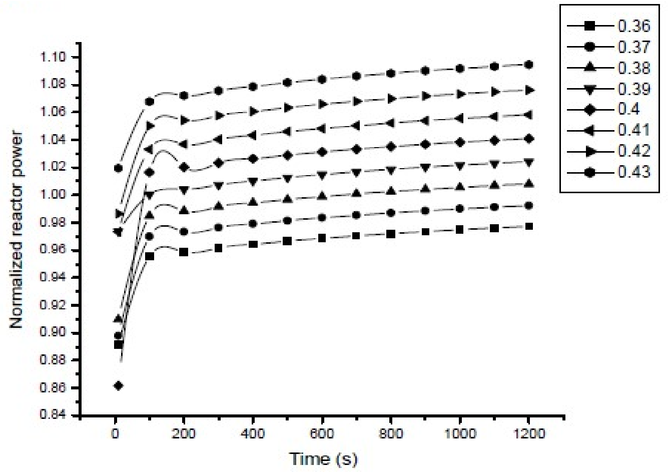

Figure 14 Transient behavior of normalized reactor power in different porosities (800s<t<1200s)

CONCLUSIONS

The focus of the present work is to evaluate the role of porosity in the thermal-fluid parameters of the PBMR core via modeling and simulation of the core by using CFD code. The numerical solution indicated that the pressure drop sensitivity to the porosity changing is more distinct than the other parameters. The results shown that the pressure drop decreases along the axial position of the core with increasing the porosity. It is obvious that the porosity has a significant effect on the pressure drop since with decreasing the porosity from 0.43 to 0.36 the value of the pressure drop becomes more than two times. The results shown that with increasing the porosity the coolant temperature increases markedly. This is due to the fact that with increasing the porosity the void fraction of the bed goes up, which leads to turbulence rising and improving the heat transfer coefficient. As was seen in this study, though with increasing the porosity the reactor power decreases, the resistance to the fluid flow to decrease and allows the fluid flow to develop better, which leads normalized reactor power to increase.

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