Simulation and Optimization of Heat Transfer in PBR Core

Masumeh Sadat LATIFI[1]

[1]*AmirKabir University of Technology, Tehran, Iran*

m.s.latifi@aut.ac.ir

Abstract: This paper discusses about simulation and optimization of heat transfer in pebble bed reactor (PBR) core. In PBR core some parameters like coolant ,mass flow rate, size and number of fuel spheres are considered as the influencing parameters in the heat transfer phenomenon. In this paper computational fluid dynamics (CFD) model is employed to simulate the thermal – fluid phenomena of the PBR core. To achieve the optimum condition, in which the desired power is obtained with minimum energy loss (coolant pressure drop), the size of fuel spheres was changed. By analyzing the results of different fuel sphere diameters it was revealed that the diameter of about 6 cm could be an optimum diameter for these reactors.

Keywords: *PBR, CFD, simulation, optimization, heat transfer*

1. Introduction

The Generation IV International Forum findings relative to the further nuclear systems (sustainability, security and reliability, economy, non-proliferation and physical protection) have given new impetus to graphite-moderated high-temperature gas cooled reactors (HTGRs). The high modular HTGR concept exhibits inherent safety features due to the low power density and the large amount of graphite present in the core which gives a large thermal inertia in the event of accidents as loss of coolant. These passive concepts were first introduced in German HTR-Module (pebble fuel) design (1, 2, 3). The fuel design of fissile kernels coated with carbon and silicon carbide layers mixed with graphite is suitable for reaching very high burnup and ensures a full confinement of volatile fission products during normal and abnormal situations (Figure 1). Other characteristics of HTGR are the capability of providing high temperature heat and suitability for various power conversion cycles.

In pebble bed reactor core, the gas flows around randomly distributed spheres and earns heat from them. This requires a variety of analysis one-dimensional models (4) that do not capture all the significant physical phenomena to large scale three dimensional computational fluid dynamics (CFD) codes(3). A huge number of grids is needed to resolve the flow structure around the spheres .

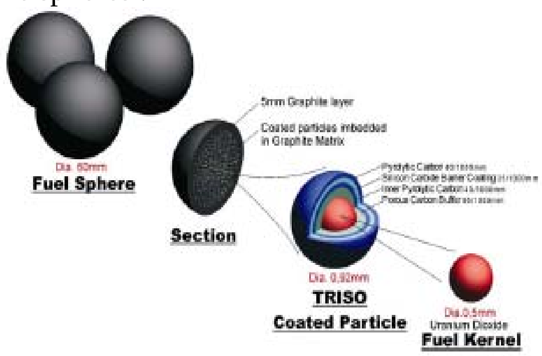

Fig. 1. Fuel Design

The aim of the present study is to simulate heat transfer in PBR core and to try optimizing it .Heat transfer phenomena at the interface between the pebble bed and gas was simulated by using FLUENT.

2. Heat Transfer and Fluid Flow Phenomena

The first phenomenon is the so- called ‘pebble to pebble effective conductivity’ within the pebble bed (5). Simulation models for the pebble bed core, such as the one employed in FLUENT, treats the simulation of the heat transfer through the pebble material combined with the heat transfer between the pebble surfaces separately from the heat transfer through the fluid that fills the voids in- between the pebbles. The model therefore employs one energy conservation equation to solve for the pebble surface temperatures and a separate energy conservation equation to solve for the fluid temperatures. The two solutions are linked through the convection heat transfer between the pebble surfaces and the fluid that appears in both equations, as illustrated below.

The energy conservation equation to solve for the pebble surface temperatures is given by

$$0 = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_{eff} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z}\left(k_{eff} \frac{\partial T}{\partial z} \right) + q_{fpc} \quad (1)$$

with T the representative pebble surface temperature, k_{eff} the pebble to pebble effective conductivity within the bed and q_{fpc} the fluid to pebble surface convection heat transfer rate unit volume. r refers to the radial coordinate direction and z to the axial coordinate direction.

The energy conservation equation to solve for the fluid temperatures within the voids in the pebble bed is given by

$$\begin{aligned} &\frac{\partial}{\partial t}(\varepsilon \rho h_0) + \frac{1}{r}\frac{\partial}{\partial r}(\varepsilon r \rho h_0 u_r) + \frac{\partial}{\partial z}(\varepsilon \rho h_0 u_z) \\ &= \frac{\partial}{\partial t}(\varepsilon p) + \frac{1}{r}\frac{\partial}{\partial r}\left(\varepsilon r k_{feff} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z}\left(\varepsilon k_{feff} \frac{\partial T}{\partial z} \right) \quad (2) \\ &+ \varepsilon \rho (g_r u_r + g_z u_z) + q_{pfc} \end{aligned}$$

With T the representative fluid temperature, t the time, ε the porosity, ρ the fluid density, h_0 the total enthalpy, u_r and u_z the directional components of the fluid velocity in the radial and axial coordinate directions respectively, p the static pressure in the fluid, k_{feff} the fluid effective conductivity, g_r and g_z the gravitational acceleration components in the radial and axial coordinate directions respectively and q_{pfc} the pebble surface to fluid convection heat transfer rate per unit volume .

The second important phenomenon is the so-called ‘pebble to reflector effective conductivity’. This is very similar to the pebble to pebble effective conductivity since it includes the same heat transfer mechanisms.

The third phenomenon addresses the total pressure drop within the flow due to the presence of the pebble bed, characterized by the Euler number. The FLUENT model of the pebble bed is based on a two dimensional axi-symmetric coordinate system (Figure 2) rather than a full three-dimensional cylindrical coordinate system. This implies that all variations in geometry or material properties around the perimeter of the reactor will be spread evenly around the circumference to form a material with constant properties at each given height and radius. The pebble bed is therefore represented by discrete control volumes consisting of a porous media. The porosity is assumed constant between control volumes in both radial and axial directions.

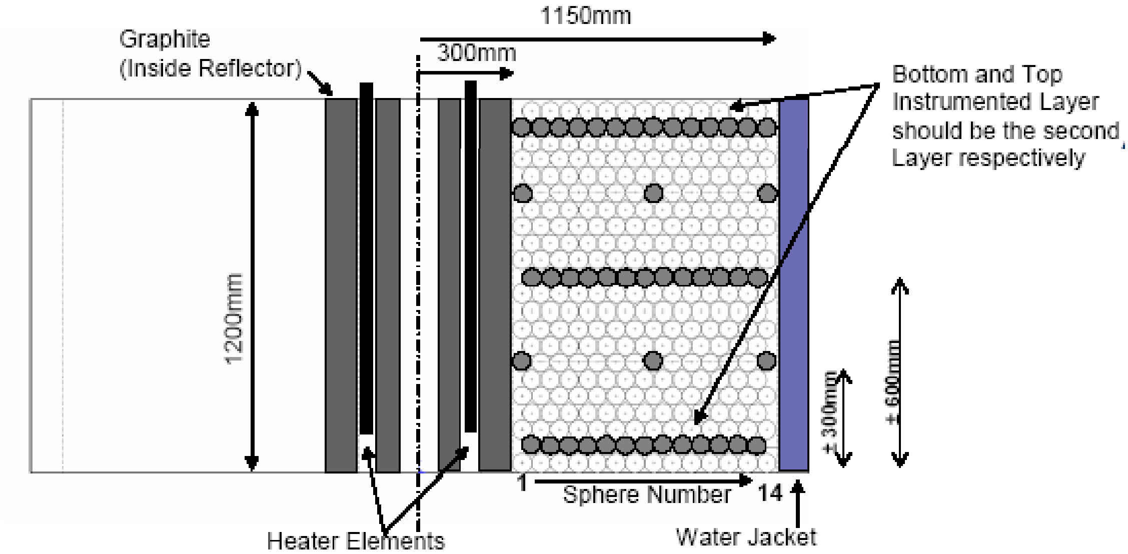

Fig.2. Geometry

The fourth phenomenon of interest is the pebble surface to fluid convection heat transfer coefficient. The energy conservation equations for the pebble surface temperatures and the fluid temperatures respectively were given in equations (1) and (2). In these equations q_{pfc} is the pebble surface to fluid convection heat transfer rate per unit volume.
The rate of heat transfer is calculated as follows:

(3)

with Q the heat transfer rate, h_{pfc} the pebble to fluid convection heat transfer coefficient, A_p the pebble outer surface area that is in contact with the fluid and T_p and T_f the pebble surface and fluid temperatures respectively.
The convection heat transfer coefficient is calculated from the Nusselt number as follows:

$$Nu = \frac{hd}{k} \quad (4)$$

The Nusselt number is typically a function of porosity, Reynolds number and Prandtl number i.e.:

$$Nu = f\ (\varepsilon, \mathrm{Re}_o, \mathrm{Pr}) \quad (5)$$

The Prandtl number is defined as

$$\Pr = \frac{c_p \mu}{k} \quad (6)$$

with c_p the fluid specific heat and μ and k the fluid dynamic viscosity and thermal conductivity respectively.

The fifth phenomenon is the reflector surface to fluid heat transfer coefficient. This is very similar to the pebble surface to fluid heat transfer coefficient except that in this case the heat transfer takes places between the fluid and the reflector wall in the near –wall region, rather than between the fluid and the pebble surface within the pebble bed.

The sixth and final phenomenon is the fluid effective conductivity or k_{feff} which is referenced in Equation (2). In the case of the pebble bed the fluid effective conductivities will be greater than the normal static values of conductivity for the particular fluid. The reason for this is that due to the interweaving nature of the flow there will be turbulent mixing in the direction perpendicular to the flow, resulting in enhanced diffusion. The magnitude of the enhancement is usually correlated in terms of the Peclet number defined as Pe=Re Pr. This phenomenon is therefore again dependent on the porosity, Reynolds number and Prandtl number i.e.:

$$k_{feff} = f\ (\varepsilon, \mathrm{Re}_o, \Pr) \quad (7)$$

If in Equation (2) it is assumed that the flow is steady, fully developed in the axial direction, that there is no internal heat generation and that the effects of gravity are negligible, then we may write:

$$\frac{\partial}{\partial z}\left(\varepsilon \rho h_o u_z\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(\varepsilon r k_{feff}\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\varepsilon k_{feff}\frac{\partial T}{\partial z}\right) \quad (8)$$

3. Case Study

It is proposed that the pebble bed reactor consists of annular bed with an inside diameter of 0.6 m , an outside diameter of 2.3 m and a height of 1.2 m. The inside wall will be heated and the outside wall will be cooled by means of water jacket. The upper and lower surfaces will be insulated to be adiabatic (6). The packed bed will consist of graphite spheres that their number is 330000. Reactor thermal power per volume is 3215252 W/m^3, operating pressure of 5 MPa, helium inlet temperature of 300 ^{o}C, helium outlet temperature of 700 ^{o}C and coolant mass flow rate of 192kg/s.

We compared the result of simulation for fuel spheres diameter of 5, 6 and 7 that is given in Table 1 .

Table 1: Results of simulation for fuel spheres with different diameter

Diameter of fuel sphere	5 cm	6 cm	7cm
Porosity	0.64	0.39	0.03
Hydraulic Diameter	0.061m	0.025m	0.0014
Pressure Drop	90KPa	600KPa	1600Mpa
Fuel sphere volume	0.00006545m^3	0.000113m^3	0.0001796m^3
Thermal Power	69.44MW	120MW	189.92MW

Conclusions
The theoretical basis of a system CFD model of a pebble bed reactor was discussed. This model is employed to simulate the thermal –fluid phenomena of the reactor core. The diameter changing of fuel spheres is effected in porosity amount so it would be effective in pressure drop amount. Also it is effective in thermal power amount. It was seen from the results that in a fuel sphere diameter of 5 cm , pressure drop is the least and also thermal power is the least and in a fuel sphere diameter of 7cm ,thermal power is maximum and also pressure drop is maximum that is not desirable so diameter of 6cm could be an optimum diameter in which the desired power is obtained with minimum energy loss (coolant pressure drop).

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