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OPTIMIZATION OF A PEBBLE-BED NUCLEAR CORE VIA ENTROPY GENERATION MINIMIZATION USING THE TWO ENERGY EQUATION MODEL

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Abstract. *This study aims to increase the efficiency of a high temperature gas cooled reactor with a pebble-bed core, indicating the best porous permeability through the entropy generation minimization method. The system, is a fast reactor where the working fluid works directly in contact with the nuclear fuel. In this study, the pebble-bed core is approximated to a porous media to evaluate the behavior of the fluid within the core using the 2EEM.*

Keywords: *Optimization. Pebble-Bed Nuclear Core. Entropy Generation Minimization. 2EEM.*

1. Introduction

The high temperature gas cooled reactor (HTGR) with pebble-bed core is a fast VI gen reactor in which the working fluid operates in direct contact with the nuclear fuel. Based on a closed Brayton cycle, the HTGR makes it unnecessary to use intermediate heat exchangers when using the fuel in a porous graphite mesh configuration. In this configuration the gas flow through the uranium dioxide core absorbing the heat from the fission reaction of the enriched material, thus initiating the process of converting nuclear energy to thermal energy through convection (Chen, et al., 2017).

By changing core operating parameters such as: flow geometry, available thermal exchange area, boundary conditions or increasing the thermal conductivity of the working fluid; heat transfer through forced convection can be improved. In general, the traditional fluids used in these applications have low thermal conductivity. Therefore, to increase the thermal exchange efficiency, it is necessary to increase the contact surface between the solid and the working fluid (Nakayama, et al., 2001). In an HTGR, the area of contact between the fluid and the solid surface is increased by disposing the fuel spheres of the core to form a porous medium, where heat is transferred by conduction into the solid and by convection into the fluid. Fig. 1 presents a schematic model of an experimental HTGR developed by Chen and Lee (2017).

Considering the configuration of the reactor shown, the present study seeks to maximize the efficiency of the nuclear energy conversion system, reducing the losses due to irreversibilities in the reactor core. To do so, techniques to analyze the number of entropy generation will be used, considering different diameters of fuel spheres and the model of two energy equations (2EEM) as the macroscopic model of the porous medium. Such methodology can be applied when the flow has a high Rayleigh number or when the solid medium has a higher thermal conductivity than the working fluid and where the temperature of the solid and the liquid differ considerably. These characteristics are usually found in heat transfer arrangements in porous media (Carvalho & De-Lemos, 2009).

Applying both techniques, Computer Fluid Dynamics (CFD) and Entropy Generation Minimization (EGM), it is possible to better understand the dynamics of the system, and to propose an optimum configuration of porosity that enables the improvement of the final efficiency of the nuclear reactor.

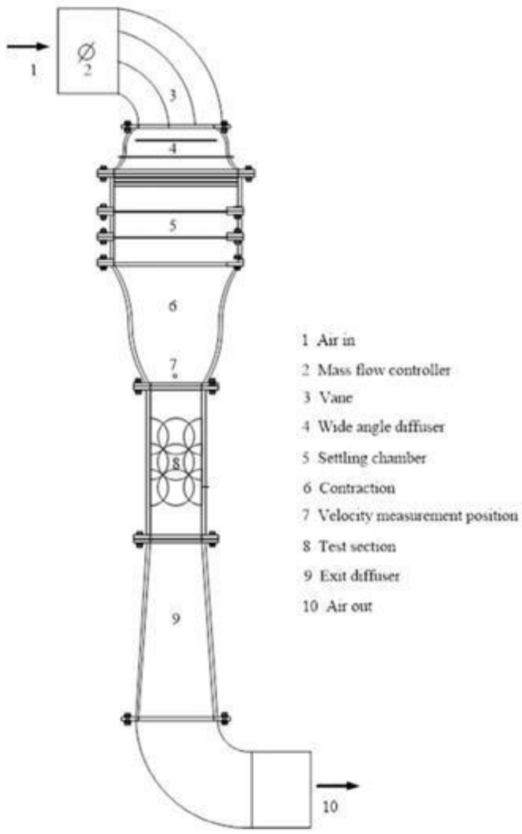


Figure 1 - Schematic Model of a High Temperature Gas Cooled Reactor (Nakayama, et al., 2001)

2. Computational Procedure

The numerical analysis was performed using the Finite Volume Method for volume control and the fluid was treated as incompressible; through the use of continuity equations, moment conservation equations and internal energy equations, as described in (Park & Kim, 2016) it was possible to elaborate a numerical model of the proposed flow. The Reynolds tensor (turbulent term of the momentum equation) can be related to the mean velocity gradient using the Boussinesq hypothesis as described (Nakayama, et al., 2001).

For the macroscopic model of the flow in porous medium, a fluid saturated in porous medium is considered to have its thermal diffusivity much smaller or larger than the solid structure. In the transient processes the local thermal equilibrium hypothesis should be discarded, with the two energy equations model (2EEM) being the most appropriate (Park & Kim, 2016).

The macroscopic flow equations are obtained by instantaneous local equations of continuity and momentum and applied to 2EEM, with distinct governing equations to the fluid and to the solid material. The macroscopic model of the flow and the models of two energy equations are described in (Carvalho & De-Lemos, 2009).

In reason to describe the behavior of the fluid inside the porous media, the Local Thermal Equilibrium (LTE) cannot be applied, thus the model namely two-energy-equation (2EEM) is used to handle the problem under studying. The macroscopic flow equations are obtained by instant local equations of continuity and momentum and applied to 2EEM, differentiating the solid material and the fluid. The macroscopic flow model and the two energy equation models are described in (Carvalho & De-Lemos, 2009), and are summarized as follows:

The permeability of the porous matrix is determined using the Equation (1),

$$K = \frac{\phi^3 \cdot D^2}{144 \cdot (1-\phi)} \qquad (1)$$

Where, ϕ is porosity and d_p porous diameter. For steady-state conditions, we consider the fluid and the solid phase energy balance Equations (2) and (3):

Fluid: $$\nabla \cdot (\rho_f \, c_{pf} \, \mathbf{u}_D \langle \overline{T_f} \rangle^i) = \nabla \cdot \left\{ \mathbf{K}_{eff,f} \cdot \nabla \langle \overline{T}_f \rangle^i \right\} + h_i a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \quad (2)$$

Solid: $$0 = \nabla \cdot \left\{ \mathbf{K}_{eff,s} \cdot \nabla \langle \overline{T_s} \rangle^i \right\} - h_i a_i \left(\langle \overline{T_s} \rangle^i - \langle \overline{T_f} \rangle^i \right) \quad (3)$$

where, a_i is the interfacial area per unit volume, h_i is the film coefficient for interfacial transport, $\langle T_f \rangle$ fluid temperature, $\langle T_s \rangle$ solid temperature, $\mathbf{u}_D$ Darcy velocity vector, ρ density, $\mathbf{K}_{eff,f}$ and $\mathbf{K}_{eff,s}$ are the effective conductivity tensors for fluid and solid, Equations (4) and (5) respectively, given by:

$$\mathbf{K}_{eff,f} = \left\{ \underbrace{\phi k_f}_{conduction} \right\} \mathbf{I} + \underbrace{\mathbf{K}_{f,s}}_{local\ conduction} + \underbrace{\mathbf{K}_{disp}}_{dispersion} \quad (4)$$

$$\mathbf{K}_{eff,s} = [(1-\phi) k_s] \, \mathbf{I} + \mathbf{K}_{s,f} \quad (5)$$

In Equations (4) and (5), $\mathbf{I}$ is the unit tensor and k_f/k_s the fluid and solid conductivity. The numerical correlation for the interfacial convective heat transfer coefficient in laminar flow, proposed by (Carvalho & De-Lemos, 2009), is demonstrated in Eq. 6.

$$\frac{h_1 D}{k_f} = \left(1 + \frac{4(1-\Phi)}{\Phi}\right) + \frac{1}{2}(1-\Phi)^{\frac{1}{2}} Re_D Pr^{\frac{1}{3}} \quad (6)$$

The equation is valid for 0.2 < Φ < 0.9, where Φ is the permeability of the medium, the relationship between the porosity, the particle diameter (D) and the permeability of the medium (K), can be given by Equation (7) and Darcy (Da) given by Eq. (8), where H is the characteristic length (Chen, et al., 2017).

$$D = \sqrt{\frac{144K(1-\Phi)^2}{\Phi^3}} \quad (7)$$

$$Da = \frac{K}{H^2} \quad (8)$$

The improvement and optimization of thermal cycles and their components can be accomplished by maximizing the exergy or minimizing the entropy generation. The method of Entropy Generation Minimization (EGM) is a widely used approach that applies thermodynamic relations to compute irreversibilites related to the heat transfer and pressure drop. For this, the entropy generation number ($\mathcal{N}_S$) is used, represented in Eq. 9.

$$\mathcal{N}_S = \frac{\dot{S}_{gen}}{\dot{m} cp} \quad (9)$$

Where $\dot{m}$ represents the mass flow, cp the heat capacity of air and the entropy generation rate (S_{gen}) is described in (Bejan, 1995). From the entropy generation number, the optimal nuclear core arrangement can be found, related to the Reynolds number of the porous medium, described in Eq. 10.

$$Re_{Dp} = \frac{U_D D_p}{V_f(1-\mathcal{E})} \qquad (10)$$

The study presented by (Chen, et al., 2017), where experiments and numerical analysis with fuel spheres were conducted, analyzing the local characteristics of heat transfer and presenting the variation of the $\mathcal{N}_S$ for different porous diameter. However, the authors do not used computer fluid dynamics (CFD) techniques and did not took into account the interaction of the porous matrix with the fluid. Many other studies perform numerical simulations through CFD approaches under different flow fields, different models of turbulence and sphere distribution [5-8]. In addition, studies on thermodynamic analysis have also been reported (Laguerre, et al., 2008).

The evaluated model was based on the High Temperature Reactor (HTR-PM) project that aims to generate 250 MW of dissipated heat, as described in Chen and Lee (2017). The contour conditions and properties of the solid and the fluid are described in Table 1.

Table 1 – Properties and boundary conditions

Sphere temperature	1850 (K)
Inlet fluid temperature	500(K)
Core Diameter	10 (mm)
Core Length	1.00 (m)
Thermal Conductivity of the solid (k_s)	2.55 (W/m.K)
Thermal conductivity of air (k_f)	1.387 (W/m.K)

The arrangement evaluated, consists in a tube of 1 meters length, 10mm internal diameter, with constant wall temperature of 1850 K, the fluid enters in the channel at 500K, as it can be seen in Figure 2.

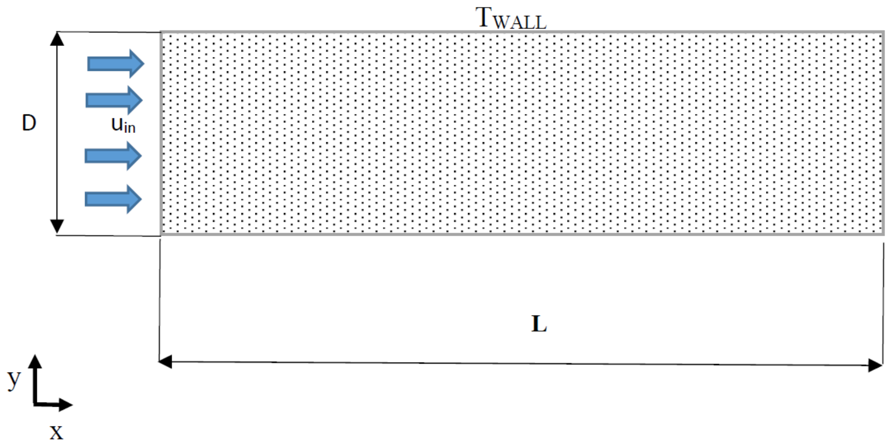


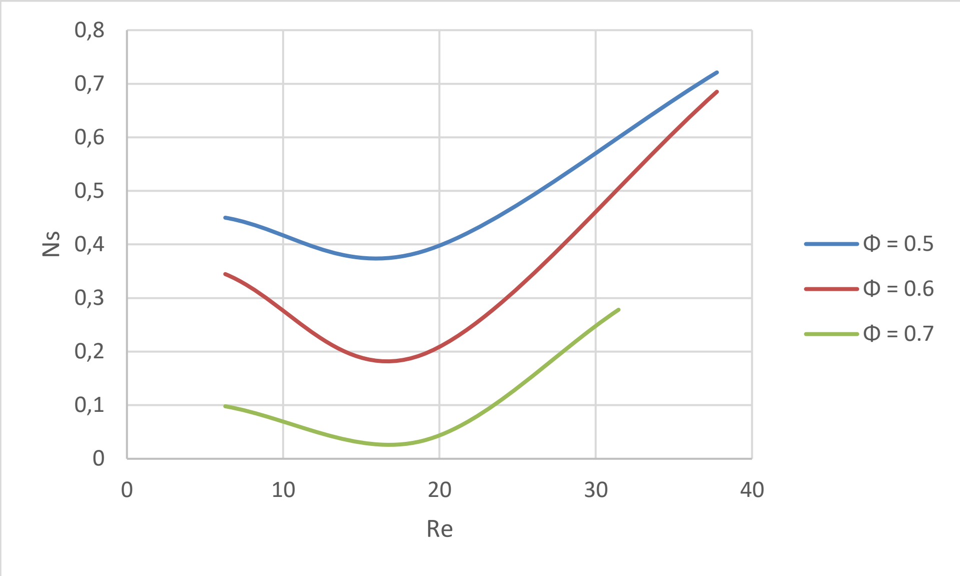
Figure 2 - Sketch evaluated

This set of partial differential equations were solved based on the finite volume method. For the mesh independence study, 100x100 and 200x200 grid sizes were applied, and a variation of the heat transfer rate smaller than 1% was found between meshes. Therefore, this study will apply the 100x100 grid as a manner to save computational time. The convergence criteria for all variables were set to 10-9. The SIMPLE method of Patankar (1980) was used to the handle the pressure-velocity coupling and applied for relaxing the systems of algebraic equations. The procedure for code validation and simulations employed here are the same used by (Carvalho & De-Lemos, 2009), or say, computations results are compared with analytical data shown in (Chen, et al., 2017).

3. Results and Discussion

The results encompass the variation of for different porosities under condition of a constant wall temperature. In the Figure 3, it is shown the result achieved for the variation of $\mathcal{N}_S$ with Reynolds Number in a porous media with Darcy Number equals to 10^{-7}, porosity of 0.5 and diameter of 0.00268m. It can be noticed that, at Reynolds 12 it is possible to achieve the minimum entropy generation, which indicates the optimum Reynolds for the system.

Figure 3 - Variation of the $\mathcal{N}_S$ with Re_{DP}



However, CFD techniques with the two energy equations method combined with the EGM approach can be used as a design tool, in order to reduce thermodynamic irreversibilites intrinsic related to the nuclear core arrangement. Therefore, applying both techniques, it is possible to better understand the dynamics of the system, and to propose an optimum configuration of porosity and pore diameter that enables the improvement of the final efficiency of the nuclear reactor.

4. Conclusion

By considering the core of the reactor as a porous matrix, it was possible to use the model of two energy equations to evaluate the thermal-hydraulic performance of the porous matrix and the fluid. Also, the Entropy Generation Minimization approach was used, aiming the optimization of the nuclear core. Thus, via thermodynamic irreversibilites minimization, an optimum porosity and pore diameter at various temperatures of the fuel sphere can be found. It is expected that these optimized nuclear core arrangements provide an increase of efficiency of this IV Generation Nuclear power plants.

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