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Effect of Boundary Layer Formation on Energy Interaction Between Fuel Pebbles in Gas Cooled Nuclear Reactors

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Abstract. Gas cooled Nuclear Reactors with the fuel pebble arrangement will create a great efficiency in the power generation. Helium as a coolant is more effective in exchanging heat between fuel pebbles and the coolant and maintains good advection ratio in the core. However, one of the more important points in nuclear power generation is to increase the heat production rate as much as possible. But, in real life, all nuclear reactors are bound in their maximum efficiency by the Carnot cycle. Hence, the only thing that can be done is to increase the heat transfer gradients in order to help increase the overall efficiency of the heat production system in a nuclear reactor. One of the most effective ways of increasing the heat transfer capacity to a flow is to utilize turbulence and therefore increase the amount of heat that is being transferred from the fuel pebble, which is undergoing the fission reaction, to the coolant itself. Naturally, various adverse pressure gradients which will become predominant in energized turbulent boundary layers, will also have to be taken into account. This paper will address the effect of boundary layer formation on energy exchange and heat interaction within the core. Moreover, the flow conditions that are designed over the fuel pebbles with grater turbulence will help to improve the energy exchange between the nuclear fuel pebble and the coolant. In this paper, we will demonstrate the added heat ratios with the help of CFD simulations with Helium as the coolant and it will address the effectiveness of energy exchange with the help of boundary layer formation over nuclear spherical fuel pebbles in gas cooled reactors.

Keywords: Fuel Pebble, Helium, Gas Cooled Rector, Thermal Boundary Layer, Velocity Boundary Layer, Energy Density.

1. Introduction

One of the most important things in our world is to have more energy to meet our domestic and industrial needs. In the 21st century, the amount of electricity that is used has more then quadrupled around the world as compared to 1930's. Due to this, more and more innovative energy production methods are being utilized to produce the electricity that is needed by the civilization. Due to limitations in the efficiency of renewable energy sources and also due to the problems associated with fossil fuel sources, nuclear energy still remains one of the more viable options for creating electricity. Especially with the advancements in the last decade, more safer and more efficient means of creating electricity from a nuclear fission reaction has become possible. Especially, the advent of Generation IV reactors, along with safer methods of electricity production through gas cooled nuclear reactors; seem to be gaining more interest in these past few years.

A significant concept in nuclear power production is to increase the amount of heat generated in the reactor itself. Due to limitations in the thermodynamic cycles, the best ideal efficiency which can be obtained is the Carnot cycle, which depends on the gradient between the highest temperature and the lowest temperature in the system [5]. Due to logistical limitations in the location placement of nuclear reactors, there is actually not much that can be done to improve this efficiency level. The coolest temperature will be the outside sea level average temperature of 17 C, while the highest temperature will depend on the nuclear fuel rods and the nuclear kinetics that are used in the nuclear reactor itself [1].

One such way to increase the amount of heat transfer that takes place inside the nuclear reactor would be by improving heat absorption to the coolant for prime moving [9]. Even though it may not be possible to increase the heat generation in the nuclear reactor itself; it can be possible to increase the amount of heat that is passed from the heat source (nuclear fission reaction that is taking place in the nuclear fuel rods). This is a significant way of improving the heat capacity in the nuclear reactor as one of the biggest problems in any heat production system is to transfer the heat to the coolant. Once the coolant becomes hot enough, then the coolant can be circulated through a turbine system to produce electricity [4]. However, the issue is the fact that the amount of heat that can be transferred will depend on the conduction, convection and the radiation capacity of the heat source, as well as the heat transfer properties of the coolant in contact with the heat source itself. In nature, it is rarely possible to utilize the full extent of the heat transfer properties of the material itself and nuclear reactors are not an exception to this general situation [14]. In gas cooled Nuclear Reactors with fuel pebble as a fuel mode; the helium cooling system is considered for the analysis. In Figure1, the effect of boundary layer formation on the flow over a spherical fuel pebble can be seen.

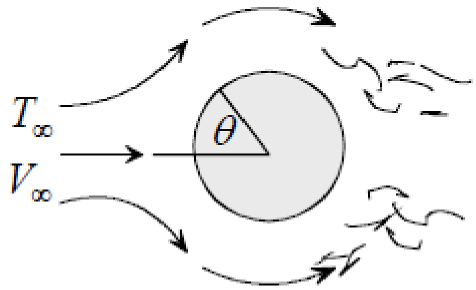


Fig. 1: Flow over the Spherical Fuel Pebble

This paper discusses the possibility of using turbulent flow and the corresponding boundary layers to help increase the amount of heat transfer from the nuclear fuel source to the coolant. Due to its nuclear kinetic characteristics as well as the dynamic characteristics, helium cooled nuclear reactor system is used as a case study and spherical nuclear fuel elements are used as the heat source. The kinetics of the fission reaction is not taken into account, as steady state fission kinetics is assumed. The general thermal and velocity boundary layer equations are considered and CFD simulations of a single fuel element are also included to help support our conclusions.

2. Heat Transfer from a Spherical Fuel Element to Helium in Nuclear Reactors

The main thing that concerns the design of a nuclear reactor is the transfer of heat to the coolant. In this, there are three modes of heat transfer which takes place. The first mode of heat transfer is conduction which takes place due to physical contact. The second and third modes of heat transfer are convection and heat radiation and these modes of heat transfer work at larger distances [7]. In this paper, spherical fuel elements are taken as a heat source in a nuclear reactor and the coolant is diatomic helium. The following table gives the operating and boundary conditions for this problem.

TABLE I: Design Parameters of Gas Cooled Reactor

Operating Parameters	Value
Coolant Temperature	950^0 C
Fuel Temperature	1600^0 C
Helium Flow Rate	320 kg/s
Thermal Power	850 MW(t)
Core Height	700 cm
Efficiency Rate	48 %
Diameter of Fuel Elements	60 mm
Avg. Heat Density	32 MW/m^3

2.1. Conduction in a Spherical Fuel Element

The main source of the fission reaction in helium cooled reactors is the conduction of heat from the fission reaction in the fuel elements to the coolant itself. The contribution of flow dynamics in the heat transfer between the fuel pebbles and the coolant will be expressed as:

$$T_f = \frac{(\overline{T_s} + T_\infty)}{2} \quad (1)$$

$$Nu_x = \frac{h_x}{k} = 0.030(\mathrm{Re}_x)^{\frac{4}{5}} \mathrm{Pr}^{\frac{1}{3}} \quad (2)$$

$$\overline{Nu}_D = \frac{\overline{h}D}{k} = 0.3 + \frac{0.62\,\mathrm{Re}_D^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}}\left[1+\left(\frac{\mathrm{Re}_D}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \quad (3)$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k \frac{\partial T}{\partial r}\right) + \dot{e}_{gen} = \rho c \frac{\partial T}{\partial t} \quad (4)$$

2.2. Convection in a Spherical Fuel Element

Convection holds a great importance since it allows the heat to be transferred to larger distances as compared to conduction. Especially in a nuclear reactor, convection can help increase the amount of heat that is transferred to the coolant after the fission reaction [10]. In fact, convection is one of the main modes of heat transfer that can be influenced by the design of the core, so that maximum amount of heat is transferred to the coolant gas or helium as it has been taken in our case study. The equation which holds true for a convection analysis in a spherical fuel element with helium as the coolant gas is expressed as:

$$C_{P_g \rho_g \varepsilon_g} \frac{DT_g}{D_t} = -P_g\left(\frac{\partial}{\partial x_i}\varepsilon_g v_{gi} + \frac{\partial}{\partial x_i}\varepsilon_g v_{si}\right) + \frac{\partial}{\partial x_i}\left(\varepsilon_g k_g \frac{\partial T_g}{\partial x_i}\right) + \alpha(T_s - T_g) + \overline{\Gamma}_{wg}; \quad (5)$$

$$c_{p_s}\rho_s\varepsilon_s \frac{DT_s}{Dt} = \frac{\partial}{\partial x_i}\left(\varepsilon_s k_s \frac{\partial T_s}{\partial x_i}\right) + \alpha(T_g - T_s) + \overline{\Gamma}_{wg} + S_f \quad (6)$$

2.3. Radiation in a Spherical Fuel Element

Even though a fission reaction is taking place, it must be understood that the nuclear fuel elements are also acting as a heat source, so also heat transfer by heat radiation will also take place inside the reactor core [2]. This radiation will also be consequential in increasing the overall heat transference to the coolant gas of Helium [11]. For a spherical fuel element with the dimensions given in our case study with helium as a coolant, the heat transfer through radiation would be expressed by:

$$-k\frac{\partial T(L,t)}{dx} = \varepsilon_2 \sigma [T(L,t)^4 - T^4{}_{surr,2}] \quad (7)$$

$$-kA_r \frac{dT}{dr} = \dot{e}_{gen} v_r \quad (8)$$

3. Boundary Layers on Spherical Fuel Elements

In any viscous flow situation, the formation of a boundary layer around a uncompounded solid object in a free flow is inevitable. The boundary layer is actually the physical location where the mass and the heat transfer takes place. In the boundary layer, the viscous effects of the flow will be felt fully and the amount of mass transfer and the heat transfer that takes place will be maximum [13]. The formation of the velocity boundary layer along with the thermal boundary layer will need to be analyzed in order to understand the full viscous interaction between the flow and the spherical fuel element. The formation of the momentum boundary layer also needs to be calculated, so that the total amount of momentum displacement can be calculated as well [6]. The calculation of these would give the exact shape and the exact configuration of the boundary layer, which will be helpful in understanding the total amount of heat transfer that is augmented [8]. The momentum exchange at the boundary layer between the fuel pebbles and helium is expressed as:

$$\frac{\partial}{\partial t}(\varepsilon_k \rho_k v_{kt}) + \frac{\partial}{\partial x_j}(\varepsilon_k \rho_k v_{ki} v_{kj}) = -\varepsilon_k \frac{\partial \rho_g}{\partial x_i} + \varepsilon_k \rho_k g_i + \beta(v_{ki} - v_{ki}) \frac{\partial}{\partial x_i}(\tau_{k_{ij}}) - \Gamma_k \quad (9)$$

It is a well known fact that turbulent boundary layers are more effective in energizing the flow and as a result, the kinetic energy of the flow can be maximized within the operating conditions and more importantly the amount of heat transferred through collisions of the particles of the flow will also increase as compared to laminar flow conditions with a laminar boundary layer [3]. Naturally, the randomized nature of the turbulent flow conditions and the turbulent boundary layers will create other problems, but it is possible to contain these problems, while maximizing the flow conditions, in order to make it more favorable for heat transfer from the spherical fuel element to the coolant in the nuclear reactor [12].

4. CFD Analysis of Boundary Layers on Heat Transfer in Nuclear Fuel Element

The conclusions reached above are shown below with the various CFD simulations which have been executed with the conditions set in Table 1. The standard size nuclear fuel element has been taken into account and the standard operating conditions for a helium cooled nuclear reactor with spherical fuel elements is taken as boundary conditions as well as initialization conditions. The system is drawn with GAMBIT and the post processing is done using Fluent. During the simulations, an error control criterion of 10^{-6} is used and it is also acceptable by nuclear kinetics standards for gas cooled reactors. In order to account for the boundary layer, both the far field and the near field has been meshed appropriately with 3:1 ratio for best results.

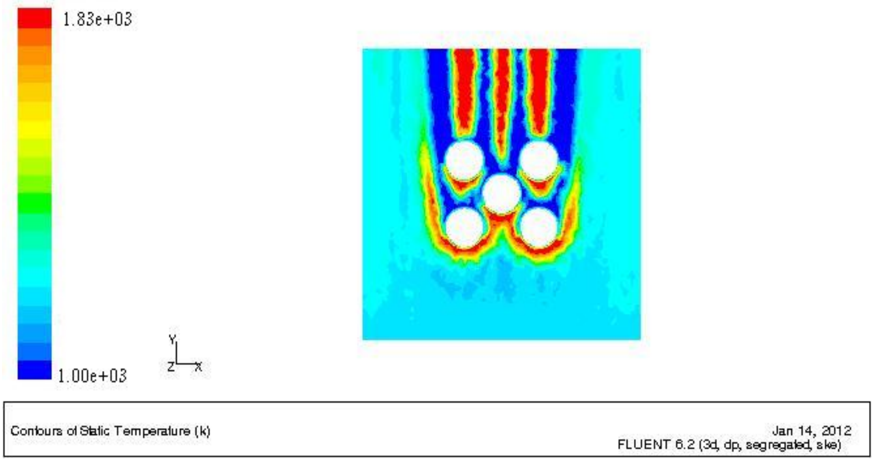
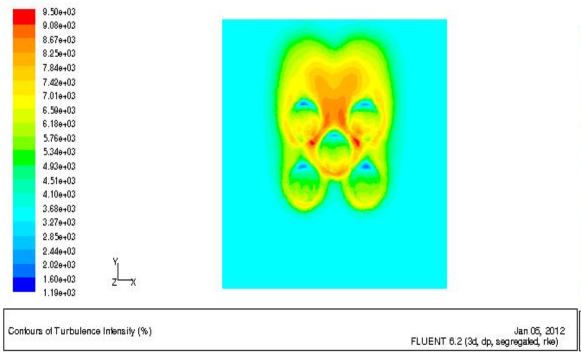


Fig. 2: Static Temperature in Spherical Fuel Pebble after Boundary Layer Interaction

The main objective of this work is to examine the change in heat exchange between the nuclear fuel pebbles and Helium with the improved turbulence in the flow. The operating temperature of the nuclear reactor is designed for 1223 k, in order to create greater amounts of enthalpy; the outer surface of fuel pebble is maintained at the temperature of 1873 k. The results obtained from the Computational fluid dynamic analysis clearly indicate the grater temperature developments with the help of static temperature contours. The variation of the temperature is observed with respective to the core of the reactor and the crust of the fuel pebble where critical operational conditions are considered. Due to the critical operation conditions at the nuclear reactor, the static temperature can reach the level of 2000 k under certain conditions, where the boundary layer formation affects the total temperature in between the range of 100-200 k. This indicates the development of greater efficiency of the system along with the improvement of the design conditions. The energy intensity counters in the Figure 4 indicates the energy exchange, where flow is dwelling on the grooves of the fuel pebbles and the reaction rate at which energy exchange is taking place. The intensity of turbulence increase in the system can be observed from the below Figure 3, as this will help us in interpretation of turbulence and energy exchange where boundary layer is effecting the flow conditions.



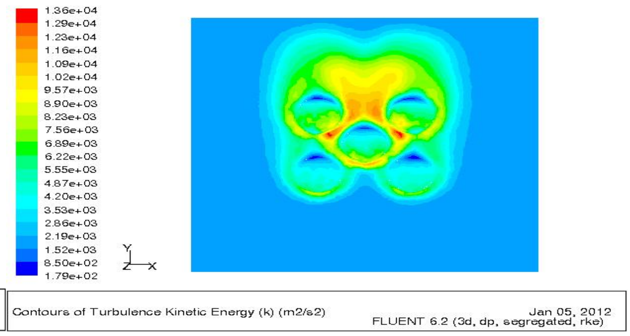


Fig. 3: Turbulence Intensity Contours

Fig. 4: Turbulence Kinetic Energy Contours

The total turbulence kinetic energy interaction which is also relatively effected by fission kinetics indicates the effective pressure distribution around the pebbles with boundary layer formation on the centred crust. The operating pressure of the reactor is maintained at 7.45 Mpa, where two compressors are employed to supply the helium with a 320 m/s flow rate. In order to maintain the inlet temperature at mean level pre cooler and inter cooler is employed to improve heat absorbing capacity at the core. Depending upon the pressure inside the core, the shear layer deflects upward by producing a compression due to the gap arranged between the fuel pebbles. As the boundary layer separates from the leading edge of the pebble system, a free shear layer forms, where we can observe the adverse pressure gradient caused by a pressure rise in the reactor is governing the flow. Static temperature for the reacting flow on the lower and upper wall is quite different due to these changes. However, it would also be helpful to mention the Karman Vortex Street oscillations, which will take place inside the coolant chamber of the nuclear reactor. The effect of these oscillations on the stability of the fission kinetics will need to be carried out in a separate study to see whether core criticality is affected in any significant way. In order to observe these changes, a microscopic numerical analysis also needs to be carried out with different operating conditions.

5. Conclusion

As it can be seen from the CFD simulations and the explanations provided above, the flow itself is energized at the boundary layer itself, as the effects of viscosity are maximized within the boundary layer. Hence, this inadvertently causes the thermal boundary layer to work in favor of this process, as the amount of heat that is transferred from the fission reaction to the coolant is increased by the turbulent kinetic energy induced by the turbulent boundary layer. In order to induce turbulent boundary layer formation, small rough edges can be integrated into the spherical fuel elements. Moreover, this will also have the effect of increasing the amount of convection and conduction as well. By proper analysis and simulation of the effect of turbulent boundary layers on the flow of the coolant over fuel elements, it will be possible to design highly efficient nuclear power reactors. Moreover, due to these properties, it can be possible to design inherently safe nuclear reactor cores which can be safe even under critical coolant circulation failure. Especially after the Fukushima incident, it is important to focus on these types of designs for inherent safety along with more efficient heat generation. It is recommended that further simulations are carried out along with the fission kinetics of helium cooled reactors for a better design.

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7. Nomenclature

v	Velocity m/s
t	Time
g	Gravitational Constant m/s^2
T_s	Avg Surface Temperature
Nu	Nusselt Number
h	Dimensionless Heat Transfer Coefficient
q	Flux of fluctuation energy, kgm^{-1} s^{-3}
Pr	Prandtl number
Re	Reynolds number
p	Pressure, Pa (N m^2)
β	Fraction of all fission neutrons
d	Diameter, m

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