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THERMALHYDRAULICS ANALYSIS OF FIXED BED NUCLEAR REACTOR IN SOME DIFFERENT CONFIGURATIONS

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ABSTRACT: The Fixed Bed Nuclear Reactor (FBNR) is a small module reactor using the spherical fuel elements. It has a simple design, inherent safety features, passive cooling for some situations, and reduced environmental impacts. The key to the safety characteristic of FBNR is simply that the core will be become empty of fuel elements, and nuclear criticality situation will be stopped when any undesired situation occurs. Any signal from any of the numerous detectors, due to any accident event, will cut-off power to the pump, causing the fuel elements to fall back into the fuel chamber where they remain in a highly subcritical and passively cooled conditions. This mechanism helps the reactor has a very high passive safety. Therefore, FBNR is one kind of IV generation according to the International Atomic Energy Agency (IAEA) defines. However, it also makes difficulties for analytical methods to understand clearly about thermalhydraulics processes in the active core. In the paper, the authors used the Computational Fluid Dynamics (CFD) method to analyze the basic thermalhydraulics parameters of FBNR such as temperature distribution of spherical fuels, and temperature, pressure and velocity of the coolant in some different configurations. The results are highly accurate and visual, helping us to evaluate more exactly about the processes of heat generation, thermal conductivity and heat exchange between fuel elements and coolant water. Finally, we can choose the best configuration of FBNR.

KEYWORDS: FBNR; TRISO; CERMET; CFD; ThermalHydraulics

INTRODUCTION

After the accidents of nuclear power plants around the world, especially the Fukushima-Japan disaster in 2011. IAEA has supported for researches about small-capacity reactors. Their aims are trying to find out the safest solution for nuclear energy. Many small reactor technologies have been proposed and developed in some advanced countries such as the US, South Korea, Japan and China. In Vietnam, our research team at Electric Power University has colaborated with the research teams in Brazil and Turkey to work together on the FBNR. Currently, researches are being conducted at the optimal design stage for FBNR. The research team has given varied configurations for the active core of the FBNR and some results about reactor physics have published in international scientific journals. In this report, the authors will present calculations of thermalhydraulics for two different configurations of the FBNR.

MAIN CONTENT

Objects and Methods

FBNR is a light water reactor with small capacity and size. A completely different point of FBNR is the use of spherical fuel elements. The reactor consists of three separate parts: the active core at the center, the upper steam generator and the fuel chamber below. A cylindrical vessel is 2.14m in diameter, 6m in height, and 15mm in thickness. The vessel contains the active core and the steam generator, the active core is 1.7m in diameter and 2m in height [7].

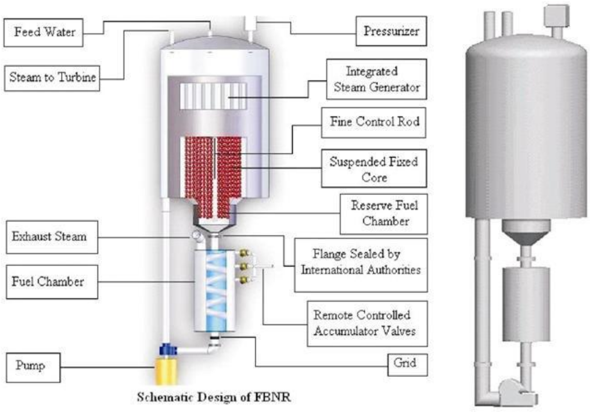

Figure1. Schematic design of FBNR.

There are two proposed ideas for the coolant flows through the active core, the first way is the coolant enters the active core from bottom and flows along the horizontal channels and goes up along the edges of the vessel; the second way is the coolant flows up in vertical direction and passes through the fuels, and goes straight to the steam generator.

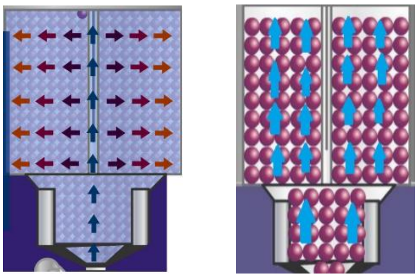

Figure 2. The first idea *(left)* and the second idea *(right)* of water flow goes through the core.

The circulating pump pushes the coolant at a rate of stable operation of 7.23m/s, corresponding to a mass flow rate of 1060kg/s, the fuel elements are held together by 0.188bar pressure, this pressure is 27.1 times their weight. The coolant flows through the active core, then absorbs the heat from the fuels and moves to the upper steam generator. The coolant then returns to the pump and thus forms a closed loop. When there is any unusual operation of the reactor, electricity will be disconnected from the pump and the coolant will stop circulating, the fuel elements will fall off the core according to gravity and be passively cooled in fuel storage chamber.

Simplified TRISO fuel element: Spherical fuel with a diameter of 15mm is enclosed in a SiC matrix and a stainless steel layer has a thickness of 0.5mm. TRISO are composed of 60% fuel UO_2 and 40% SiC matrix. UO_2 kernels with a diameter of 0.5mm are covered by a 0.1mm thick carbon shell. This carbon shell has the main task of storing fission products at high temperature. The densities of UO_2, Carbon and SiC are 10.97 g/cm^3, 1.0 g/cm^3, and 3.2 g/cm^3 respectively. The stainless steel 304 with density of 8.03 g/cm^3 is composed of 70% Fe, 19% Cr, and 11% Ni.

Table 1. Specifications of FBNR reactor

Parameters	Value	Parameters	Value
Thermal Power	218 MWt	Outer diameter of fuel element	15 mm
Electric Power	70 MWe	Number of fuel elements in the core	1,62 millions
Coolant	Light water	Fuel Enrichment	5%

Moderator	Light water	Fuel cycle	25 months
Thermodynamic Cycle	Rankine	Fuel Burnup	15.3 MWd/kg
Active Core Height	2 m	Mass flow rate	1060 kg/s
Core Diameter	1,7m	Operation pressure	16 Mpa
Power Density	45 MW/m^3	Inlet Temperature	290ºC
Fuel type	TRISO	Outlet Temperature	326ºC

In this research, the authors used the CFD method to calculate the heat generation processes in fuel elements, conduction of heat from fuel elements to water and the turbulent flow processes of water, as well as the pressure drop when water goes through the active core. CFD is based on physical theories such as the law of mass conservation, the law of energy conservation, the law of momentum conservation to build a system of partial differential equations that govern the transports of the water and heat exchange. This system of equations is often referred to the Navier-Stocks equation system. The finite element method (FEM) will then be applied to find the properties that govern the water flow such as velocity, pressure, flow rate [1].

The thermal conductivity equation in fuel elements depends on location and time as follows [4-5]:

$$\rho \times c_p\left(\vec{r},T\right)\times\frac{\partial T\left(\vec{r},t\right)}{\partial t}=\nabla\left(k\left(\vec{r},T\right)\nabla T\left(\vec{r},t\right)\right)+q'''\left(\vec{r},t\right) \tag{1}$$

Heat exchange formula between the fuel clad and the coolant:

$$\overrightarrow{q''}=h\left(T_w-T_b\right)\vec{n} \tag{2}$$

The coefficient h is determined through the formula Nusselt:

$$Nu=f\left(\mathrm{Re},\mathrm{Pr},Gr,\frac{\mu_w}{\mu_b}\right)=\frac{hD_H}{k}=0.023\,\mathrm{Pr}^{0.4}\,\mathrm{Re}^{0.8} \tag{3}$$

The formula determines the temperature of the coolant when it flows through the fuel region with the height of z:

$$\dot{m}c_p\int_{T_{in}}^{T_b(z)}dT=\int_{-L/2}^{z}q'(z)\,dz \tag{4}$$

Results

After constructing the correct model of fuel elements and active region with ANSYS ICEM CFD program, the whole model will be imported into ANSYS CFX program to take steps to set up calculation parameters and analyses.

The coolant flows along the horizontal channels

The coolant after entering the active core will flow into the horizontal channels, take heat from the fuel elements and then go to the edges of the vessel and go up to the steam generator. The diameter of the active core is 1.7m, therefore to ensure that the outlet water temperature reached 326°C, the research team analyzed with the values of different heat flux and used the various turbulence models.

Comparison between turbulent models:

There are four turbulent models used popular, namely: K-epsilon (K-E), Shear Stress Transport (SST), BSL Reynolds Stress (BSL) and SSG Reynolds Stress (SSG). To find out which turbulent model is the most appropriate, the authors used heat flux of 3.5MW/m^2, the results showed that Shear Stress Transport is consistent with the most natural phenomenon.

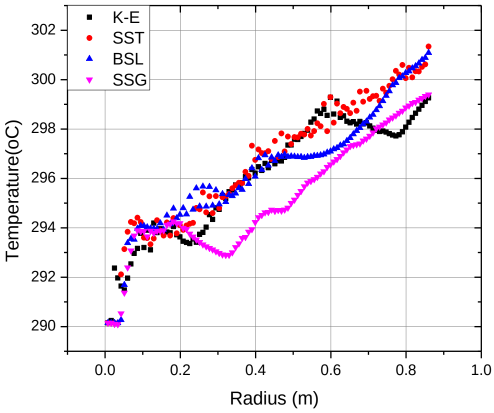

Figure 3. Temperature of coolant in a heat channel

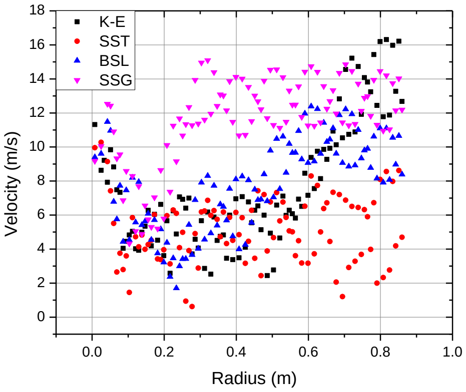

Figure 4. Velocity of coolant in a heat channel

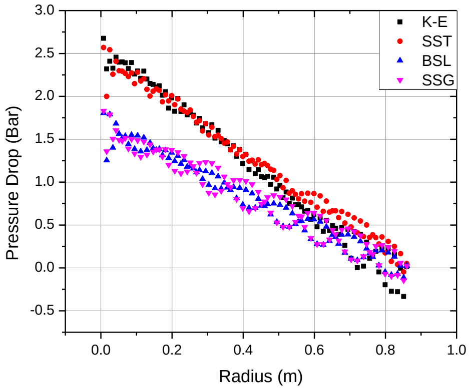

Figure 5. Pressure drop of coolant in a heat channel

Using SST model: We continue to carry out the analyses with values of heat fluxes are 10.2MW/m^2, 11.2MW/m^2 and 12.1MW/m^2, respectively. We obtained the following results:

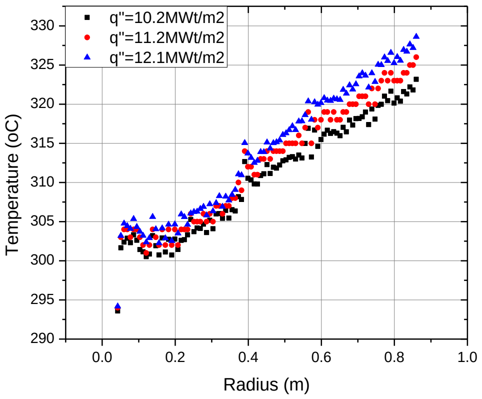

Figure 6. Temperature of coolant in a heat channel

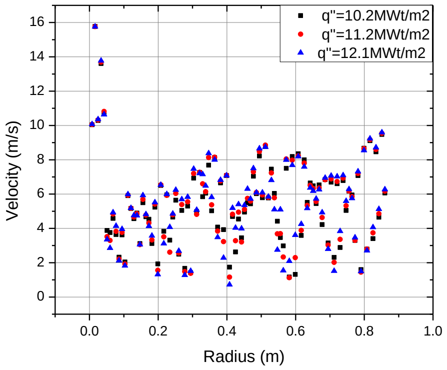

Figure 7. Velocity of coolant in a heat channel

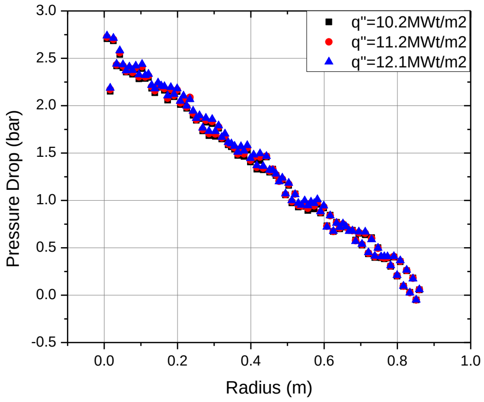

Figure 8. Pressure drop of coolant in a heat channel

After the analyses, we get a heat flux value of 11.2MW/m^2 that will match the requirement compared to the design of the FBNR reactor. The coolant is absorbed enough heat energy and reached 326^{o}C at the outlet.

Once all the results of the coolant are obtained, we continue to investigate the temperature distribution of the fuel elements. The results are as follows:

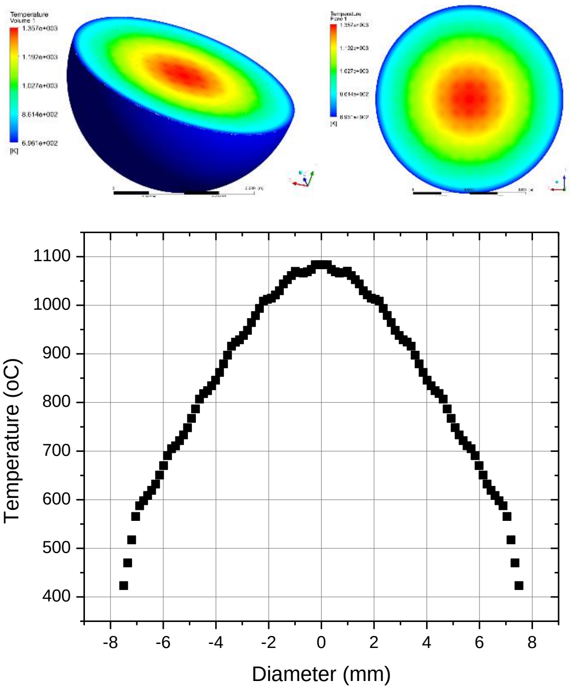

Figure 9. Temperature distribution of a fuel element

Table 2. Temperature value of fuel elements

Component	$T_{min}(^oC)$	$T_{max}(^oC)$	$T_{ave}(^oC)$
UO_2	586.1	1084.23	767.92
SiC	577.47	1079.19	727.28
SS304	423.14	590.27	499.89

From the results obtained, the average temperature of the UO_2 kernels is 767.92°C and the average temperature of the clad SS304 is 499.89°C. The melting point of UO_2 is 2850 °C [10], so we ensure that UO2 fuel elements will be safe during operation conditions. The pressure drop when the coolant flows fuel elements in the horizontal channel is 2.75 bar. The change of pressure over the core is also in the safety margin of the materials.

The coolant flows vertically through the active core

Regarding the second configuration, the coolant will go straight through the core, take heat energy from the fuel elements and then flow to the steam generator.

By analyzing with different levels of heat flux values, the authors have determined the value of the appropriated heat flux is $q'' = 3.06$ MW/m^2. The results are similarly presented with the first case above [2-3].

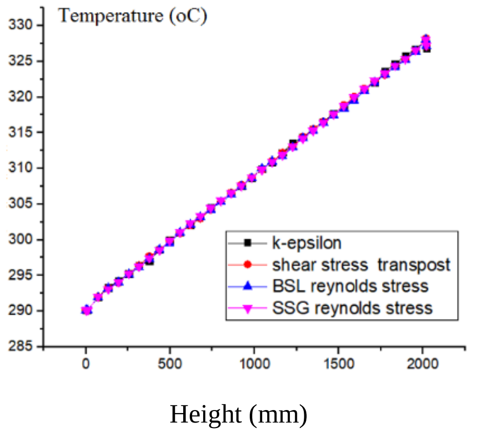

Figure 10. Temperature of coolant in a heat channel

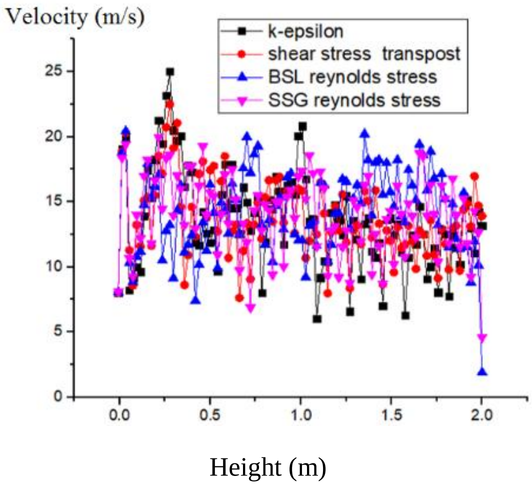

Figure 11. Velocity of coolant in a heat channel

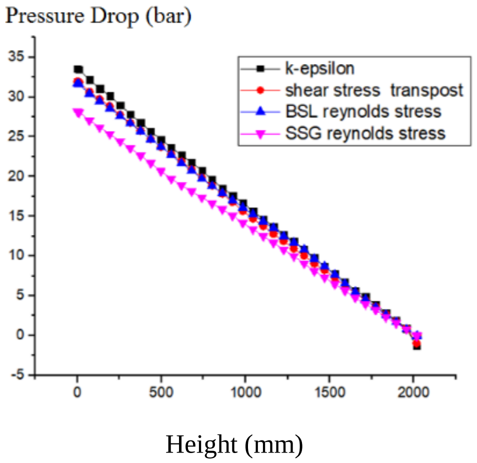

Figure 12. Pressure drop of coolant in a heat channel

Considering the heat source, the coolant can receive enough heat energy and reach an outlet temperature of 326ºC, we see that in the case of horizontal channels, it is necessary to provide a heat flux of 11.2 MW/m^2. This value is approximately four times greater in comparison with water flows in a vertical channel, 3.06MW/m^2.

Similarly, once all the temperature distribution of the coolant are obtained, we continue to investigate the temperature values of the fuel elements.

Table 3. Temperature value of fuel elements

Component	T_{min} (°C)	T_{max}(°C)	T_{ave}(°C)
UO_2	388.90	458.67	419.80
SiC	386.81	457.87	412.90
SS304	339.57	390.03	362.71

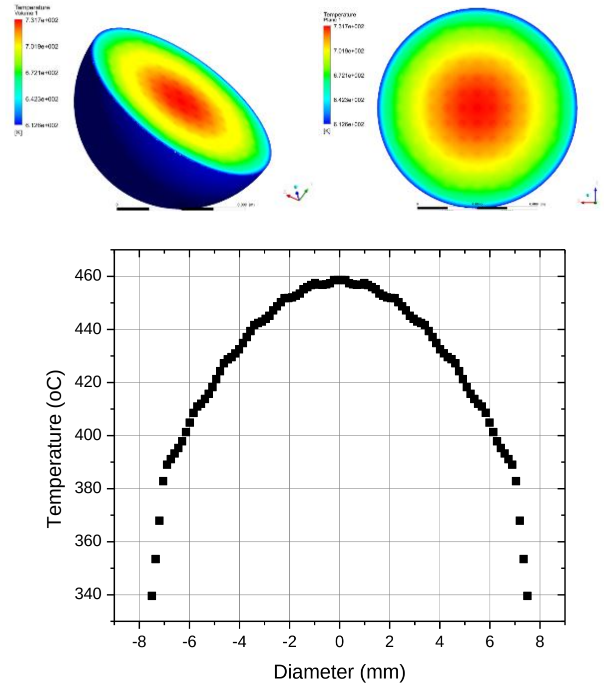

Figure 13. Temperature distribution of a fuel element

From the results obtained in table 3, the average temperature of the UO_2 kernels is 419.80°C and the average temperature of the clad SS304 is 362.71°C. The maximum temperature of UO_2 is only 458.67°C, this value is very far from melting point. However, the pressure drop when the coolant flows fuel elements in the vertical channel is 32bar. This value is high, however, the safety of materials is still maintained.

Comparing the temperature values of fuel elements between the two configurations is shown in Figure 14.

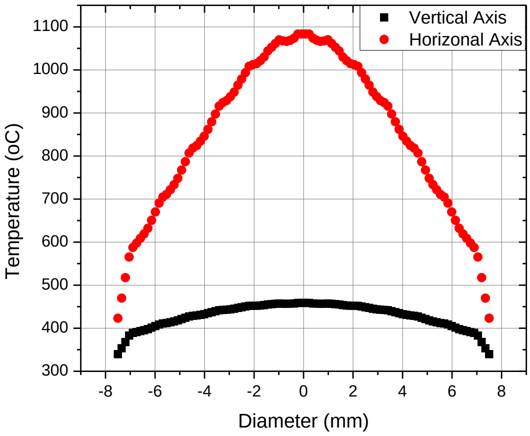

Figure 14. Temperature distribution of a fuel element

From Table 2, Table 3 and Figure 14, we can see a significant difference in the temperature of the fuel elements. In case of water flows into the horizontal channels, the temperature of the fuel is very high, whereas for the case of water flows through the vertical channels, the temperature of the fuel is smaller. Obviously, the second configuration get the higher safety levels. Besides, there are considerable difference in the pressure drop of the coolant between two layouts because of the gravity and the length of the channels.

CONCLUSION

From the results obtained, the authors have made some comments as follows:

CFD method is the advanced method, suitable for the thermalhydraulics analyses in the field of general nuclear power. The results obtained from this method are very intuitive and highly accurate.

The values of temperature, pressure drop and flow velocity of coolant and fuel elements in FBNR reactor in operation conditions are under safety limits. Even when the reactor operates with the higher powers, the parameters are still ensure below the melting points of the material components, as well as the safety of the stress when considering the total pressure drop.

From the above results, the research team encourages the operation of the FBNR reactor with the second configuration, in which, the coolant will be pumped into the active core from the bottom, and then the coolant flows along the vertical heat channels. This makes the temperature values of the fuel elements become lower, from which the FBNR reactor will be reached the safer states.

In the future, the research team will continue to calculate with the different operation conditions and when unexpected events occur to see if the characteristics of FBNR reactor are exceeded the safety limits. The authors hope that the results from the paper will contribute a clearer aspect about the safety of the FBNR reactor.

NOMENCLATURE

c_p: Specific heat, J/(kg.K)

k: Thermal conductivity, W /(m.^{o}C)

h: Heat transfer coefficient, W/(m^2. ^{o}C)

ρ: Density, kg/m^3.

T: Temperature, ^{o}C.

q': Linear heat-generation rate, W/m.

q'': Surface heat flux, W/m^2.

q''' : Volumetric heat generation rate, W/m^3.

Re: Reynolds Number.

Pr: Prandtl Number.

Nu: Nusselt Number.

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