Neutronic modelling of nanofluids as a primary coolant in VVER-440 reactor using the Serpent 2 Monte Carlo code

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Abstract. The nanofluids as an engineered fluid offer a large enhancement in heat transfer, in particular for boiling heat transfer and critical heat flux. These features lead to increase the power density of the nuclear reactor. In this paper, we investigate the neutronic simulation of nanofluids as a primary coolant in VVER-440 reactor and study the availability of using it without changing the system characteristics. The analysis of nanofluid fuel assembly is performed by using Serpent code. As a result of changing effective multiplication factor of the six types of nanoparticles which have been studied extensively for their heat transfer prosperities and absorption cross sections including Al₂O₃, Si, Zr, TiO₂, CuO, and Ti with different volume fractions, it can be concluded the optimum nanoparticles are alumina at concentration 0.01 volume fraction.

1. Introduction
Many studies have investigated heat transfer enhancement by replacing base fluid with a nanofluid [1-3]. The various applications of using nanofluids in the reactor have could be shown as the following [4]:

- Primary reactor coolant for pressurized water reactors (PWRs) / (VVERs).
- Coolant for the emergency core cooling system (ECCS) of both PWRs and boiling water reactors.
- Coolant for in-vessel retention of the molten core during severe accidents in high-power-density light water reactors.

The numerical and experimental studies have shown that nanofluids have a higher critical heat flux (CHF) and lead to improvement in a minimum departure from nucleate boiling ratio [5]. This feature leads to increase the power density with a considerable value which is very attractive economically. From the neutronic’s point of view, many studies discussed the effect of using nanoparticles on the neutronic characters and how they effect on the system [6-8].

In this study, neutronic analyses of nanoparticles in the primary coolant for a VVER-440 reactor using serpent are investigated. The main purpose for the neutronic analysis is to study the effect of the nanoparticles on the neutronic system and investigate the ability of using it without changing the
system characteristics. The considered nanofluid is a mixture composed of water and particles of Al₂O₃, Si, Zr, TiO₂, CuO and Ti with different volume concentrations.

2. Methods and materials
Among variety of nanofluids available for our objective, we considered the nanoparticles with low thermal neutron absorption cross section. The modelling has been investigated using serpent2 code.

2.1. Fuel assembly modelling
The VVER-440 Model V230 was the most common design, delivering 440 MW of electrical power. Recently there VVER-440 reactor exists in four countries: Russia, Bulgaria, Germany and Slovakia. The V230 has six primary coolant loops each with horizontal steam generators. For the fuel assemblies design, The VVER-440 fuel assembly has a hexagonal shape and contains 126 fuel rods. All the rods in an assembly are of the same enrichment. The distance of the centrelines of the assemblies is 14.4 cm. All together 349 assemblies can be inserted into the reactor core and 312 out of these are fuel assemblies [9]. The simulation of the VVER-440 fuel assembly is shown in Figure 1.

2.2. Applying nanoparticles
The all six types of nanoparticles have been applied in the fuel assembly with different volume fractions (0-0.1). The density of the nanofluid mixture using formula (1) for the six types has been calculated using the characteristics of nanoparticles which is shown in table 1 [10].

| Nanoparticle | Name            | ρ(g/cm³) |
|-------------|-----------------|---------|
| Al₂O₃       | Alumina         | 3.90    |
| Si          | Silicon         | 2.33    |
| TiO₂        | Titania         | 4.25    |
| CuO         | Copper oxide    | 6.50    |
| Zr          | Zirconium       | 6.49    |
| Ti          | Titanium        | 4.50    |

The simulation has been investigated in case steady state.
\[ \rho_{nf} = (1 - \varphi) \rho_{bf} + \varphi \rho_{np}, \]  

where, \( \rho_{nf} \): the density of the nanofluid; 
\( \rho_{bf} \): the density of the base fluid (water); 
\( \rho_{np} \): the density of the nanoparticles; 
\( \varphi \): the volume fraction of the nanoparticle in the fluid.

3. Results

As shown in Figure 2 the results of infinite multiplication factor study show that by increasing the amount of nanoparticles, the \( K_{\text{eff}} \) will drop; however, there is a different response for different types of nanoparticles.

The decreasing in \( K_{\text{eff}} \) is much more for cupric oxides nanoparticles and less for Alumina nanoparticles. These phenomena could be explained by the density and absorption cross-section of relevant nanoparticles \([11-12]\).

Among all types of nanofluids, the Titanium has the highest and Al\(_2\)O\(_3\), has the lowest. By increasing the amount of nanoparticles, the rate of moderation will be reduced.

![Figure 2. Effective multiplication factor with different volume fractions.](image)

4. Conclusion

Analysis of a VVER-440 fuel assembly using nanofluid as the base coolant is performed by neutronic model. In previous studies that nanofluid substitution with water coolant in VVER-1000 has shown to enhance the heat transfer coefficient. In this study we aimed to investigate the neutronic simulation of Al\(_2\)O\(_3\), Si, Zr, TiO\(_2\), CuO, and Ti water-based nanofluid application in vver-440 fuel assembly to study how they effect on the neutronic system.

The results showed that by increasing the volume percentage of nanoparticles, the \( K_{\text{eff}} \) would be severely reduced. Unlike the others, it can be concluded that the \( K_{\text{eff}} \) has a gentler slope with Al\(_2\)O\(_3\), Zr and Si by using those three nanoparticles below 1% vol the criticality would be better. Despite the neutronic characteristic of silicon because of its low thermal conductivity, alumina is preferred in nuclear power application.

For the safety concern, the temperature coefficient of reactivity for the Al\(_2\)O\(_3\) is required to be calculate. Besides, further thermalheuydrullaic and corrosion studies are recommended.
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