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ORIGINAL PAPER

Neutronic analysis of nanofluids as a coolant in the Bushehr VVER-1000 reactor

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Abstract. The main goal of this study was to perform the neutronic analysis of nanofluids as a coolant in reactor simulation. The variation of multiplication factor and thermal power have been investigated in the Bushehr VVER-1000 reactor core with using different nanofluids as coolant. In the applied analysis, water-based nanofluids containing various volume fractions of Al_2O_3, TiO_2, CuO and Cu nanoparticles were used. The addition of different types and volume fractions of nanoparticles were found to have various effects on reactor neutronic characteristics. By using WIMS-D5 and CITATION code, the appropriate nanofluid with optimum volume percentage of nanoparticles was achieved. The results show that at low concentration (0.1% volume fraction) alumina is the optimum nanoparticle for normal reactor operation.

Key words: nanofluids • neutronic analysis • VVER-1000 • WIMS-D5 • CITATION

Introduction

Nanofluids are engineered colloidal dispersions of nanoparticles in base fluids such as water, oils or refrigerants. The nanoparticles can be metals such as copper, silver, gold or metal oxides such as alumina, zirconia, silica or various forms of carbon such as diamond, carbon nanotubes, graphite, etc.

The study of nanofluids engineering applications have become one of the important subjects in recent years. The nanofluids thermal conductivity enhancement suggests the possibility of using them in nuclear reactors [3]. The nuclear effects of nanofluids have been studied in the recent literatures [2, 6] but their neutronic behavior have not been discussed in details for the whole reactor core.

In this research, WIMS-D5B [10] and CITATION-LDI2 [5] codes are used for the neutronic analysis of nanofluids as a coolant. The neutronic group constants are calculated by solving neutron transport equation in the WIMS code for each fuel assembly, then CITATION code is used to calculate neutron flux and thermal power for the whole core. This method was used in our previous study [8]. Due to the common calculation errors in using the hexagonal meshing, this analysis is performed by considering the triangular meshing for the reactor core and fuel assemblies.

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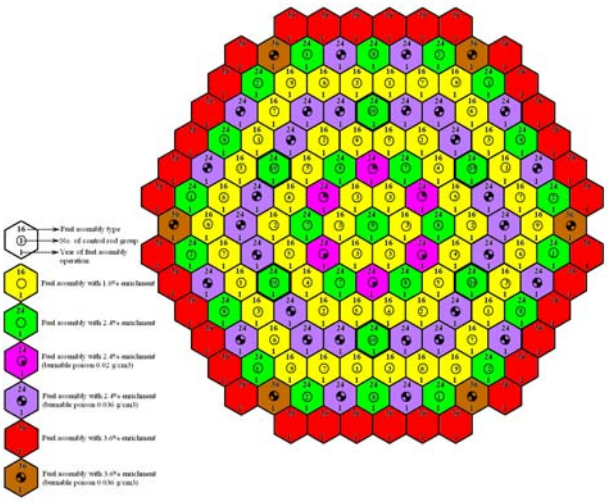


Fig. 1. Scheme of the VVER-1000 reactor core in first cycle.

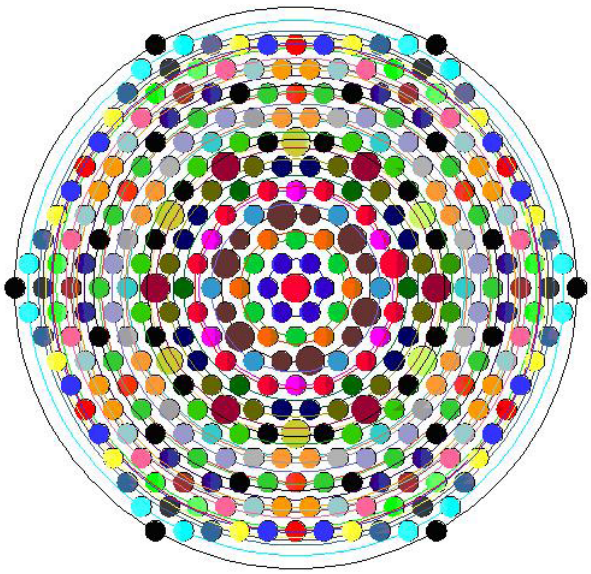


Fig. 2. Regulating arrays.

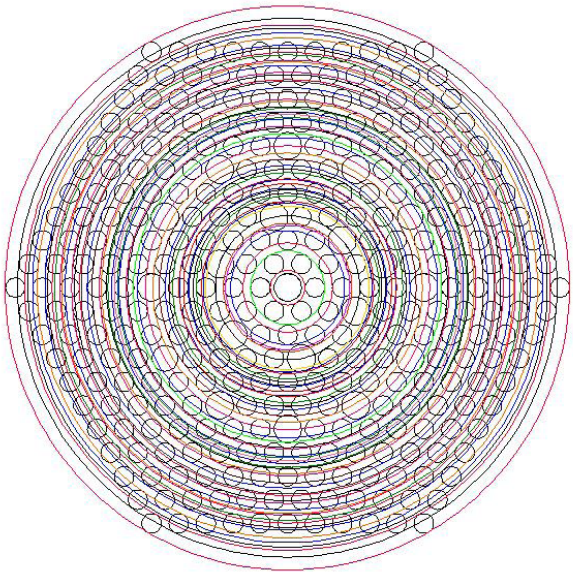


Fig. 3. Regulating annuluses used in modeling fuel assembly by WIMS-D5 code.

Methods and materials

A view of the VVER-1000 reactor core is presented in Fig. 1 [4]. The power distribution and the effective multiplication factor are defined by cell and core calculations in the neutronic simulation.

In the first step, by using the WIMS-D5 code the neutronic group coefficients will be calculated. With regarding to the structure and arrangement of the reactor core (in the first cycle), modeling is performed by considering fuel assemblies with 1.6, 2.4 and 3.62% enrichments, a reflector and nanoparticles with different volume fractions. By coupling WIMS and CITATION code, the neutron flux and power are calculated. Based on the radius and angular location of each fuel rod in the assembly, a 36-fold array in the fuel assembly has been considered as shown in Fig. 2.

In Fig. 3, the method of regularity for the 54-fold annulus used in modeling of a fuel assembly by WIMS--D5 code has been shown.

By inserting the relevant group constants in CITATION input file (card 008-Macroscopic cross section), the thermal power distribution in each fuel assembly is investigated.

Since the CITATION code in the triangular modeling of the core is more acceptable compared with the hexagonal one [7], the triangular meshing is used.

In the CITATION code, the core with the reflector and the black absorbers is described via a 70 × 140 lattice (Fig. 4) and each fuel assembly is approximated by 24 meshes (Fig. 5).

Since, the reactor power is continuously varying from cold zero to nominal power, these variations should be considered in the neutronic calculations using the WIMS code through the POWERC card. The first cycle is divided into 28 steps which are shown in Table 1 [1].

To determine the appropriate nanofluid with optimum volume percentage, four nanofluids Al_2O_3, TiO_2, CuO and Cu with 0.001 to 10 volume percentages have been modeled in the first cycle of the VVER-1000 reactor and the neutronic effects of the cross sections, power spectrum and the effective multiplication factors

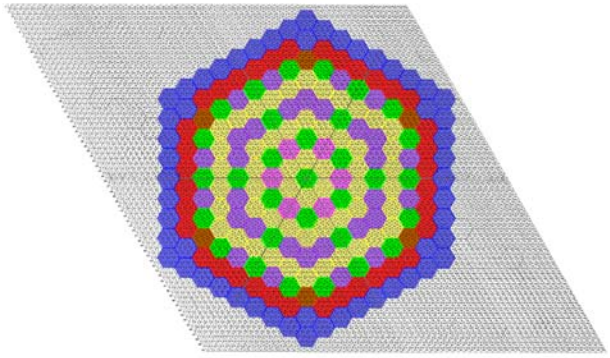


Fig. 4. Meshing process in the reactor core by using the CITATION code.

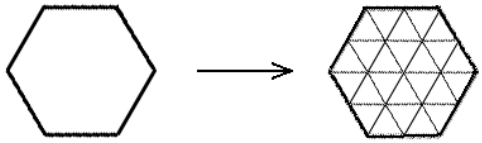


Fig. 5. Approximation of a fuel assembly by 24 triangular meshes.

Table 1. The first cycle nominal parameters of the Bushehr nuclear power plant

T_{eff} (day)	T_{input} (°C)	H_{10} (%)	N (MW)	C_{ba} (g/Kg)
0.00	280.0	60	0	7.38
0.00	280.1	60	30	7.25/7.35
0.10	280.5	60	150	6.90/7.31
0.20	282.8	60	750	6.12/7.11
1.00	282.8	60	750	6.07/7.06
2.00	284.4	70	1200	5.74
5.00	284.4	70	1200	5.61
10.00	285.5	80	1500	5.36
15.00	285.5	80	1500	5.31
20.00	288.3	80	2250	4.94
30.00	288.3	80	2250	4.86
40.00	288.3	80	2250	4.75
50.00	288.3	80	2250	4.62
60.00	288.3	80	2250	4.49
70.00	289.9	80	2700	4.16
75.00	290.5	80	2850	4.03
80.00	290.5	90	2850	3.98
100.00	291.0	90	3000	3.58
120.00	291.0	90	3000	3.22
140.00	291.0	90	3000	2.86
160.00	291.0	90	3000	2.49
180.00	291.0	90	3000	2.11
200.00	291.0	90	3000	1.73
220.00	291.0	90	3000	1.34
240.00	291.0	90	3000	0.96
260.00	291.0	90	3000	0.57
280.00	291.0	90	3000	0.19
289.71	291.0	90	3000	0.00

Table 2. Thermophysical properties of nanoparticles and base fluids

Property	Water	Al_2O_3	TiO_2	CuO	Cu
C (J/kg·K)	4179	765	686.2	535.6	385
ρ (kg/m^3)	997.1	3970	4250	6500	8933
k (W/m·K)	0.605	40	8.9538	20	400
α (m^2/s)	1.47	1317	30.7	57.45	1163

are calculated. The physical and thermal properties of nanoparticles and base fluid are shown in Table 2 [9].

Results and discussion

In Fig. 6, the power density distribution with water as the coolant in the hundredth day (nominal power) is presented.

It is evident that the power density has a Gaussian distribution. In Figs. 7 and 8, changes in the power density distribution are presented for four nanoparticles in the coolant with 0.001 and 0.01 volume percentage, respectively.

Compared to Fig. 6, the power density distributions resulting from Figs. 7 and 8 show no significant changes.

Figure 9 shows the changes in the power density distribution in 0.1 volume percentage. Unlike the pre-

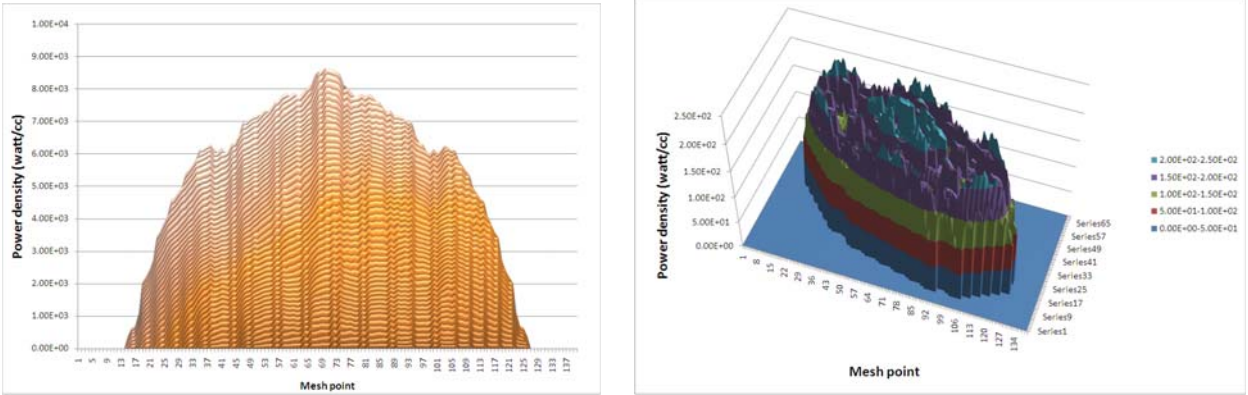
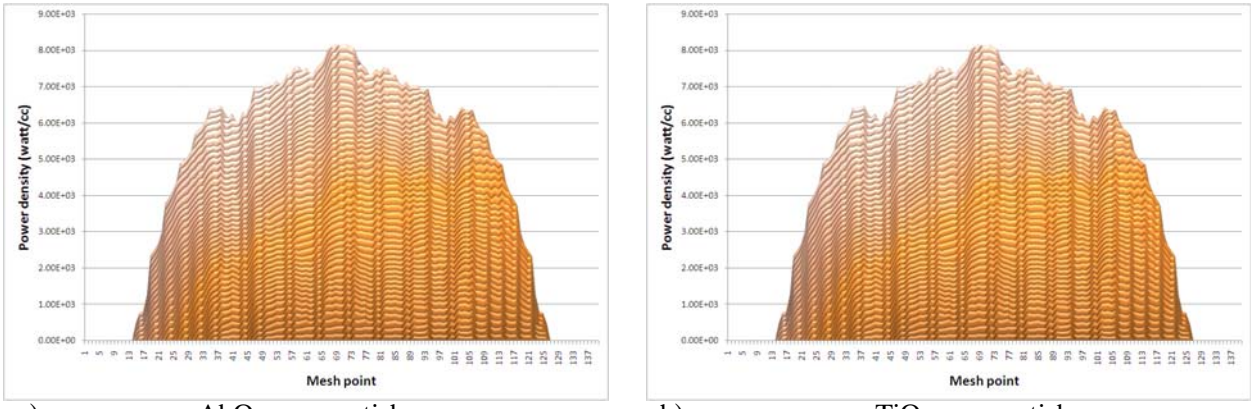
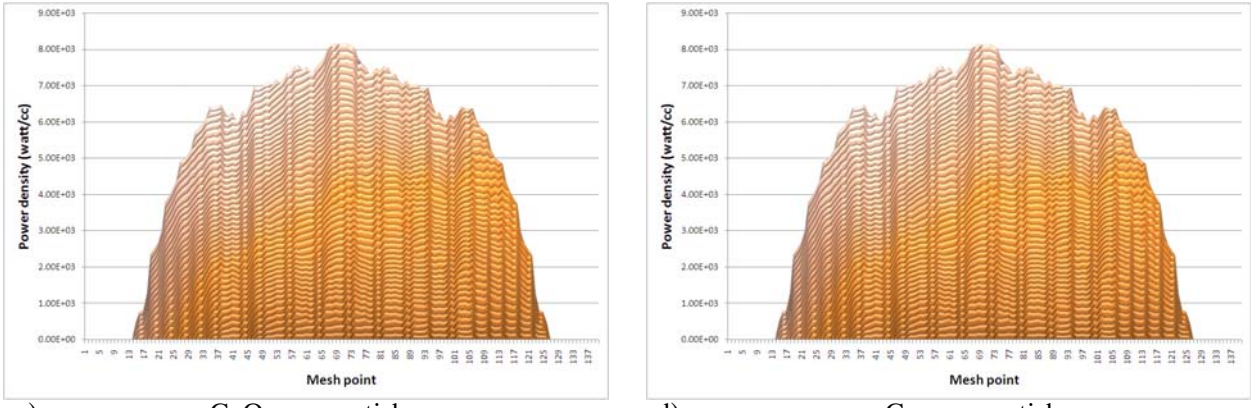


Fig. 6. Two- and three-dimensional distribution of power density at nominal power with water as coolant.

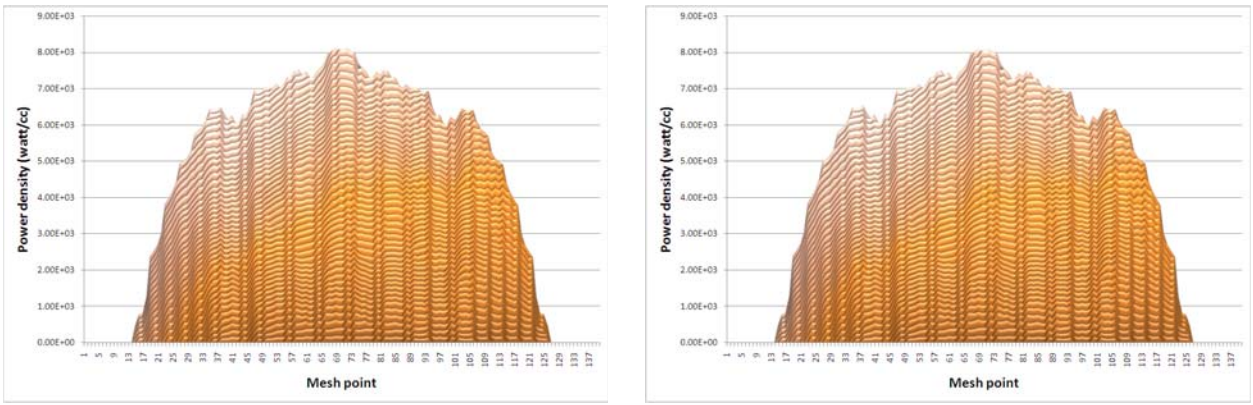


a) Al_2O_3 nanoparticle b) TiO_2 nanoparticle

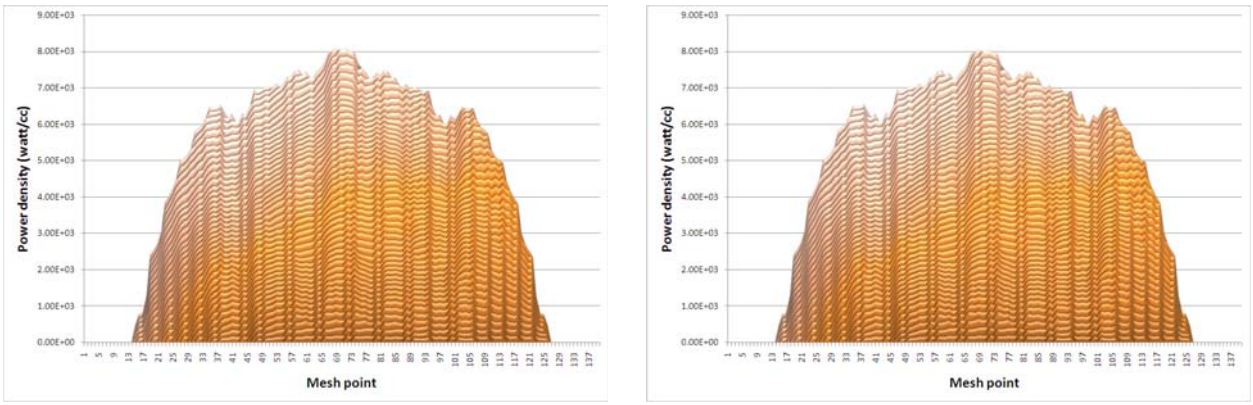


c) CuO nanoparticle d) Cu nanoparticle

Fig. 7. Changes in the power density distribution for four nanoparticles in 0.001 volume percentage.

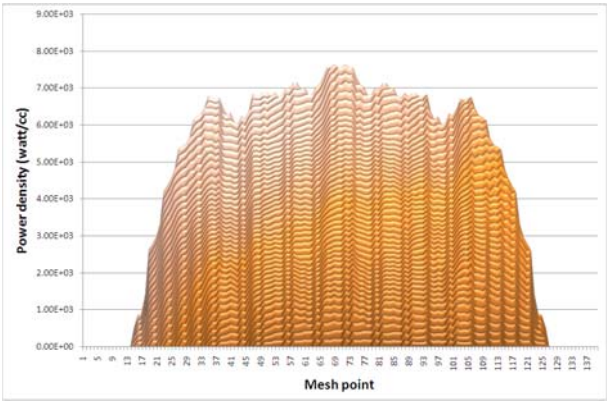


a) Al_2O_3 nanoparticle b) TiO_2 nanoparticle

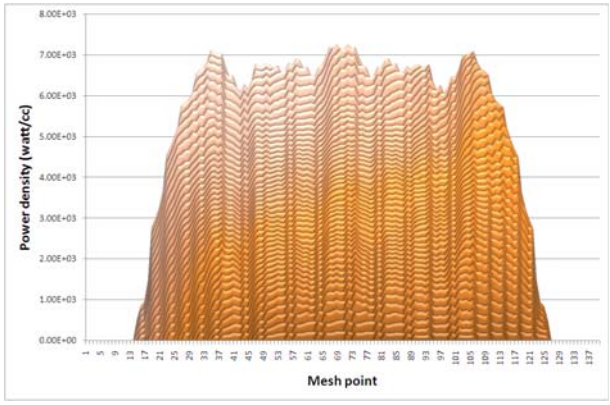


c) CuO nanoparticle d) Cu nanoparticle

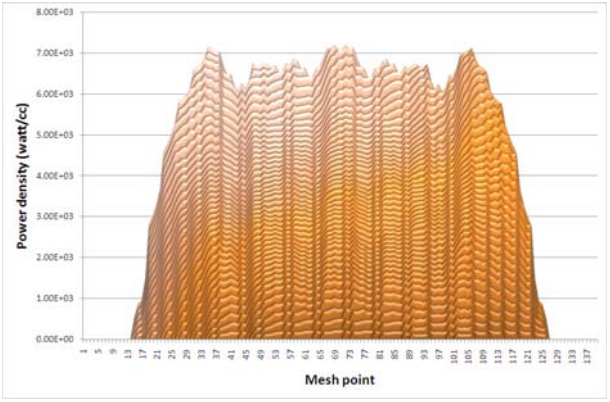
Fig. 8. Changes in the power density distribution for four nanoparticles in 0.01 volume percentage.



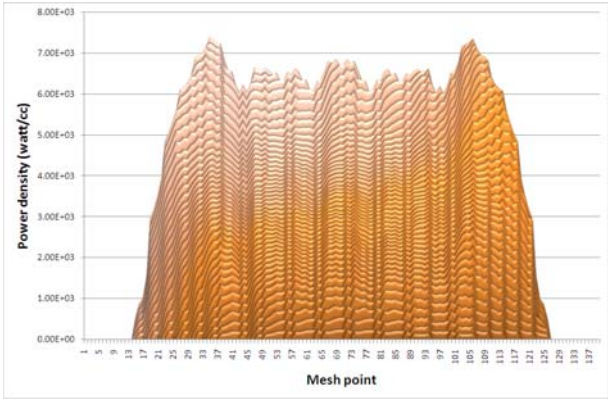
a) Al_2O_3 nanoparticle



b) TiO_2 nanoparticle

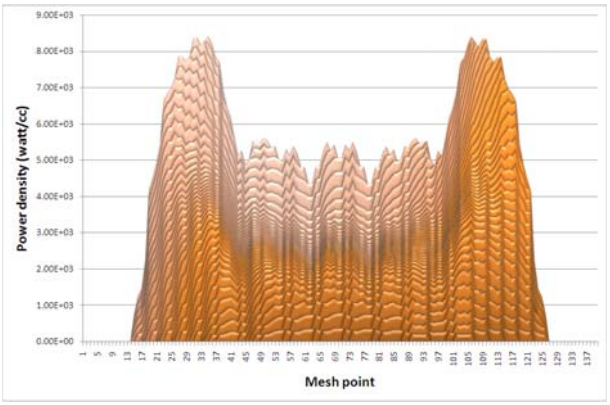


c) CuO nanoparticle

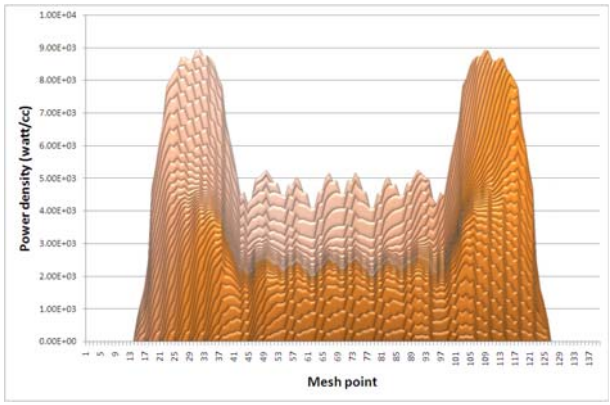


d) Cu nanoparticle

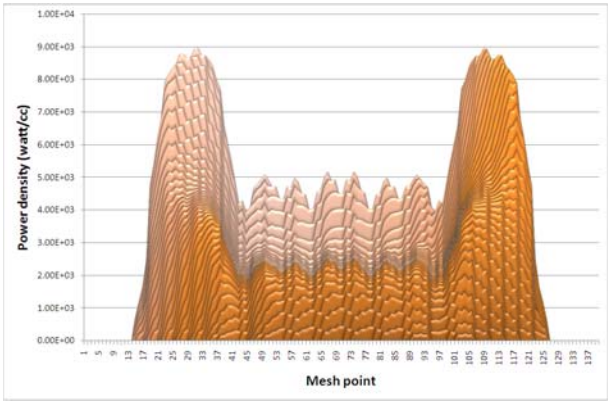
Fig. 9. Changes in the power density distribution for four nanoparticles in 0.1 volume percentage.



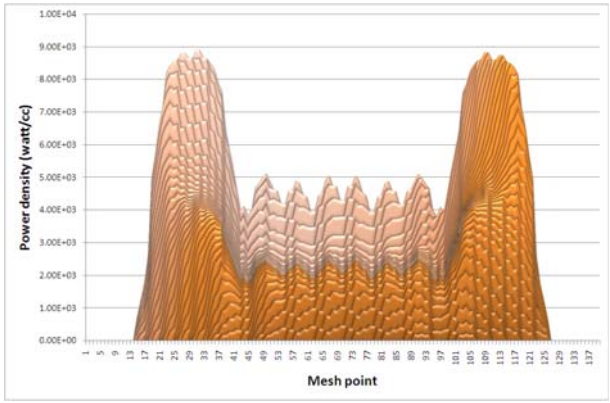
a) Al_2O_3 nanoparticle



b) TiO_2 nanoparticle



c) CuO nanoparticle



d) Cu nanoparticle

Fig. 10. Changes in the power density distribution for four nanoparticles in 1 volume percentage.

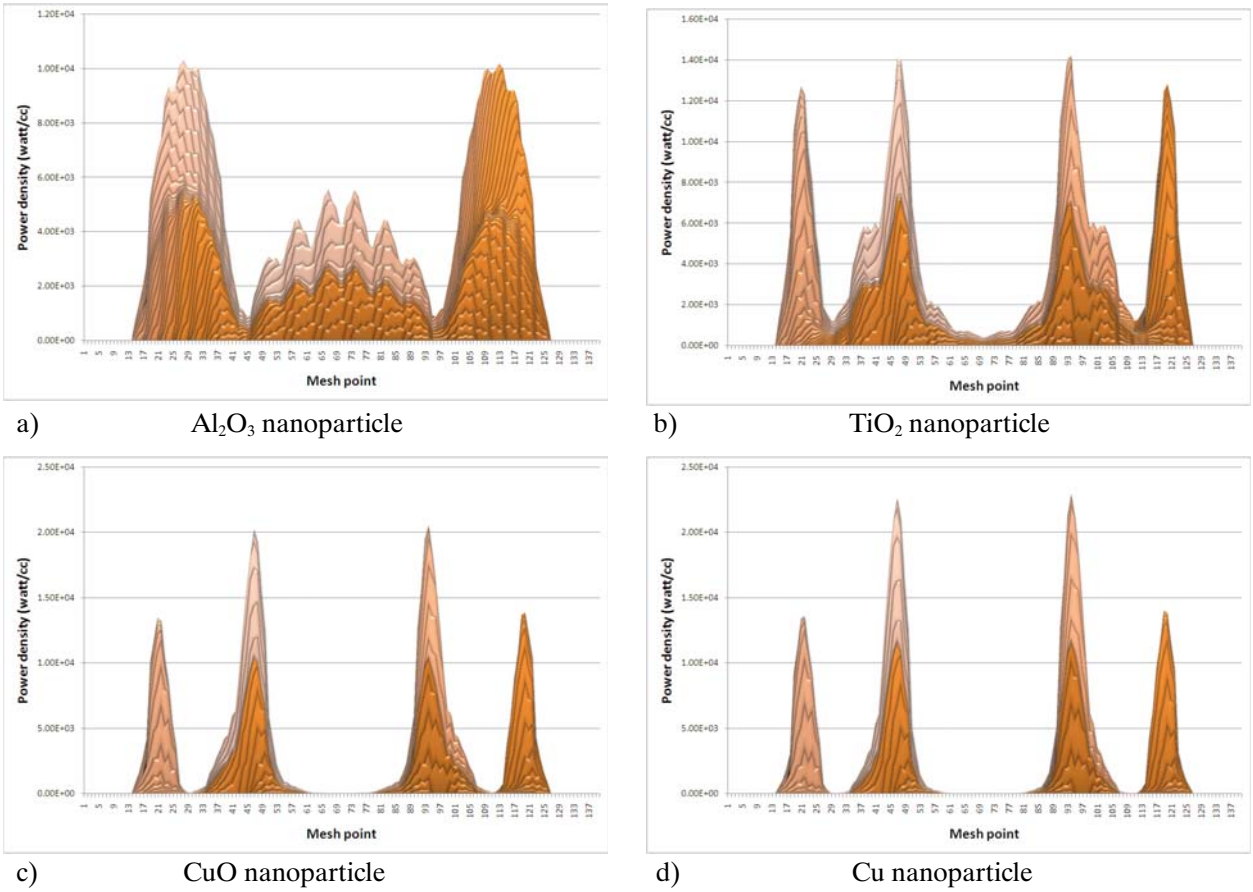


Fig. 11. Changes in the power density distribution for four nanoparticles in 10 volume percentage.

vious cases, the peak of power density decreases in the center of the core and increases around it. As a result, the distribution would be more flattened.

Changes in the power density distribution at the 1 and 10 volume percentages are illustrated in Figs. 10 and 11. At the 1 volume percentage, the reactor power peak increases around the core and decreases at its center. By increasing the volume percentage of nanoparticles from 1 to 10%, the power peak increment around the core continues and leads away from the desired results.

In Fig. 12, the variation of the effective multiplication factor for four nanoparticles are given at different volume percentages.

It can be seen, by increasing the amount of nanoparticles, that the effective multiplication factor will drop sharply. Reduction in the effective multiplication factor is much more intensive for the copper nanoparticles and milder for alumina nanoparticles. This phenomenon can be attributed to the density of these nanoparticles inserted into coolant.

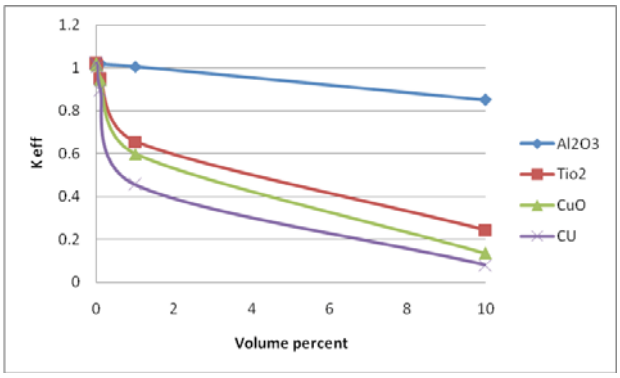


Fig. 12. Changes in the effective multiplication factor in different concentrations of four nanoparticles in the coolant.

Among the four selected nanoparticles, copper has the highest density and alumina has the lowest. By increasing the amount of nanoparticles, the rate of moderation will be reduced in the reactor core. If the added nanoparticles are heavier, the less neutron energy losses will occur and this will in turn reduce the effective multiplication factor.

Conclusion

The central idea of this study is the neutronic analysis of nanofluids as coolant in the nuclear reactor core.

Surveying the results, it can be concluded that by increasing the volume percentage of nanoparticles, the effective multiplication factor will be severely reduced due to the reduction of water moderation in the reactor core.

Moreover, comparing the power distribution related charts; it can be observed that by increasing the volume percentage of nanoparticles, the spectrum will lose the Gaussian shape, so that the flux peak is gradually decreased at the center of the core.

The reasons for these changes is the reduction of the thermal neutron flux moderation at the center of the core due to the increase of nanoparticles at the reactor

core and this will in turn reduce the power density. On the other hand, since more fuel enrichment (3.6%) as well as more cooling is available around the core, it will cause the peak flux around the core.

According to the results, it can be noted that the multiplication factor reduction has a gentler slope with alumina nanoparticles, and unlike the other three nanoparticles, it is at a critical state up to 0.1 volume percentage of the reactor and in this case, the power density distribution has also a more desired form.

It would be concluded that the alumina nanoparticles with a concentration higher than 0.1 volume percentage are not recommended under the normal operation conditions of the reactor.

Nomenclature

C – specific heat (J/Kg·K)
C_{ba} – critical boron concentration in the primary coolant loop (g/Kg)
H_{10} – location of control rods of type 10 (%)
k – thermal conductivity (W/mK)
N – reactor thermal power (MW)
T_{eff} – effective time (day)
T_{input} – coolant inlet temperature (°C)

Greek symbols

α – molecular thermal diffusivity (m^2/s)
ρ – density (kg/m^3)

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