Neutronic study for the dual use of nanofluid as a primary coolant and neutron absorber in VVER-1000 nuclear power reactor

H Abdullah1,2,*, A D Smirnov2, G V Tikhomirov2 and A S Gerasimov3

1 Institute of Graduate Studies and Research, Alexandria University, El-Horeya Rd, Bab Sharqi WA Wabour Al Meyah, Qesm Bab Sharqi, Alexandria Governorate
2 Institute of Nuclear Physics and Engineering, National Research Nuclear University MEPhI, Kashirskoe Shosse, 31, Moscow, Russian Federation, 115409
3 Institute for Theoretical and Experimental Physics, 117218, Bolshaya Cheremushkinskaya Street, 25, Moscow, Russia

* hadeershehata031@gmail.com

Abstract. The use of nanofluid as a primary coolant and reactivity controller in VVER-1000 reactor to enhance the heat transfer is the goal of this study. In this study, we have studied using nanofluid in the reactor for two cases: first, only using nanofluid as primary coolant, second, using nanofluid as a primary coolant and reactivity controller. The simulation has been done in case of normal operation of the reactor with several concentration for the different types of nanofluid. Their effect on the neutronic field has been investigated to obtain the optimum type of nanofluid from the neutronics point of view. It can be concluded that among the four types of nano fluids Al2O3, CuO, Cu and Ag2O for the first case Ag2O is the optimum type, however, Cu is the optimum type for the second case where the boron is absent.

1. Introduction
Nanofluid is a mixture between nanoparticles and a base fluid. Nanoparticles are colloidal dispersion of nanometer-sized materials (stable metals, metal oxides, oxide ceramics, metal carbides, etc.) with an average diameter of smaller than 100 nm.

Enhancing the heat transfer and the efficiency of the power density are the concern of many researches to develop a modern heat- transfer system using coolant fluids (Todreas and Kazimi, 1993). Recently researchers are studying enhancing the convective heat transfer effect of water by adding nanoparticles with high thermal conductivity (Buongiorno, 2006). Using nanofluids with high thermal conductivity as a coolant have shown a considerable increasing in the convective heat transfer (Xiang and Arun, 2007). Also (Buongiorno et al., 2009) shown that there is a remarkable improvement in Critical Heat Flux (CHF) as well as Departure from Nucleate Boiling Ratio (DNBR) as the result of the base fluid replacement with nanofluid. However, (Buongiorno and Truong, 2005) mentioned using nanofluid in the event of a loss of coolant accident (LOCA) as a coolant to be promising to enhance the safety.
From the thermal hydraulic studies, they concluded that heat transfer coefficient increased with increasing the volume fraction of nanoparticles and experimental studies have shown that nanofluids have a higher critical heat flux (CHF) and improve the minimum departure from nucleate boiling ratio (Bang and Chang, 2005; Kim et al., 2007; Jackson et al., 2006).

From the neutronic point of view, (Hadade et al., 2010, 2013; Nazififard et al., 2012; Safarzadeh et al., 2014) simulated different types of nanoparticles using MCNP. The nuclear effects of different types and volume fractions of nanoparticles have been studied using Monte-Carlo. They concluded that $\text{Al}_2\text{O}_3$/water nanofluid is the optimum type which could be used without much effect on the criticality of the reactor.

In this study, we investigated the effect of using nanofluid in the Khmelnitsky VVER-1000 nuclear power reactor on the neutron-physical characteristics and chose the optimum type of nanofluid to be used in the reactor using nanofluid as only primary coolant. The simulations and calculations divided into two tasks:

- using nanofluids as a primary coolant only;
- using nanofluids as a primary coolant and neutron absorber in the primary loop.

2. Methods and materials

In this study, the effect of dual using of nanofluid as a primary coolant and neutron absorber was studied. The case study is VVER-1000 fuel assembly and the neutronic simulation has been investigated for four different types of nanofluids: $\text{Al}_2\text{O}_3$, CuO, Cu and $\text{Ag}_2\text{O}$.

The choice of those types of nanofluid has been made according to: thermal neutron absorption cross section, their efficiency for enhancing heat transfer and their thermo physical properties.

2.1. Neutronic simulation

The simulation was investigated to Khmelnitsky nuclear power plant. The Khmelnitsky nuclear power plant is located Ukraine. It contains four units; of which two units (VVER V-320) are in operation and two units (VVER V-392B) are under construction. The nuclear power fuel assembly is modeled by SERPENT2 code for the neutronic calculation. Nuclear power TVSA fuel assemblies are hexagonal fuel assemblies designed for VVER type of pressurized water reactor manufactured by Russian company TVEL. the reactor has eight different fuel assemblies.

The simulation has been done for 13AU fuel assembly type which has equally enriched fuel pins and no gadolinium burnable absorber using Serpent (code version 2.1.27) in 2D infinite lattice. Nuclear data were obtained from ENDF/B-VII.0 libraries. Fuel assembly parameters are based on the documentation (Lötsch et al., 2009, 2010, 2011). Each fuel assembly contains 312 fuel pins, 18 guide tubes, and one central tube in a triangular lattice with the pitch of 12.75 mm. 13AU fuel assembly simulation is shown in Fig. 1.

![Figure 1. 13AU Fuel assembly simulation using Serpent code.](image)
2.1.1. Primary coolant application. In this task, we focus on the study of neutron-physical simulations of TVS type 13 AU VVER-1000 reactors with nanofluids only as a primary coolant. The constants and cross sections of the neutron groups were calculated during the first cycle of operation of the VVER-1000 reactor for the various types of nanoparticles and different volume fractions of nanoparticles. An effective multiplication factor was determined for each of volume fraction. The simulations were done for nanofluids with volume fraction in the range 0.001-1%. Neutron-physical parameters, such as the effective multiplication factor and the neutron spectrum were calculated. The thermophysical properties of the chosen nanoparticles and the base fluid are shown in Table 1. The nanofluid density has been calculated using the following equation:

\[ \rho_{nf} = (1 - \varphi) \rho_{bf} + \varphi \rho_{np} \]  

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

| Parameter | \( C \) [J/kg K] | \( \rho \) [kg/m\(^3\)] | \( K \) [W/mK] |
|-----------|-----------------|-----------------|-------------|
| H\(_2\)O   | 4179            | 997.1           | 0.605       |
| Al\(_2\)O\(_3\) | 765             | 3970            | 40          |
| Cu        | 385             | 8933            | 400         |
| CuO       | 535.6           | 6500            | 240         |
| Ag\(_2\)O | 234.4           | 10.500          | 42.9        |

2.1.2. Primary coolant and neutron absorber. In this study, the calculations have been done as the same method as the first task but with removing the boric acid from the calculations. The neutron-physical effect of the nanofluid as a reactivity controller on the system was investigated.

3. Results

3.1. Neutronic simulation

The variation of the effective multiplication factor for the 4 nanoparticles is given for different volume fractions (Fig. 2). The results of the study of the effective multiplication factor show that, by increasing the amount of nanoparticles, the effective multiplication factor drops sharply; however, for different types of nanoparticles there is a distinct response. The decrease in the effective multiplication factor is much more intense for silver nanoparticles and is milder for aluminum oxide particles. This behavior can be explained by the absorption cross section for the corresponding type of nanoparticles. Among the four selected nanoparticles, silver has the highest absorption cross section, and aluminium has the lowest value. By increasing the concentration of nanoparticles, the multiplication factor will decrease. The critical volume fraction (the fraction corresponding to the critical state of the reactor) for four nanoparticles is shown in Table 2.
Table 2. Critical volume percentages of nanoparticles.

| Type  | Critical volume percentage |
|-------|---------------------------|
| H$_3$BO$_3$ | 0.1                       |
| Al$_2$O$_3$ | 40                        |
| CuO    | 8.3                       |
| Ag$_2$O | 0.2                       |
| Cu     | 5.2                       |

3.2. **Primary coolant and neutron absorber application result**

Figure 3 shows that the effective multiplication factor decreases with increasing volume fraction of the nanofluid. Variations in the value of the effective multiplication factor with respect to the volume fraction were constructed for 4 types of nanofluids. For this task, the optimal nanofluid should have the smallest volume fraction and at the same time ensure criticality of the reactor. Nanofluids with nanoparticles such as Ag$_2$O, Cu, and CuO satisfy these conditions.
Figure 3. The effective multiplication factor for the different nanoparticles with different volume fractions (in case of removing boric acid).

4. Conclusion
Analysis of a VVER-1000 using nanofluid as the base coolant is performed by neutronic model. In this paper, the Monte-Carlo transport code Serpent 2 was used to investigate the effect of dual use nanofluid as a primary coolant and reactivity controller in Khmelnicky VVER-1000 nuclear power plant on the neutronic characteristics, in order to choose the optimum type of nanofluid from the neutronic point of view.

For using nanofluid as a primary coolant, the neutronic study showed that the decrease in the multiplication factor is minimal when adding nanoparticles based on alumina and silicon to the coolant. Despite the permissible neutron-physical properties, silicon nanoparticles have low thermal conductivity, so aluminium oxide is most preferred for use in nuclear reactors.

For using nanofluid as a primary coolant and reactivity controller, among the four types of nanoparticles, alumina has the lowest neutron absorption cross section, and for the criticality of the system, large volume fractions of nanoparticles are required. Therefore, nanoparticles based on silver oxide and copper with reasonable volume fractions are considered for practical application and further analysis. Neutron-physical modelling has shown that oxides of copper and silver with the same low concentration can guarantee the criticality of the system.

Conflict of interest
The authors declare no conflict of interest.

Acknowledgements
This work was supported by Competitiveness Program of National Research Nuclear University MEPhI.

References
[1] Xiang-Qi Arun S. Mujumdar.,2007 Heat transfer characteristics of nanofluids: a review International Journal of Thermal Sciences 46 (2007) 1–19
[2] Buongiorno J., Hu, L.W., Apostolakis, Hannink, G., Chupin, R.T.A., 2009. A feasibility assessment of the use of nanofluids to enhance the in-vessel retention capability in light-water reactors. Nucl. Eng. Des. 239, 941–948.
[3] Buongiorno, J., Truong, B., 2005. Preliminary study of water-based nanofluid coolants for PWRs. Trans. Am. Nucl. Soc. 92, 383–384.

[4] Hadad, K., Hajizadeh, A., Jafarpour, K., Ganapol, B.D., 2010. Neutronic study of nanofluids application to VVER-1000. Ann. Nucl. Energy 37 (11), 1447–1455.

[5] Hadad, K., Rahimian, A., Nematollahi, M.R., 2013. Numerical study of single and two-phase models of water/Al2O3 nanofluid turbulent forced convection flow in VVER-1000 nuclear reactor. Ann. Nucl. Energy 60, 287–294.

[6] Nazififard, M., Nematollahi, M., Jafarpur, Kh., Suh, K.Y., 2012. Numerical simulation of water-based alumina nanofluid in subchannel geometry. Sci. Technol. Nucl. Instal.

[7] Safarzadeh, O., Shirani, A.S., Minuchehr, A., Saadatian-derakhshandeh, F., 2014. Coupled neutronic/thermo-hydraulic analysis of water/Al2O3 nanofluids in a VVER 1000 reactor. Ann. Nucl. Energy 65, 72–77.

[8] Todreas, N.E., Kazimi, M.S., 1993. Nuclear Systems, vol. 1. Hemisphere, New York, USA.

[9] Buongiorno, J., 2006. Convective transport in nanofluids. ASME J. Heat Transfer 128 (3), 240–250.

[10] Bang, I.C., Chang, S.H., 2005. Boiling heat transfer performance and phenomena of Al2O3–water nano-fluids from a plain surface in a pool. Int. J. Heat Mass Transfer 48 (12), 2407–2419.

[11] Kim, S.J., Bang, I.C., Buongiorno, J., Hu, L.W., 2007. Surface wettability change during pool boiling of nanofluids and its effect on critical heat flux. Int. J. Heat Mass Transfer 50, 4105–4116.

[12] Jackson, J.E., Borgmeyer, B.V., Wilson, C.A., Cheng, P., Bryan, J.E., 2006. Characteristics of nucleate boiling with gold nanoparticles in water. In: Proceedings of IMECE 2006, November 5–10, Chicago, USA.

[13] Ulset E T, Kosinski P and Balakin B V. 2018 Solar steam in an aqueous carbon black nanofluid Appl. Therm. Eng. 137 62–5