NEUTRONIC SIMULATION OF A CANDU-6 REACTOR WITH HEAVY WATER-BASED NANOFLUID COOLANT

by

Reza MIRGHAFFARI, Gholamreza JAHANFARNIA*, and Mitra ATHARI ALLAF

Department of Nuclear Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

Scientific paper
http://doi.org/10.2298/NTRP1704320M

In recent years, extended studies are developed for investigation the effects of using nanofluids in NPP as coolant. CANDU-6 reactors have the potential to use nanofluid coolants because in these reactors, the moderator system is fully independent of the primary heat transport system. MCNPX code has been used for modelling and simulation of a CANDU-6 reactor containing a nanofluid as primary coolant. The variation of multiplication factor and total neutron flux distribution along a fuel channel, next to the central axis, has been investigated by using different nanofluids. In this analysis, heavy water-based nanofluids containing various volumetric percentages of Al_2O_3, TiO_2, CuO, Ti, Cu, Zr, and Si nanoparticles were used. A typical CANDU-6 reactor was selected as reference for reactor core modelling. The results of the neutronic analysis show that Al_2O_3 nanofluids with 1% volumetric percentage are the most suitable coolant for CANDU-6 reactors which can increase the coolant heat transfer coefficient and consequently enhance the plant efficiency.

Key words: nanofluid, CANDU-6, MCNPX, neutronic analysis

INTRODUCTION

Economic aspects of electricity generation (*i. e.* price expressed in dollars per generated electric energy kWh) in power plants have always been the most challenging issue in selecting the type of the power plants (including fissile fuelled, nuclear reactor, wind farm, *etc*.) in industrial countries. A considerable effort has been devoted to develop the power plant design and reduce the electricity pricing in each type, in order to attract the investors. In this manner, development and use of nuclear energy is currently growing very rapidly, in order to achieve increasingly advanced technology, both in terms of design, economic factors and safety factors [1].

Economic studies conducted on nuclear reactor power plants show that ~65 % of the total power cost is referred to the capital cost of the power plant itself (including buildings, reactor core, safety features, *etc*.) [2]. Therefore, a reasonable method to reduce the electricity pricing in nuclear power plants would be increasing the power density (*i. e*., power produced per unit volume of the reactor core) of the nuclear reactors; that means extracting more energy from an existing reactor or reducing the physical size of future nuclear reactors which may considerably reduce the total cost of nuclear power.

The most important subject in high heat flux systems, such as nuclear reactors, is the heat transfer method. Considering the above mentioned issue (increasing the power density), selection of the heat transfer method (coolant itself, and heat removal systems), will be even more challenging. The most important intrinsic limitation consists of the relatively low thermal conductivity of conventional coolant fluids. About two decades ago, the concept of combining a conventional fluid with a metal (with high thermal conductivity) was introduced to the scientific community [3], called nanofluid, to enhance the thermal conductivity of conventional fluids.

Recent studies showed that nanofluids can be applied as an alternative for the nuclear reactors coolant or, as a safety system coolant to cover the core in the event of accidental loss of coolant [4]. In fact, enhancement of the critical heat flux (CHF) is the main factor which encourages the designers and/or researchers to investigate different aspects of applying a nanofluid in the conventional systems. Yet, there have been done a number of studies about applying a water base nanofluid as coolant in pressurized water rectors (PWR) [5].

The nuclear aspect of applying a nanofluids in the LWR reactors have been studied in various litera-

* Corresponding author; e-mail: rezajahan@yahoo.com

tures, but using of nanofluids in the PHWR reactors have not yet been investigated. According to the Zarifi *et al*., 2012 report [6], by increasing the volume percentage of nanoparticles, the effective multiplication factor will be intensively reduced due to the reduction of neutron moderation ratio in the reactor core. The multiplication factor reduction has a smooth slope with alumina nanoparticles below 0.1 vol. % and the reactor can remain in the critical state [6]. In this research, MCNPX 2.6.0 code is used for neutronic analysis of the CANDU-6 reactor with various nanofluids as coolants.

MATERIAL AND METHODS

The neutronic literature review of CANDU-6 reactor (core layout, operation and safety assessment) indicates that the frequently applied method is Monte Carlo N-Particle (MCNP) neutron transport model. In this study, the MCNPX 2.6.0 has been applied as a proven particle transport code with the capacity to measure steady-state reaction rates and other neutronic parameters.

The neutron flux and effective multiplication factor were calculated by neutronic analysis of CANDU-6 reactor core including 380 fuel channels using MCNPX 2.6.0 code. Figure 1 shows a typical CANDU fuel channel. The calandria tube, made of zircalloy-2, is inserted in D_2O moderator. Fuel channels are set in a square configuration in the core.

The heat generated in the fuel rod is transferred to the power conversion system via D_2O coolant. Pressure tube is made of Zr-Nb. D_2O coolant enters the tube at 266 °C and leaves at 310 °C at a pressure of 10 MPa. The gap is filled with CO_2 gas. In the CANDU reactor, each fuel channel includes 37 fuel rods in the fuel bundle zone, as shown in fig. 2.

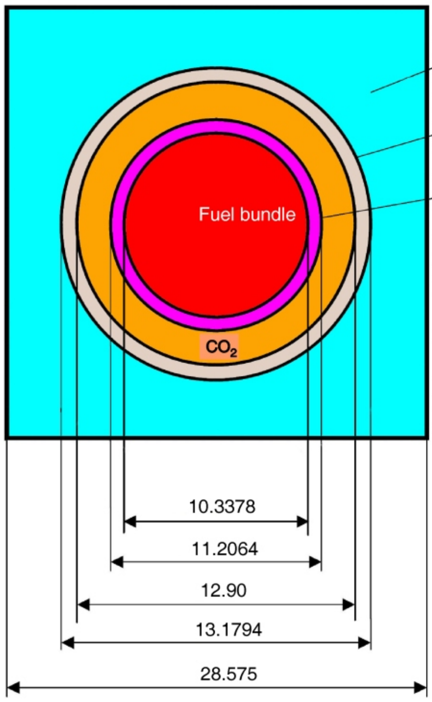

Figure 1. Cross-sectional view of the fuel channel (dimensions are in centimetres)

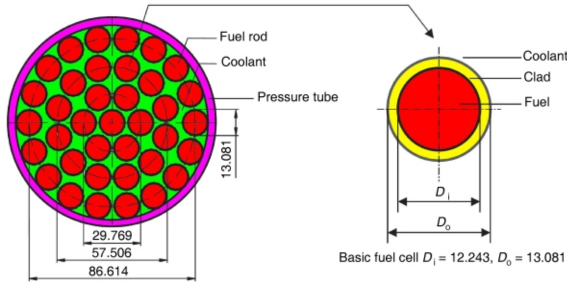

Figure 2. Layout of 37 fuel rods in the bundle (dimensions are in millimetres)

According to core design concept, the selected cladding material is zircalloy-4. Table 1 represents the main core design parameter of CANDU-6 reactor [7].

The pitch between two adjusted neighbouring channels is 28.575 cm with 22 horizontal rows and 22 vertical columns. The geometry produced in MCNPX code is demonstrated in fig. 3.

Figure 4 shows channel configuration, major calandria dimensions and pattern of reactor reactivity mechanisms above the core. The reactivity control devices contain 28 shutoff rods (SOR), 21 adjusters (ADJ), 6 zone control units (ZCU), and 4 mechanical control absorbers (MCA) [8].

Table 1. Design data of CANDU-6 core and fuel

Number of fuel channels	380
Lattice pitch	28.575 cm (square)
Inner radius of calandria	379.7 cm
Length of fuel channels	594.4 cm
Reactor core radius	314.3 cm
Reflector thickness	65.6 cm
Number of adjuster rods	21
Number of light water control zone units	6
Fuel pin	
– Number of pins	37
– Fuel pin radius	0.608 cm
– Cladding radius	0.648 cm
Pressure tube	
– Inner radius	5.179 cm
– Outer radius	5.163 cm
Calandria tube	
– Inner radius	6.450 cm
– Outer radius	6.590 cm
Fuel density	10.492 gcm^{-3}
Clad density	6.520 gcm^{-3}
Pressure tube density	6.515 gcm^{-3}
Coolant D_2O purity	99.10 [wt.%]
Moderator D_2O	99.85 [wt.%]

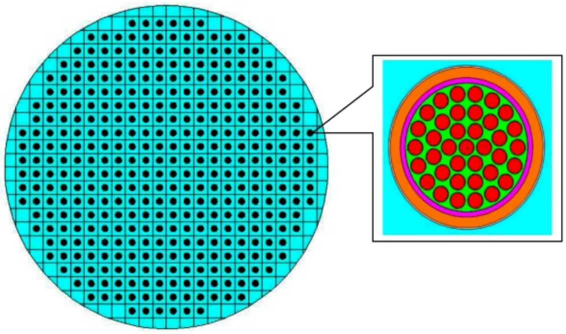

Figure 3. Cross-sectional view of the CANDU-6 reactor core modelled by MCNPX code near the reactor end face

The reference benchmark CANDU-6 MCNP model in this study includes two control devices: 21 adjusters (ADJ) and 6 zone control units (ZCU), as depicted in fig. 5.

The adjuster rods are placed perpendicular to the fuel channels, repeated axially in 3 rows of 7, as demonstrated in fig. 6. The material composition and atomic data for the adjuster rod alloy (Stainless Steel type 304 L) are given in tab. 2 [9].

The dimensions of the inner and outer adjuster rod parts are given in tab. 3 [10].

Zone controller units adjust the reactor power at each zone by changing the amount of light water in each section. In this paper, the considered zone controller units are assumed to be filled partially with 50 vol. % of light water (fig. 7).

Calculation of neutron multiplication factor in reactor core was carried out by using KCODE and KSRC card in MCNPX. In this manner, 8 neutron sources were defined in reactor core and 400 cycles with 400,000 initial particles were considered in calculations. The effective multiplication factors were evaluated in 4 different

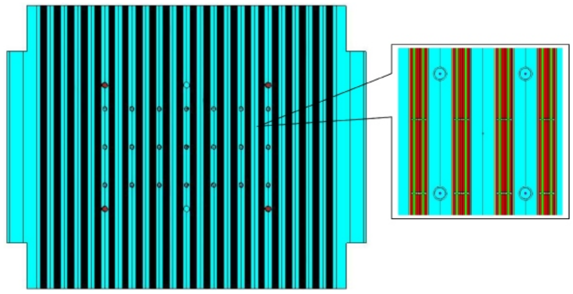

Figure 5. Top view of the CANDU-6 MCNP model (near the horizontal mid-plane)

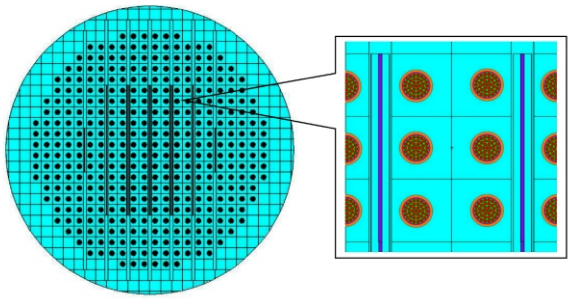

Figure 6. CANDU-6 reactor model vertical cross-sectional view with adjuster rod cluster layout

cases as listed in tab. 4 and were compared with those reported in IAEA-TECDOC-887 [11].

Three-dimensional thermal neutron flux density distribution for the CANDU-6 is obtained by using F4 card in MCNPX and is shown in fig. 8.

Figure 9 represents the two-dimensional graph of the whole-core thermal neutron flux density of CANDU-6 reactor. The positions of the adjuster rods and zone controller units in the core are readily recog-

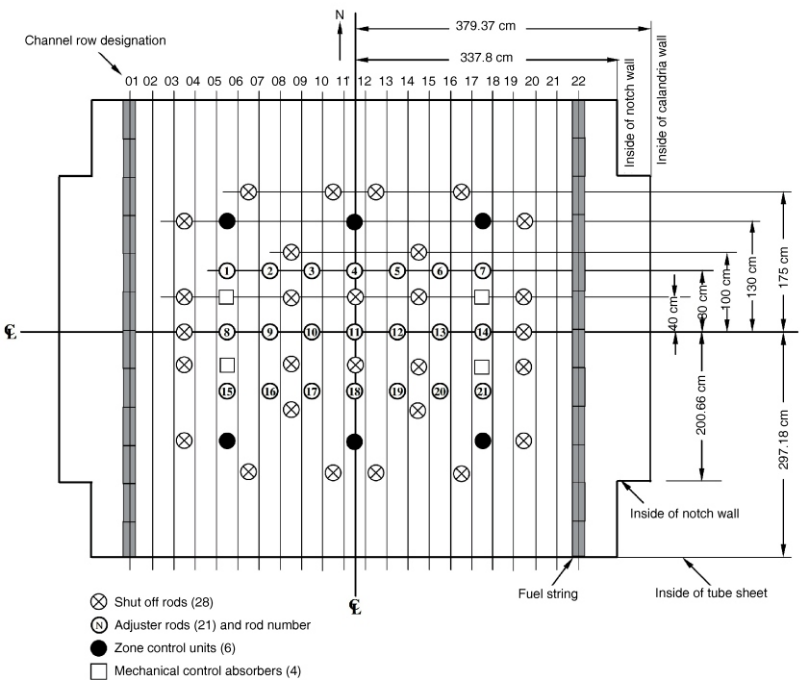

Figure 4. Top view of the reactor showing the layout of reactivity devices

Table 2. Composition and atomic data of stainless steel type 304 l

Element	Weight fraction [%]	Mass density [gcm^{-3}]	Atomic weight [g]
Carbon	0.035	1.60	12.011
Manganese	1.5	7.20	54.94
Phosphorus	0.04	1.82	30.975
Sulphur	0.30	2.07	32.066
Si1icon	0.75	2.42	28.09
Nickel	10.5	8.90	58.71
Chromium	19.0	7.10	52.01
Iron	67.875	7.86	55.85

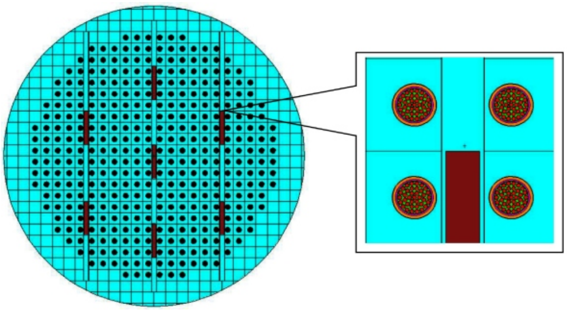

Figure 7. CANDU-6 reactor model vertical cross sectional view with zone controller locations.

nizable and show the accuracy of the modelling. The presence of these control devices cause the neutron flux density in the core to flatten out.

RESULTS AND DISCUSSION

CANDU-6 reactor consists of two separated coolant loops (primary and secondary). The primary loop includes pressurized single phase heavy water

Table 3. Adjuster rod dimensions

	Inner element [cm]	Outer element [cm]
Shim OR	0.650	0.710
Steel tube IR	3.607	3.607
Steel tube OR	3.725	3.690
Guide tube IR	4.519	4.519
Guide tube OR	4.572	4.572

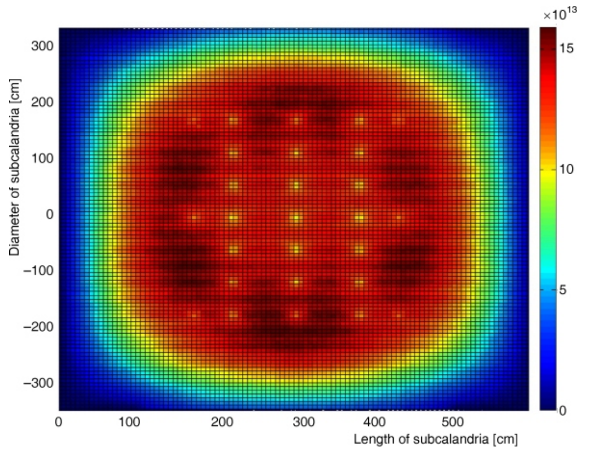

Figure 9. Two-dimensional graph of the whole core thermal neutron flux density of CANDU-6 reactor

coolant which is suitable to apply a nanofluid as coolant in order to enhance the heat transfer coefficient and plant efficiency.

As it was mentioned, neutronic calculations in reactor core were performed with MCNPX code. The achieved results showed a good agreement with those reported in IAEA-TECDOC-887, tab. 4 [11]; which, in turn, indicates the accuracy of simulation. After comparing the calculated results (MCNPX outputs) of neutron

Table 4. The k_{eff} values of the present model and the reference results

Computer codes used	Reference case with given burnup distribution	Fresh core	Adjustes withdrawn out of the core	Zone controlles empty
PP – V + MULTICELL + FMDP (Romania)	0.9988	1.0725	1.0916	1.0761
PP – V + MULTICELL + CHEBY (Romania)	–	1.0707	1.0907	1.0749
MCNPX 2.6 (present model)	1.0002	1.0796	1.0932	1.073
Standard deviation	0.00025	0.00023	0.00028	0.00023

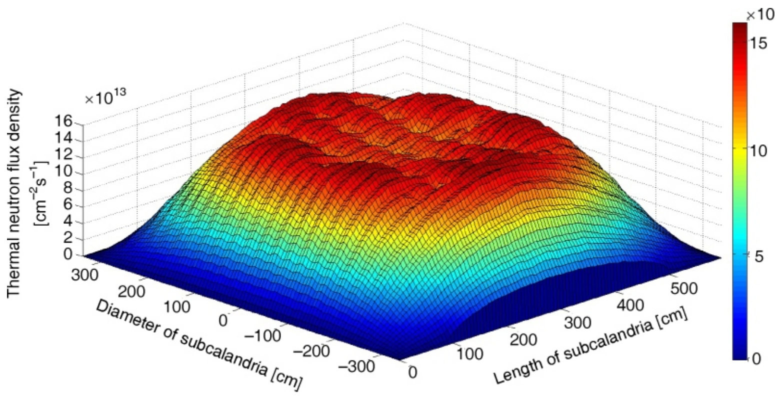

Figure 8. 3-D graph of the whole-core thermal neutron flux density of CANDU-6 reactor

flux density in CANDU-6 reactor for pure heavy water, the influence of the presence of nanoparticles (Cu, Ti, CuO, TiO_2, Zr, Si, and Al_2O_3) in heavy water coolant, in the pressure tubes, on neutron flux density and k_{eff}, were investigated. The volumetric percentages of the nanoparticles vary between 0.001 % and 10 %. The neutronic parameters, such as effective multiplication factor and neutron flux density for the fuel bundle in the calandria tube next to the central axis of the reactor core, have been calculated and the results are shown in figs. 10-17. Figure 10 shows the variation of k_{eff} for different nanofluids. It can be seen that increasing the nanoparticles concentrations within the pressure tubes, the effective multiplication factor strongly decreases. Due to the different absorption cross-section of each nanoparticle, different values for k_{eff} are expected. The nanoparticles of Al_2O_3 and Cu have the lowest and highest impacts, respectively, on the reduction of the effective multiplication factor. By increasing nanoparticles concentration,

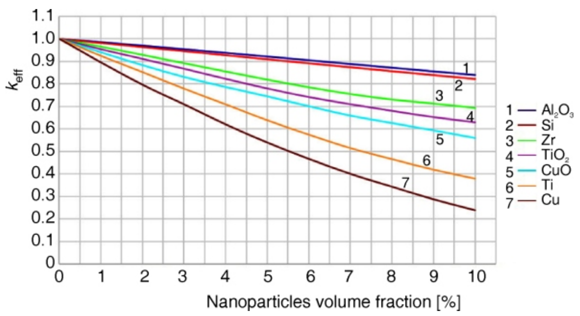

Figure 10. Variation of the k_{eff} for 7 nanoparticles with different volume fractions in the coolant

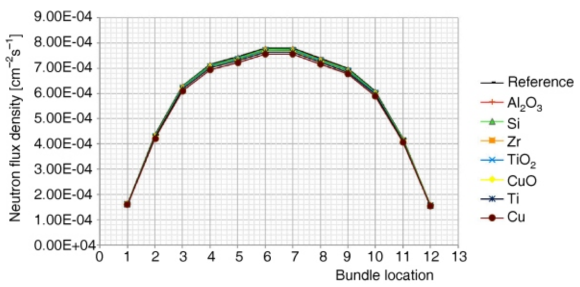

Figure 11. Neutron flux density distribution along a fuel channel next to the central axis for seven nanoparticles in 0.5 vol. %

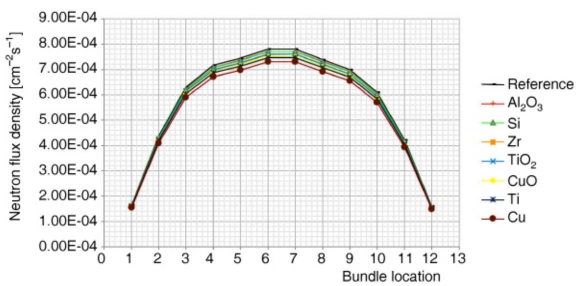

Figure 12. Neutron flux density distribution along a fuel channel next to the central axis for seven nanoparticles in 1 vol. %

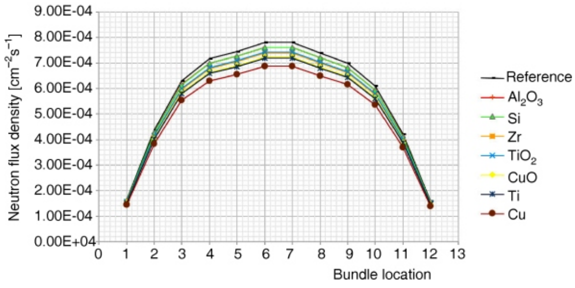

Figure 13. Neutron flux density distribution along a fuel channel next to the central axis for seven nanoparticles in 2 vol. %

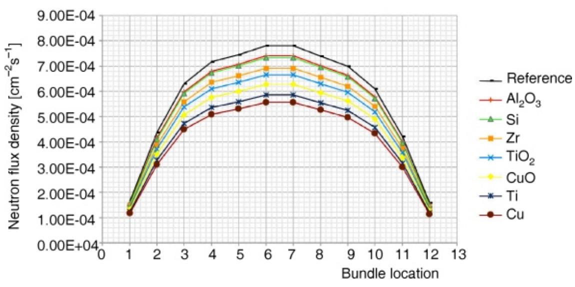

Figure 14. Neutron flux density distribution along a fuel channel next to the central axis for seven nanoparticles in 4 vol. %

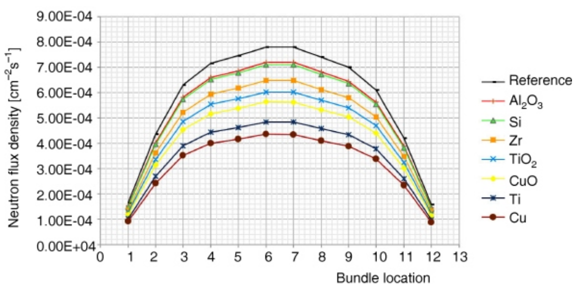

Figure 15. Neutron flux density distribution along a fuel channel next to the central axis for seven nanoparticles in 6 vol. %

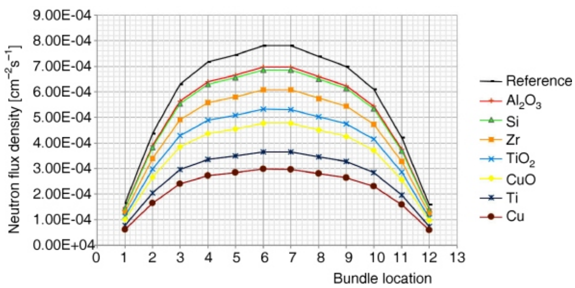

Figure 16. Neutron flux density distribution along a fuel channel next to the central axis for seven nanoparticles in 8 vol. %

the neutron absorption in the moderator is increased and consequently, k_{eff} and the reactor power undergo a decrease.

The variation of neutron flux density in 12 fuel bundles in fuel channel next to the central axis of the

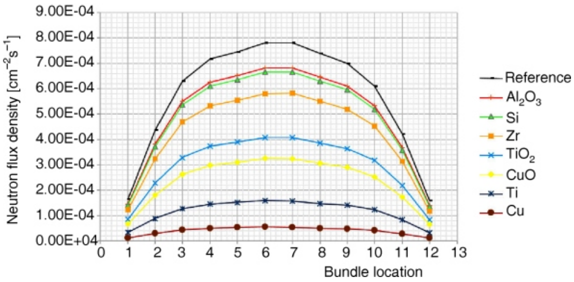

Figure 17. Neutron flux density distribution along a fuel channel next to the central axis for seven nanoparticles in 10 vol. %

CANDU-6 reactor core, with different volumetric percentages of nanoparticles, are shown in figs. 11-17.

As shown in figs. 11-17, by increasing the concentration of nanoparticles, there will be a rise in loss of neutron flux density. The reduction of neutron flux density in central fuel bundles is more evident than in fuel bundles at either end of the fuel channel, *i. e.*, the effect of nanoparticles at high volumetric percentages is more significant at higher neutron flux density zones. The reduction of neutron flux density in figures 15-17 for Cu and Ti nanoparticles, in comparison with other nanoparticles, are quite noticeable. This is because of their higher mass densities, giving rise to larger weight fractions on the same volumetric basis. It can be observed that adding the nanoparticles of alumina and silica to the coolant has a less significant influence on the reactor power. At the same time, copper nanoparticles, having high neutron absorption cross-sections, lead to more significant drop in neutron flux density and consequently, reactor power.

CONCLUSIONS

Neutronic analysis has been performed to assess the possibility of utilization of nanofluids as coolant in the CANDU-6 reactors. In this study, the heavy water-based nanofluids with nanoparticles such as Cu, Ti, CuO, TiO_2, Zr, Si, and Al_2O_3 have been used with the volumetric percentages in the range 0.001 %-10 %. The results show that by increasing the volume fraction of nanoparticles in the coolant of CANDU-6 reactor, k_{eff}, neutron flux density and reactor power decrease. The nanoparticles Si and Al_2O_3, with the volumetric percentage below 1 % in the coolant of CANDU-6 reactor, are observed to have less impact on the effective multiplication factor and neutron flux density than Cu, Ti, CuO, TiO_2, and Zr nanoparticles. It should be noted that in the contrary with PWR, the coolant and moderator in CANDU-6 reactor are physically separated. Therefore the overall neutronic effect of applying a nanofluid coolant in CANDU-6 is less; thus, a higher volume percentage of nanoparticle can be used (1 % in CANDU-6 instead of 0.1 % in PWR) [5].

According to physical properties of nanoparticles [12], Al_2O_3 nanoparticles have a higher thermal conductivity compared to Si nanoparticles; therefore, it is suggested to apply Al_2O_3 nanofluid in the reactor core as coolant [6]. Furthermore, the presence of nanoparticles such as Cu and Ti, even in low concentrations, are harmful and have negative effects on the effective multiplication factor and neutron flux density. The results of this study do not recommend using these materials as practical coolants in CANDU-6 reactors.

AUTHORS' CONTRIBUTIONS

The main idea of applying a nanofluid coolant in CANDU-6 reactor was put forward by G. Jahanfarnia, the calculations were done by R. Mirghaffari, and analysis and discussion were carried out by R. Mirghaffari. The manuscript and figures were prepared by R. Mirghaffari and were revised by G. Jahanfarnia and M. Athari Allaf.

REFERENCES

[1] Ramadhan, A. I., *et al.*, Effect Analysis of Volume Fraction of Nanofluid Al_2O_3-Water on Natural Convection Heat Transfer Coefficient in Small Modular Reactor, *Wo. J. of Nuclear Science and Technology,* (2016), 6, pp. 79-88

[2] Buongiorno, J., Hu, L. W., Nanofluid Heat Transfer Enhancement for Nuclear Reactor Applications, *Proceedings*, ASME 2009 2nd Micro/Nanoscale Heat & Mass Transfer International Conference, ASME 517-522, Shanghai, China, December 18-21, 2009

[3] Choi, S. U. S., Developments and Applications of non-Newtonian Flows, *American Society of Mechanical Engineers,* (1995), pp. 99-105

[4] Mirghaffari, R., Jahanfarnia, G., Spatial Distribution of Nanoparticles in PWR Nanofluid Coolant Subjected to Local Nucleate Boiling, *Kerntechnik, 81* (2016), 6, pp. 609-615

[5] Zarifi, E., *et al.*, Neutronic Simulation of Water-Based Nanofluids as a Coolant in VVER-1000 Reactor, *Progress in Nuclear Energy, 65* (2013), May, pp. 32-41

[6] Zarifi, E., *et al.*, Neutronic Analysis of Nanofluids as a Coolant in the Bushehr VVER-1000 Reactor, *Nukleonika, 57* (2012), 3, pp. 375-381

[7] Abdul Motalab, M., *et al.*, Detailed Monte Carlo Evaluation of the Power Coefficient of Reactivity of CANDU Reactor, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 29-30, 2014

[8] Cho, D. K., *et al.*, Sensitivity of Physics Parameters for Establishment of a Burned CANDU Full-Core Model for Decommissioning Waste Characterization, *Journal of Nuclear Science and Technology, 48* (2011), 2, pp. 215-226

[9] Bertachas, Y., Adjuster Rod Design in a CANDU Reactor and Flux Distributions Due to an Arbitrary Source of Neutrons, M. Sc. thesis, Department of Engineering Physics McMaster University, Hamilton, Ont., Canada, 1978

[10] Pounders, J. M., *et al.*, A 3-D Stylized Half-Core CANDU Benchmark Problem, *Annals of Nuclear Energy,* (2011), 38, pp. 876-896

[11] ***, AEOI, In-Core Fuel Management Benchmarks for PHWR, IAEA-TECDOC-887, Vienna, 1996
[12] Lomascolo, M., *et al*., Review of Heat Transfer in Nano Fluids: Conductive, Convective and Radiative Experimental Results, *Renewable and Sustainable Energy Reviews, 43* (2015), March, pp. 1182-1198

Received on June 6, 2017
Accepted on October 4, 2017

Реза МИРХАФАРИ, Голамреза ЈАХАНФАРНИЈА, Митра АТАРИ АЛАФ

НЕУТРОНСКА СИМУЛАЦИЈА CANDU-6 РЕАКТОРА ХЛАЂЕНОГ НАНОТЕЧНОШЋУ НА БАЗИ ТЕШКЕ ВОДЕ

У последње време дошло је до развоја обимних студија у којима се испитује примена нанотечности као средства за хлађење у нуклеарним електранама. CANDU-6 реактори имају могућност примене нанотечности као средства за хлађење јер је код ових реактора модераторски систем потпуно независан од примарног система за пренос топлоте. Применом програмског пакета MCNPX моделован је и симулиран рад CANDU-6 реактора са нанотечношћу као примарним хладиоцем. Испитивана је варијација мултипликационог фактора и расподела укупног неутронског флукса дуж горивног канала поред централне осе, за различите нанотечности. Анализиране су нанотечности засноване на тешкој води са додатим наночестицама Al_2O_3, TiO_2, CuO, Ti, Cu, Zr и Si, у различитим процентима укупне запремине. Као референтни модел реакторског језгра одабран је типични CANDU-6 реактор. Резултати неутронске анализе показују да нанотечност са додатим 1 % наночестица Al_2O_3 укупне запремине представља најприкладније средство за хлађење CANDU-6 реактора, јер може повећати коефицијент трансфера топлоте и тиме побољшати ефикасност рада електране.

Кључне речи: нанотечност, CANDU-6, MCNPX, неутронска анализа