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Neutronic and Thermalhydraulic Evaluation of Annular Fuel in PWR with Three Different Nanofluids

Ali TİFTİKÇİ*[1]

Abstract

In pressurized nuclear reactors, one of the fuel design principles is the fuel centerline temperature limit. Since the thermal conductivity of UO_2 is not high, the temperature increases rapidly from the fuel surface to the fuel center. To overcome this limitation, the use of annular type fuels instead of solid fuels is one of the improvement efforts. In this study, the effects of using annular fuel in a typical PWR are investigated. At the same time, the effects of adding nanoparticles (Al_2O_3, Cu and TiO_2-with volume fractions of $0 < \varphi < 0.2$ for neutronic and $0 < \varphi < 0.03$ for thermalhydraulic calculations) and to the coolant water in the case of solid and annular fuels are also investigated. For both cases, neutronic and thermalhydraulic calculations are made and compared. In neutronic point of view, it has been shown that the use of annular fuel does not cause a significant change in the k_{eff} value but the presence of nanoparticles reduces the k_{eff}. This reduction is maximum for Cu+water and minimum for Al_2O_3+water nanofluids. In thermalhydraulic point of view, it has been shown that the annular fuel positively affects the fuel temperature limits and the addition of nanoparticles could provide an additional contribution to this, provided that it is in very small amounts ($\varphi < 0.01$). Among the three nanoparticles examined, Cu+water is found to be the least suitable both in terms of neutronics and termalhydraulic considerations. TiO_2+water and Al_2O_3+water are comparable. It has also been shown that the optimum value for the annular fuel inner radius is approximately 0.4 cm.

Keywords: Annular fuel, nanofluid, Monte Carlo method, termalhydraulics

1. INTRODUCTION

Fuel rods used in nuclear reactors generally have a solid cylindrical geometry and the heat transfer is provided to the coolant from the outermost surface of the rod. Recently, different nuclear reactor fuel and coolant combinations have been studied to strengthen nuclear reactor safety and economy. One of these studying areas is the dual-cooled annular type fuel rods. Since the use of

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such systems will allow to move away from the fuel centerline temperature limit set for solid cylindrical fuel, fuel heat generation rates can be increased and the thermal performance and burn-up time to be obtained from the fuel could be optimized. Tak et al. [1] proposed a dual-cooled annular-type fuel concept in prismatic VHTR (Very High Temperature Reactor) reactors to solve the central fuel temperature problem. They performed thermal-hydraulic performance analysis for this reactor and as a result showed that the use of annular type fuel gives better results in terms of thermal-hydraulic performance. Lee et al. [2] compared pressure drops at nominal operating conditions for 16x16 solid cylindrical and 12x12 dual-cooled annular fuel bundle configurations for the OPR1000 reactor. According to the results, it was shown that the pressure drop is 15% less for a flat type spacer grid and 7% less for a spacer grid with mixing wane. Three-dimensional coupled neutronic and thermo-hydraulic analyzes for SCWR (Supercritical Water Reactor) reactor core have been performed by Zhao et al. [3] and according to their results, it has been shown to be promising for SCWR reactors. Ghazanfari et al. used an Al_2O_3 nanofluidic water coolant in addition to a dual-cooled annular-type reactor fuel and they investigated their thermal-hydraulic performances. As a result, it was observed that the coolant temperature increased and the fuel temperature decreased with the addition of nanofluidic water coolant. Therefore, the fuel melting temperature margin has increased and it has been stated that the safety and efficiency of the nuclear power plant will increase with the addition of annular-type fuel and nanofluid particles [4]. Işık and Tugan [5] investigated the thermal performance of nanofluids used in automobile radiators experimentally and numerically. They observed that the nanofluids convective heat transfer was higher than the base fluid and increases with volumetric flow rate and air velocity. Peyghambarzadeh et al. [6] studied experimentally forced convective heat transfer in Al_2O_3 nanofluidic water compared to that of pure water in an automobile radiator. They showed that the low concentration Al_2O_3 nanofluid can enhance heat transfer efficiency up to 45% in comparison with pure water. Ebrahimian et al. [7] studied the thermo-hydraulic effects of nanofluid particles on annular type dual cooled fuel geometry for VVER-1000 reactors. According to their results, they showed that the heat transfer coefficient of the external coolant (outside of the annular fuel) can be increased with the addition of nanofluid, which decreases with the use of annular-type fuel, and at the same time, MDNBR increases. Nejad et al. [8] proposed an annular fuel design for small modular reactors and investigated the effects of fuel internal diameter on power peaking factor and natural convection. According to the results, it has been observed that the use of annular fuel increases the neutron moderation and the excessive reactivity increases for this reason. Thus, it is predicted that the fuel can burn more in the core without changing the fuel.

In this study, the effect of three different nanoparticles for solid and annular fuel and the effect of fuel inner diameter for annular type fuel are investigated in terms of neutronics and thermalhydraulics. In thermalhydraulic point of view, fluid outlet temperature, maximum fuel temperature and maximum fuel surface temperatures are compared in terms of nanoparticle volume fraction and fuel inner diameter. The results have shown that annular-type fuel improves the thermalhydraulic performance and positively affects the safety margin. Also, the addition of nanoparticles for certain nanoparticle volume ratios also positively affects reactor heat transfer performance. In neutronic point of view, the effect of nanofluid volume fraction and fuel inner diameter is investigated by comparing the change in effective multiplication factor $\delta k/k$. In terms of neutronic calculations, the addition of nanoparticles and the increase of the fuel inner diameter reduce the k_{eff} value for all nanoparticle types.

2. MODELLING and METHOD

2.1. Neutronic Calculations

Neutronic calculations of nanofluids for solid cylindrical and annular type fuel PWR unit cell are performed using Monte Carlo method via

OPENMC [9] simulations. In this study, firstly, nanoparticles with a specified volume fraction are added to water both for solid and annular type geometry. While these additions are made, it is assumed that the fuel mass/volume and the moderator-to-fuel volume ratios are to be constant. Solid fuel and annular fuel neutronic performances are compared. Then, the effect of internal diameter in annular fuel is investigated for constant nanofluid volume fraction.

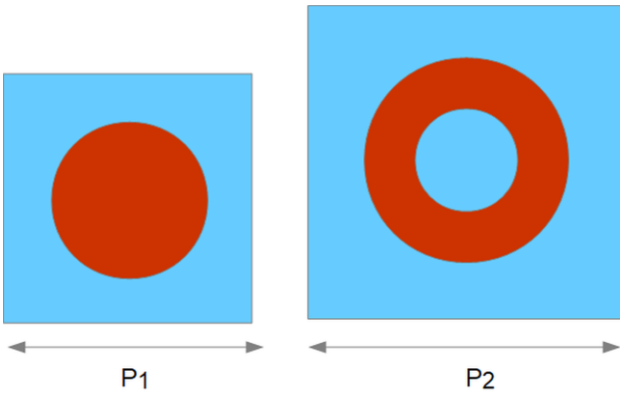

Figure 1 PWR unit cell for solid and annular fuel (not scaled)

Figure 1 shows a typical PWR unit cell for solid and annular fuel. Since the fuel mass and moderator-to-fuel volume ratios are fixed, the pitch length ($P_2 > P_1$) will increase slightly in annular type fuel. This means that the size of the annular type fueled reactor will be slightly larger than the solid cylindrical reactor.

The volume of pellet for a typical solid cylindirical fuel rod can be written as

$$V_{SF} = \pi R^2 H. \quad (1)$$

Here, R is the fuel pellet radius and H is the height of the solid fuel. Beside the fuel volume, the moderator-fuel volume ratio is also kept constant within the scope of this study. The main reason for this is to maintain the optimum moderator-fuel ratio which is specified for a typical PWR design.

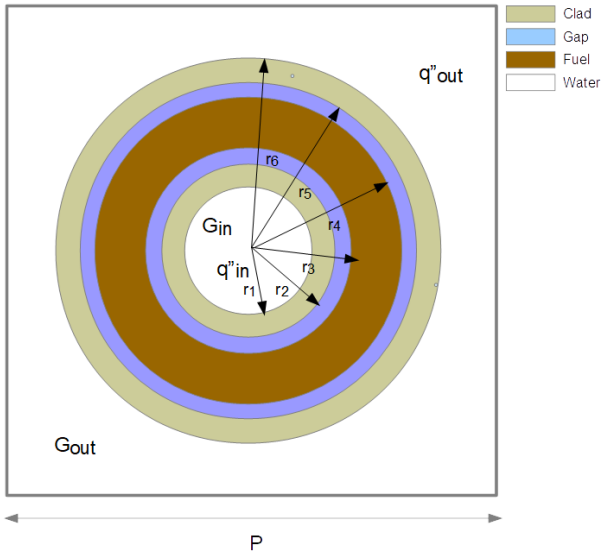

Figure 2 Schematical representation of annular fuel

As shown in Figure 2, when the thicknesses of the fuel clad (inner and outer clad for annular type fuel) and gap region are kept constant, the annular fuel pellet volume V_{AF} can be written as,

$$V_{AF} = \pi(r_4^2 - r_3^2)H \quad (2)$$

where $r_3 = r_1 + t_c + t_g$, $r_4 = r_3 + t_F$. Here, r_1: fuel rod inner radius, r_3: fuel pellet inner radius, r_4: fuel pellet outer radius, t_c: clad thickness, t_g: gap thickness, t_F: fuel thickness and r_6: fuel rod outer radius and $r_6 = r_4 + t_c + t_g$. For annular type fuel,

$$V_{AF} = \pi(r_4 - r_3)(r_4 + r_3)H \quad (3)$$

$$V_{SF} = V_{AF} = \pi(t_F)(r_3 + t_F + r_3)H \quad (4)$$

Therefore, the fuel thickness t_F can be evaluated as

$$t_F = \frac{-2r_3 \pm \sqrt{(2r_3)^2 + \frac{4V}{\pi H}}}{2}. \quad (5)$$

Thus, the moderator-fuel ratio is calculated as

$$\frac{V_M}{V_{AF}} = \frac{P^2 - \pi(r_6^2 - r_1^2)}{\pi(r_4^2 - r_3^2)}. \quad (6)$$

The unit cell parameters for annular type fuel can be obtained from Eqs. (3)-(6). The next step is to calculate the density of the mixture formed when

nanoparticles are added into water. The mixture density ρ_m [4-7] is determined by Eq.(7).

$$\rho_m = \rho_w \cdot (1-\varphi) + \rho_{np} \cdot \varphi \quad (7)$$

Here, ρ_w is the density of original water, ρ_{np} is the density of nanoparticles and φ is the volume fraction of nanoparticles in mixture. The unit cell OPENMC simulations are performed both for solid cylindrical and annular type cylindrical fuel geometries at different volume percentages ($0 < \varphi < 0.2$) of Al_2O_3, Cu and TiO_2 containing nanofluids. The fuel enrichment is selected as 3.57 w% and the periodic boundaries on lateral sides and vacuum boundaries on top and bottom sides of unit cell are implemented. ENDF/B.VIII.0 cross section data libraries are used for neutronic calculations and the k_{eff} values are obtained depending on the volumetric fractions of nanoparticles.

2.2. Thermal- Hydraulics Calculations

In this section, a typical PWR subchannel thermo-hydraulic parameters are analyzed analytically in order to evaluate the neutronic analysis together. As a reference, the results obtained for the PWR solid cylindrical fuel cell are compared with the annular type fuel cell.

If the average temperature in the direction of r, θ for each coolant point z is $T_m(z)$, one dimensional coolant temperature distribution can be obtained analytically. Also, if the heat transfer in the direction θ at any z point is neglected, the temperature distribution from the outer surface of the fuel clad to the center of the fuel can be calculated.

The heat diffusion equation at steady-state conditions can be written as

$$\nabla \cdot k(\vec{r},T)\nabla T(\vec{r},t) + q'''(\vec{r}) = 0. \quad (8)$$

Considering the thermal conductivity is constant for a cylindrical fuel rod, the diffusion equation becomes

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{q'''}{k_f} = 0. \quad (9)$$

The solution of heat diffusion equation for a solid cylindirical fuel

$$T(r) = T_s + \frac{q'''}{4k_f}\left(R_f^2 - r^2\right) \quad (10)$$

and for an annular-fuel,

$$T(r) = T_i + \frac{q'''}{4k_f}\left(R_f^2 - r^2\right) + \left[\frac{(T_o - T_i) + \frac{q'''}{4k_f}\left(R_f^2 - r^2\right)}{ln\frac{r_4}{r_3}}\right]\left(ln\frac{r}{r_3}\right). \quad (11)$$

Here, T_i is clad outer temperature at the inner surface of the fuel and T_o is the clad outer temperature at the outer surface of the fuel. Heat fluxes for internal flow and external flow are calculated according to the point where the fuel temperature is maximum [10].

$$q''_{in} = \frac{Q_{in}}{A_{in}} = Q_{total} \times \frac{V_{in}}{V_{fuel}} \times \frac{1}{A_{in}} = Q_{total} \times \frac{1}{A_{in}} \times \frac{r_m^2 - r_3^2}{r_4^2 - r_3^2} \quad (12)$$

$$q''_{out} = \frac{Q_{out}}{A_{out}} = Q_{total} \times \frac{V_{in}}{V_{fuel}} \times \frac{1}{A_{out}} = Q_{total} \times \frac{1}{A_{out}} \times \frac{r_4^2 - r_m^2}{r_4^2 - r_3^2} \quad (13)$$

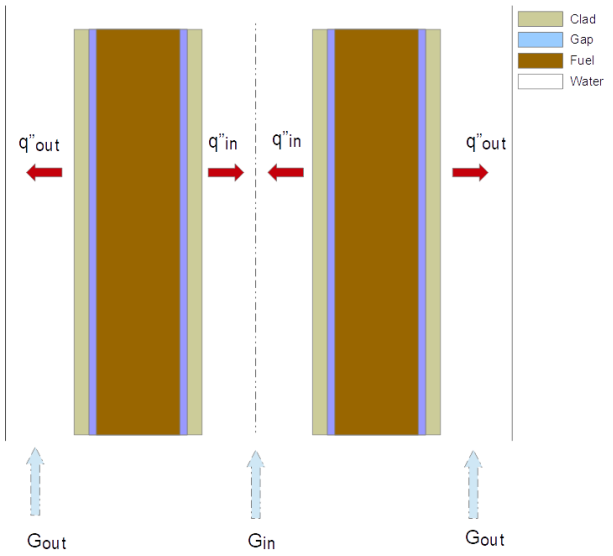

Figure 3 Axial view of annular fuel subchannel

As it is seen from Figure 3 and Eqs. (12)-(13), the heat fluxes transferred by the fuel to the inner and outer coolant may differ from each other. In order to calculate these heat fluxes, it is necessary to find the point r_m where the fuel temperature is maximum. The point r_m depends on the difference between the interior and exterior surface temperatures of annular fuel pellet. In this study, $T_o - T_i$ is assumed to be 5 ℃.

After calculating the fuel internal and external heat fluxes, the internal and external coolant temperature distributions are calculated. First of all, it is necessary to find the physical parameters (density, specific heat, viscosity and conductivity) of the relevant nanofluid. These parameters are calculated according to the volumetric fraction of nanoparticle (in this study, $0 < \varphi < 0.03$). Some of the thermophysical properties of base fluid water and three nanofluids are tabulated in Table 1. The calculation of density and specific heat of nanofluids is based on mixing theory. However, viscosity and conductivity calculations needs special attention. Viscosity is an important thermo-physical parameter especially for calculating core pressure drop and pumping power requirements. Several correlations for nanofluid viscosities are [11-14]. The thermal conductivity and the viscosity of resulting nanofluid are somewhat different from base fluid since Brownian motion effect of nanoparticles has to be taken into account. To do this, Jang and Choi model [15] for thermal conductivity of nanofluid is selected. The thermophysical properties of base fluid water and nanoparticles are given in Table 1.

Table 1
Thermophysical properties of water (at T=300 °C) and nanoparticles (T=20 °C)

Property	*Water*	*Al_2O_3*	*Cu*	*TiO_2*
$\boldsymbol{\rho\ (kg/m^3)}$	726.51	3970	8933	4260
$\boldsymbol{c_p(J/kgK)}$	5458.3	765	385	686.2
$\boldsymbol{k(W/mK)}$	0.5624	40	400	8.9538

Pak and Cho [12] suggested viscosity correlations for Al_2O_3+water and TiO_2+water as follows

$$\mu_{Al_2O_3} = \mu_w(533.9\varphi^2 + 39.11\varphi + 1) \qquad (14)$$

$$\mu_{TiO_2} = \mu_w(108.2\varphi^2 + 5.45\varphi + 1) \qquad (15)$$

Batchelor correlation [16] which recognizes the effect of Brownian motion is used for Cu+water nanofluid.

$$\mu_{Cu} = \mu_w(6.2\varphi^2 + 2.5\varphi + 0.1) \qquad (16)$$

Jang and Choi correlation [15] which includes Brownisn motion effect is used for all three nanofluids thermal conductivity calculation.

$$k_{nf} = k_{bf}(1-\varphi) + \beta k_p \varphi + C\frac{d_{bf}}{d_p} k_{bf} Re_p^2 Pr\varphi \qquad (17)$$

where constant related to Kapitza resistance $\beta = 0.01$, $C = 18 \times 10^6$, d_p is the diameter of nanoparticle, d_{bf} is the diameter of base fluid, Re_p is the Reynolds number of nanoparticle and defined as $Re_p = \frac{V_B d_p}{\nu}$ where $V_B = \frac{k_b T}{3\pi\mu_{bf} d_p l_{bf}}$ $k_b = 1.3807 \times 10^{-23}\ J/K$ is the Boltzmann constant, l_{bf} is the mean free path of base fuluid molecules. For water based nanofluids at $T = 27$ ℃, d_{bf} can be taken as 0.384 nm and l_{bf} can be taken as 0.738 nm.

The effective specific heat of nanofluids are calculated as [17]

$$c_{p,m} = \frac{\varphi(\rho c_p)_{np} + (1-\varphi)(\rho c_p)_w}{\rho_m} \quad (18)$$

Considering that the pressure drop due to friction will be equal for inner and outer channels,

$$\Delta P = \left(\frac{0{,}184}{Re^{0,2}}\right) \times \rho \times v^2 \times \frac{1}{2D_e}$$

Then,

$$G_{in} = \frac{\dot{m}}{\left(A_1 + A_2\left(\frac{D_{e,1}}{D_{e,2}}\right)^{0,67}\right)}$$

$$\dot{m}_1 = G_{in} \cdot A_1$$

Here, A_1 and A_2 are respectively the inner and outer flow areas, $D_{e,1}$ and $D_{e,2}$ are the equivalent diameters for the inner and outer flow. $\dot{m}$ is total subchannel coolant flow rate , $\dot{m}_1$ and $\dot{m}_2$ are the internal and external coolant flow rates respectively.

If the energy balance is written for the coolant flow in the channel,

$$q_1'(z) = q_{0,1}' \cdot \cos\left(\frac{\pi z}{L}\right)$$

$$q_2'(z) = q_{0,2}' \cdot \cos\left(\frac{\pi z}{L}\right)$$

$$\dot{m}_1 c_{p,1} \frac{dT_{m,1}}{dz} = q_1'(z)$$

$$\dot{m}_2 c_{p,2} \frac{dT_{m,2}}{dz} = q_2'(z)$$

Fuel inner and outer surface temperatures are calculated using Newton's law of cooling.

$$q_1''(z) = h_1[T_{s1}(z) - T_{m1}(z)]$$

$$q_2''(z) = h_2[T_{s2}(z) - T_{m2}(z)]$$

If thermal resistances are used for the fuel envelope and gap region, the fuel pellet inner and outer surface temperatures are calculated and the temperature distribution within the fuel pellet can be found for any axial location.

3. RESULTS and DISCUSSION

3.1. Neutronics (Solid Fuel)

Figure 4 shows the results of OPENMC simulations for solid cylindrical fuel geometry. It is seen that the k_{eff} value decreases with the increase in volumetric fraction of nanoparticles for three different nanofluids. The slope of the graph is minimum for Al_2O_3 added nanofluid, while it is maximum for Cu added nanofluid. This is because copper has a higher density than the other two nanoparticles and therefore absorbs more neutrons, since its macroscopic neutron absorption cross section is higher.

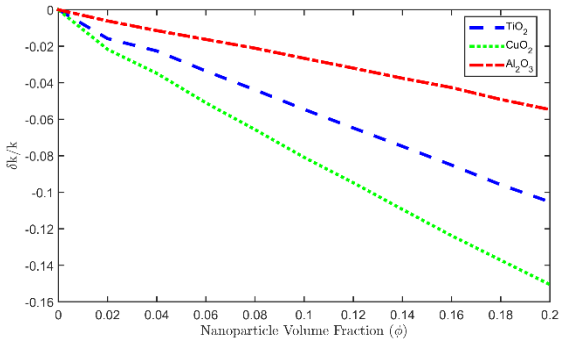

Figure 4 Solid fuel k_{eff} values for different nanoparticle fractions

3.2. Neutronics (Annular Fuel)

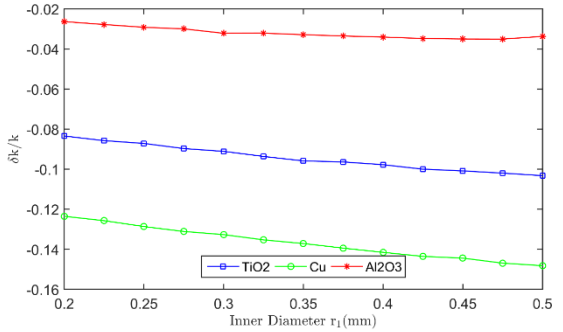

Figure 5 Change in effective multiplication factor $\delta k/k$ values of annular fuel for different inner diameters

Figure 5 shows the results of OPENMC simulations for annular-type cylindrical fuel geometry. Here, the effect of the change in fuel inner diameter on the k_{eff} value has been

investigated. For these simulations, the volumetric fraction φ is fixed at 0.1. For all three fluids, the increase in the inner diameter of the fuel causes a decrease in the k_{eff} value. For Al_2O_3 added nanofluid, the change in the fuel inner diameter has a minimum effect, while the maximum effect is seen for the Cu added nanofluid. This is because the fuel gets thinner as the inner radius increases, and the neutrons interact more within the nanofluid moderator until fission occurs. This can cause extra neutron absorption, and this is particularly evident for the copper-containing nanofluid.

3.3. Thermal-Hydraulics (Solid)

While all other parameters are constant, the effect of nanoparticle fraction for a solid fuel in a typical PWR subchannel is investigated. The nominal average linear heat rate of 17.86 kW/m is used. At the nominal PWR pressure, the addition of nanoparticles above a certain ratio causes boiling. Therefore, the volumetric percentage of nanoparticles is limited to 0.03.

Figure 6 shows fluid outlet temperature as a function of nanoparticle volume fraction ($0 < \varphi < 0.03$) for a typical PWR and for three different nanoparticle types. The fluid outlet temperatures increase with nanoparticle fraction since possible specific heat (c_p) reduction from the base water (has higher c_p than nanoparticles). Cu+water nanofluid has maximum slope, Al_2O_3+water and TiO_2+water shows similar behavior.

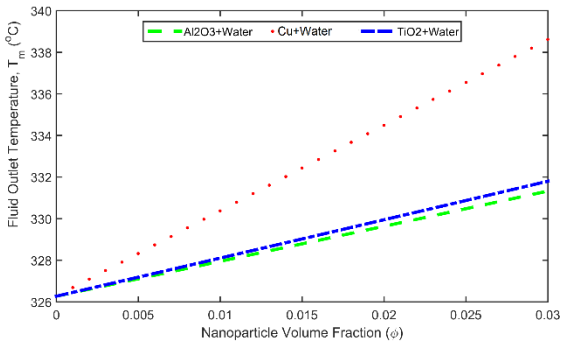

Figure 6 Fluid outlet temperature of subchannel for different nanoparticle fractions

Figure 7 shows fuel centerline temperature as a function of nanoparticle fraction for a typical PWR and for three different nanoparticle types. It is observed that the fuel centerline temperature decreases as the nanoparticle ratio increases up to $\varphi = 0.01 - 0.015$. A significant increase is observed after this range in Cu+water, while the decrease continues for Al_2O_3+water and TiO_2+water. Figures 6, 7 and 8 should be considered together for the discussion of Figure 7. In Figure 8, the heat transfer coefficients increase with the increase of nanoparticles, but the lowest increase is seen in Al_2O_3+water. At the same time, as mentioned earlier, the coolant temperature also increases as a result of nanoparticle increase in Figure 6. According to Newton's law of cooling, for the same heat flux and fuel conductivity values, the fuel surface temperature T_s and also fuel centerline temperature depends on the coolant temperature and heat transfer coefficient h. While the increase in the heat transfer coefficient is effective up to the $\varphi \cong 0.01$ point, the increase in the coolant temperature after this point causes the fuel surface temperature and thus the fuel centerline temperature to increase for Cu+water nanofluid. When TiO_2+water and Al_2O_3+water are compared, it can be said that the nanofluid with the best performance is TiO_2+water, since the improvement in the heat transfer coefficient of Al_2O_3+water is the least one.

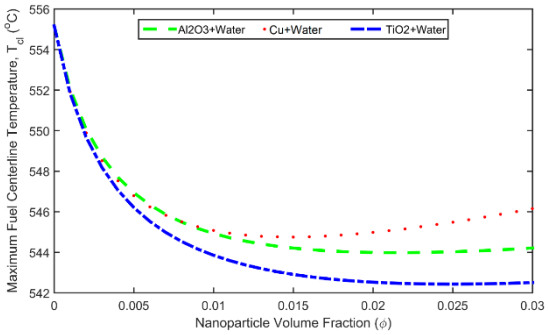

Figure 7 Fuel centerline temperature of solid fuel in PWR hot channel for different nanoparticle fractions

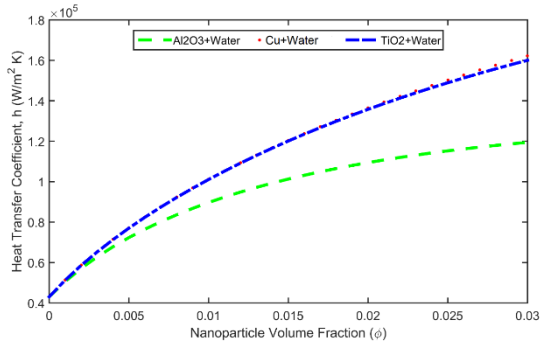

Figure 8 Heat transfer coefficient of subchannel

3.4. Thermal-Hydraulics (Annular)

3.4.1. Effect of Inner Diameter

The effect of inner diameter in case of an annular type fuel is investigated. Firstly, temperature dependencies of inner and outer fluid and inner and outer surface of fuel are evaluated in the absence of nanoparticles. The inner and outer fluid temperatures, inner and outer clad maximum temperatures, fuel maximum temperature and heat transfer coefficient of inner and outer fluid as a function of inner diameter are shown in Figs. 9-12.

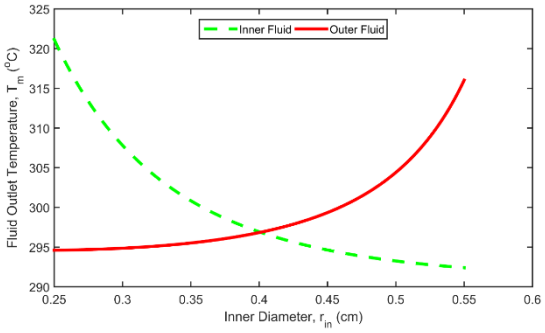

Figure 9 Fluid outlet temperature of inner and outer coolant as a function of inner diameter

As seen in Figure 9, as the fuel internal diameter increases, the internal flow temperature decreases while the external flow temperature increases. They become equal to each other approximately $r_{in} = 0.4$ cm.

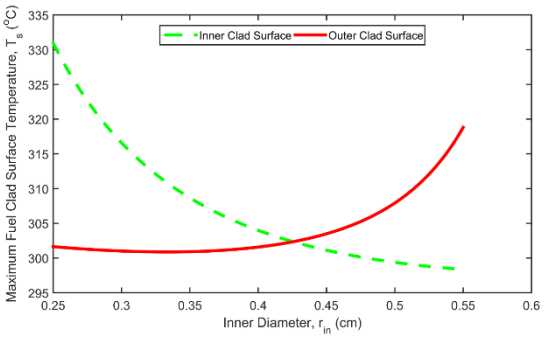

Figure 10 Maximum fuel clad temperature of inner and outer surface as a function of inner diameter

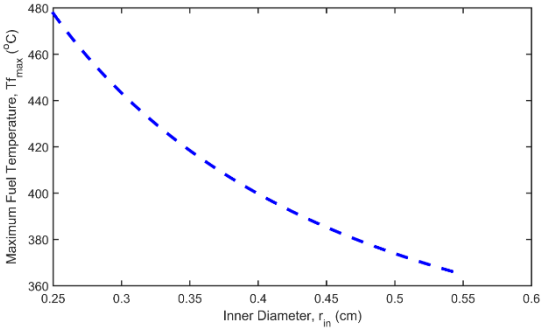

Figure 11 Maximum fuel temperature as a function of inner diameter

As demonstrated in Figure 11, as the inner radius increases, the fuel centerline temperature decreases, but the fuel outer clad temperature (Figure 10) increases rapidly after $r_{in} \cong 0.4 - 0.45\ cm$ range. This is due to the deterioration in the heat transfer coefficient is shown in Figure 12. Considering Figs. 9-12 together, $r_{in} \cong 0.4\ cm$ might be considered as an optimum option.

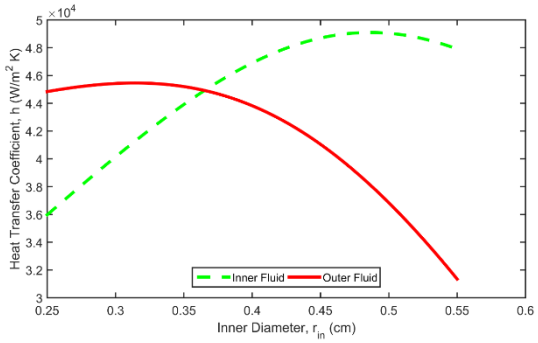

Figure 12 Heat transfer coefficient of inner and outer coolant as a function of inner diameter

3.4.2. Effect of Nanoparticle Fraction

In this part, the effect of nanoparticle volume fraction is investigated. The inner radius of fuel is fixed as $r_{in} = 0.4$ cm. The inner fluid outlet, outer fluid outlet, maximum inner and outer clad and maximum fuel tempertaures as a function of nanoparticle volume fraction are shown in Figs. 13-17.

The effect of nanoparticle volume fraction on selected fuel parameters are similar that of solid fuel case except the temperature values are lowered. Here, when all nanofluids are compared TiO_2+water can be considered as the best option in terms of safety.

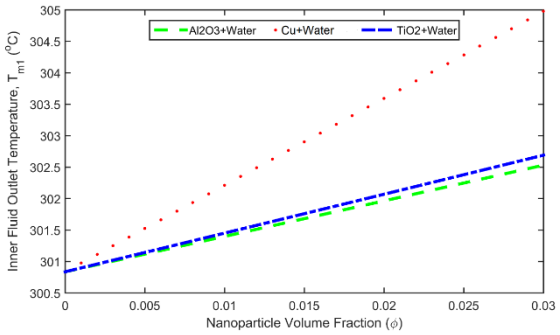

Figure 13 Fluid outlet temperature of inner coolant as a function of nanoparticle volume fraction

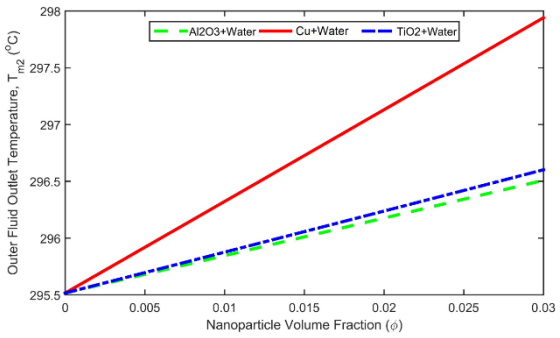

Figure 14 Fluid outlet temperature of outer coolant as a function of nanoparticle volume fraction

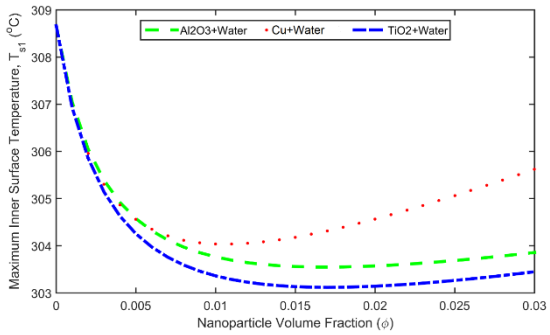

Figure 15 Maximum inner fuel clad temperature as a function of nanoparticle volume fraction

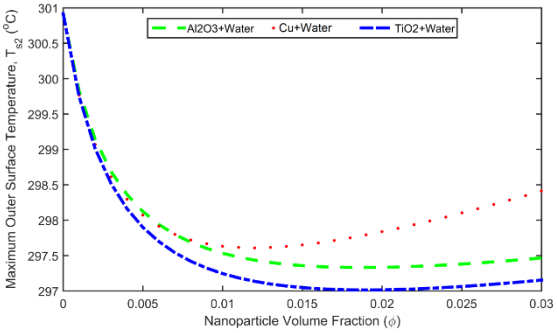

Figure 16 Maximum outer fuel clad temperature as a function of nanoparticle volume fraction

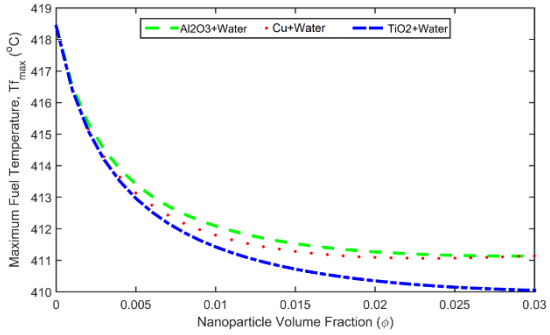

Figure 17 Maximum fuel temperature as a function of nanoparticle volume fraction

4. CONCLUSIONS

In pressurized nuclear reactors, one of the fuel design principles is the fuel centerline temperature limit. Since the thermal conductivity of UO_2 is not high, the temperature increases rapidly from the fuel surface to the fuel center. In order to overcome this, there have been studies such as the use of some metal alloys in new generation fuels. In addition to these studies, it is thought that this problem can be prevented with

annular fuels. In addition, it is envisaged to increase the thermal performance by adding nanoparticles to the coolant. The data obtained in this study show that, the addition of nanoparticles causes a decrease in the k_{eff} value. The minimum amount of decrease occurs in Al_2O_3+water and the maximum decrease occurs in Cu+water for solid fuel case. Therewithal, the effect of inner diameter on k_{eff} value of annular fuel is investigated for a fixed volume fraction of $\varphi = 0.1$. The results showed that the increase in inner fuel diameter causes decrease in k_{eff} value. The minimum decrease is seen in Al_2O_3+water nanofluid and the maximum is in Cu+water since the fuel gets thinner when the inner diameter increases and neutrons make more interactions while slowing down to thermal energies. This causes extra neutron absorptions within the copper containing nanofluid. It has also been observed that the addition of excess nanoparticles for PWR reactors leads to boiling. Additionally, the fuel centerline temperature begins to increase for $\varphi > 0.01$. In case of the change in inner diameter of annular fuel, the k_{eff} values are not significantly affected except Cu+water nanofluid. $r_{in} \cong 0.4$ cm could be considered as an optimum choice when the inner and outer coolant temperatures and the inner and outer clad temperatures are examined together. Finally, it has been shown that the annular fuel positively affects the fuel temperature limits and the addition of nanoparticles could provide an additional contribution to this, provided that it is in very small amounts ($\varphi < 0.01$). Among the three nanoparticles examined, Cu+water is found to be the least suitable both in terms of neutronics and termal considerations. TiO_2+water and Al_2O_3+water are comparable. It can be said that Al_2O_3 from the neutronic calculations and TiO_2 from the thermal point of view show the relatively best performance. This study could be improved in the future with fuel burnup and detailed computational fluid dynamics calculations. In addition, fuel material behavior analyzes should be performed for the fuel configuration that is found to be neutronically and thermally suitable.

Nomenclature and List of Abbreviations

φ	Volume fraction of nanofluid
k_{eff}	Effective multiplication factor
OPR1000	Optimized Power Reactor (1000 MWe)
VVER1000	Water-Water Energetic Reactor (1000 MWe)
MDNBR	Minimum Departure From Nucleate Boiling Ratio
PWR	Pressurized Water Reactor
$k(\vec{r},T)$	Space and temperature dependent thermal conductivity ($W/m \cdot K$)
$q'''(\vec{r})$	Space dependent volumetric heat generation rate (W/m^3)
μ_w	Dynamic viscosity of water
k_{bf}	Conductivity of base fluid ($W/m \cdot K$)
h_1	Heat transfer coefficient of inner nanofluid ($W/m^2 \cdot K$)
h_2	Heat transfer coefficient of outer nanofluid ($W/m^2 \cdot K$)

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The Declaration of Conflict of Interest/ Common Interest

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The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declare that he complies with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that he does not make any falsification on the data collected. In addition, he declares that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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