# A Comparative Thermal-hydraulic Study on Nano-fluids as a Coolant in Research Nuclear Reactors

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**Abstract:** Nanofluids, which are engineered suspensions of nanoparticles in a solvent such as water, have been found to show enhanced coolant properties which is a useful characteristic in nuclear reactors. This study attempt to provide data when using nano-fluids in nuclear reactors cooling. Distilled water and $AL_2O_3$ -water based nano-fluids with different volume fraction (2% ,4% ,6%) were used as coolant in 22 (MW) research reactor. The effect of nanoparticles on centerline fuel, clad and coolant temperatures were investigated when distilled water were used. The results compared with $AL_2O_3$ –water based nano-fluids with 2% ,4% and 6% volume fraction for hot and average channels. It was observed that $AL_2O_3$ –water based enhanced the heat transfer coefficient compared to distilled water, hence the clad temperatures reduced at the same operating conditions of the reactor.

**Index Terms**— Nano-fluids , Heat transfer enhancement, Research reactors, Physical properties.



## 1. Introduction

Nano-fluids that harbor nano-sized particles or engineered colloids are a new type of heat transfer coolants. Their initial concepts suggested by Choi [1] started with an idea that solids have thermal conductivities that are orders of magnitude larger than those of traditional heat transfer fluids such as water, ethylene glycol and refrigerants. That means particles-fluids mixtures have higher thermal performances than conventional fluids due to suspended nanoparticles. The correlations to predict the Nusselt number under laminar and turbulent flow conditions is developed [2]. These correlations are useful to predict the heat transfer ability of nano-fluids and takes care of variations in volume fraction, nanoparticle size and fluid temperature. The improved thermophysical characteristics of a nano-fluid make it excellently suitable for future heat exchange applications. Heat transfer enhancement in horizontal annuli using variable properties of $Al_2O_3$ – water nano-fluid is investigated. Different viscosity and thermal conductivity models are used to evaluate heat transfer enhancement in the annulus. The average Nusselt number was reduced by increasing the volume fraction of nanoparticles [3]. As a fluid class, nano-fluids have a unique feature which is quite different from those of conventional solid-liquid mixture and or micrometer-sized particles are added. Such particles settle rapidly, clog flow channels, erode pipelines and cause severe pressure drops. All these shortcomings prohibit the application of conventional solid-liquid mixtures to micro channels while nano-fluids instead can be used in micro-scale heat transfer. Furthermore, compared to nucleate pool boiling enhancement by addition of surfactants nano-fluids can enhance the critical heat flux (CHF) while surfactants normally do not [4]. Thus, nano-fluids appear promising as coolants for dissipating very high heat flux in various applications. Past research has focused on better understanding of physical phenomena of nuclear thermal-hydraulic, that is, boiling and condensation, and better correlations to predict the phenomena and thereby produce better simulation codes. In addition, with increasing nuclear reactor generation with accompanying emphasis on both economics and safety systems have changed from active cooling systems to passive cooling systems in order to secure safety. In particular, works introducing nanotechnology to boiling and condensation have been boosted by new developments in nanomaterials having unique properties arising from their nanoscale dimensions [5]. Past researches have shown that a very small amount of suspending nanoparticles have potential to enhance the thermo physical, transport and radiative properties of the base fluid. Due to improved properties better heat performance is obtained in many energy and heat transfer devices as compared to traditional fluids which open the door for field of scientific research and innovative applications [6]. Turbulent forced convection flow of Al2O3 – water nano-fluid in a single – bare sub channel of a typical pressurized water reactor is numerically analyzed. The single – phase model is adopted to simulate the nano-fluid convection of 1% and 4% by volume concentration. The renormalized group k- ϵ model is used to simulate turbulence in ANSYS FLUENT 12.1. Result show that the heat transfer increases with nanoparticle volume concentration in the sub channel geometry. The highest heat transfer rates are detected, for each concentration, corresponding to the highest Reynolds number Re. the maximum heat transfer enhancement at the center of a sub channel formed by heated rods is ̴15 % for the particle volume concentration of 4% corresponding to Re = 80000 [7]. A thermal-hydraulic model is formulated for a typical MTR reactor using finite difference approximation of a group of differential equations that describe the reactor core, heat exchanger and cooling tower. The model includes both the primary and secondary cooling system and predicts the fuel, clad and coolant temperatures in the core [8].

## 2. Mathematical model

### 2.1. Heat flux

The total desired reactor core thermal power (Qth) is 22 (MWth), on which all reactor core calculations are based. The reactor average power density $(q'''_{ave})$ is given by,

$$q'''_{ave} = Q_{th}/V_{core} \tag{1}$$

Where Vcore is the fuel meat volume of the reactor core. The maximum core power density $(q'''_{\max})$ is given by,

$$q'''_{\max} = F_{HC} \times q'''_{ave} \tag{2}$$

Where, FHC is the hot channel factor, given by,

$$F_{HC} = F_E \times F_{NUC} \tag{3}$$

where FE is the engineering peaking factor and FNUC is the nuclear peaking factor given by,

$$F_{NUC} = F_A \times F_R \tag{4}$$

The core axial power; $q'''(z)$ distribution is assumed to follow a cosine shape given by,

$$q'''(z) = q'''_{\max} \cos\left(\frac{\pi z}{H}\right) \tag{5}$$

Where, z is measured from the midpoint of the fuel element and H is the total fuel element length (core height). There is negligible variation in $q'''$ in the x- and y-directions of the plate element. The axial distribution of heat flux; $q''(z)$ is given by,

$$q''(z) = \frac{q'''(z)}{SVR} = \frac{w_f \times t_f}{2(w_f + t_f)} q'''(z) \tag{6}$$

Where SVR is the fuel meat surface to volume ratio, wf and tf are the fuel meat width and thickness, respectively.

### 2.2. The fuel centerline distribution

The fuel maximum center-line temperature is determined by combining the heat transfer equations for the coolant bulk-cladding outer surface, cladding outer surface-inner surface and fuel outer surface-fuel centerline interfaces. These equations are,

$$T_b = \frac{1}{2}(T_{in} + T_{out}) \tag{7}$$

$$T_{co} = \frac{q'''_{\max} \times t_f}{h} + T_b \tag{8}$$

$$T_{ci} = T_{co} + \frac{q'''_{\max} \times t_c t_f}{k_c} \tag{9}$$

$$T_{fc} = T_{fs} + \frac{q'''_{\max} \times t_f^2}{4k_f} \tag{10}$$

Where Tb is the bulk coolant temperature, Tin and Tout are the reactor core coolant inlet and outlet temperatures, respectively, Tci and Tco are the cladding inner and outer surface temperatures, respectively, Tfs is the fuel surface temperature, Tfc is the maximum fuel centerline temperature, h is the coolant heat transfer coefficient, kw, kc, kf are the coolant water, clad and fuel meat thermal conductivities, respectively. Combining equations (7 - 10) and assuming perfect heat transfer across the fuel surface/cladding inner surface interface (i.e. Tci = Tfs); the following equation for the centerline fuel temperature is obtained as follows:

$$T_{fc} = q'''_{\max}\left(\frac{t_f^2}{4k_f} + \frac{t_c t_f}{k_c} + \frac{t_f}{h}\right) + \frac{1}{2}(T_{in} + T_{out}) \tag{11}$$

### 2.3. The temperature along the coolant channel

The local temperatures of coolant, clad outer surface and the fuel surface at the distance z from the entrance of sub-channel were calculated with the local heat flux, the coolant mass flow rate and the inlet temperature of the coolant for the hot channel.
The bulk coolant temperature as a function of position Tb (z), along the hottest channel is given by,

$$T_b(z) = T_{in} + \frac{q'''_{\max}(z) A_f H}{\pi G_{ch} c_p}\left[1 + \sin\left(\frac{\pi z}{H}\right)\right] \quad (12)$$

Where Af is the cross-sectional area of the fueled portion of the fuel plate, Gch is the coolant mass flow rate through the channel and cp is the specific heat of the coolant water. According to equation (12) the coolant temperature increases along the channel and reaches the maximum value at the exit of the channel.

$$T_{b,\max} = T_{in} + \frac{2 \times q'''_{\max} V_f}{\pi G_{ch} c_p} \quad (13)$$

Where Vf is the volume of the fueled portion of the fuel plate. The clad outlet temperature can be calculated as a function of position along the channel as follows:

### 2.4. The clad outlet temperature

$$T_{co}(z) = T_{in} + \frac{q'''_{\max} V_f}{\pi G_{ch} c_p}\left[1 + \sin\left(\frac{\pi z}{H}\right)\right] + q'''_{\max} V_f R_h \cos\left(\frac{\pi z}{H}\right) \quad (14)$$

Where Rh is the resistance for convective heat transfer = 1/hAp, and Ap is the surface area of the fuel plate. The centerline fuel temperature (Tm) can be calculated by,

$$T_{fc}(z) = T_{in} + \frac{q'''_{\max} V_f}{\pi G_{ch} c_p}\left[1 + \sin\left(\frac{\pi z}{H}\right)\right] + q'''_{\max} V_f R_t \cos\left(\frac{\pi z}{H}\right) \quad (15)$$

Where Rt is the total thermal resistance = $\frac{t_f}{2k_f A_p} + \frac{t_c}{k_c A_p} + \frac{1}{hA_p}$ and tc is the clad thickness. The position of the maximum fuel temperature (zm,max) is given by,

$$z_{m,\max} = \frac{H}{\pi}\cot^{-1}\left(10^3 \times \pi G_{ch} c_p R_t\right) \quad (16)$$

Similarly, the position of the maximum cladding temperature (zc,max) is given by,

$$z_{c,\max} = \frac{H}{\pi}\cot^{-1}\left(10^3 \times \pi G_{ch} c_p R_h\right) \quad (17)$$

### 2.5. The coolant heat transfer coefficient

#### 2.5.1. Single - phase turbulent regime

The heat transfer coefficient of the coolant in the hot channel of each reactor core can be determined by use of the familiar Dittus-Boelter equation, Reynolds > 10000.

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \quad (18)$$

Where Nu, Re and Pr are the Nusselt, Reynolds and Prandtl numbers, respectively which are defined as follows,

$$Nu = \frac{hD_h}{k_w} \quad (19)$$

$$\mathrm{Re} = \frac{\rho v_{ch} D_e}{\mu_c} \quad (20)$$

$$\mathrm{Pr} = \frac{\mu_c c_p}{k_w} \quad (21)$$

Where Dh is the hydraulic diameter of the coolant channel and is defined as:

$$D_h = \frac{4A_w}{P_h} \quad (22)$$

Where Ph is the heated perimeter = 2wp, De is the equivalent diameter of the coolant channel = $4A_w/P_w$ , and Pw is the wetted perimeter = 2wp+2tw.

### 2.6. The thermophysical properties of the nano-fluid (AL2O3)

In this model the homogenous mixture is assumed. For the single phase fluid flow that the presence of nano-particles is realized by modifying physical properties of the mixture fluid. It is assumed that there is no velocity difference between fluids and the particles, and the fluids and the particles are in thermal equilibrium.

$$\rho_{nf} = (1-\phi)\times\rho_{bf} + \phi\times\rho_{p} \quad (23)$$

$$(\rho\times C_p)_{nf} = (1-\phi)\times(\rho\times C_p)_{bf} + \phi\times(\rho\times C_p)_{P} \quad (24)$$

$$\mu_{nf} = \left(123\times\phi^2 + 7.3\times\phi + 1\right)\times\mu_{bf} \quad (25)$$

$$k_{nf} = \left(4.97\times\phi^2 + 2.72\times\phi + 1\right)\times k_{bf} \quad (26)$$

**Table1. Thermal conductivities of Various Solids and Liquids at Room Temperature [4].**

| Material | Form | Thermal conductivities (W/m.K) |
|---|---|---|
| Carbon | Nano-tubes<br>Diamond<br>Graphite<br>Fullerences film | 1800 – 660<br>2300<br>110 – 190<br>0.4 |
| Metallic Solids (pure) | Silver<br>Copper<br>Nickel | 429<br>401<br>237 |
| Non-metallic Solids | Silicon | 148 |
| Metallic Liquids | Aluminum<br>Sodium at 644 K | 40<br>72.3 |
| Others | Water<br>Ethylene Glycol<br>Engine Oil<br>R134a | 0.613<br>0.253<br>0.145<br>0.0811 |

**Table2. Thermophysical properties of nanoparticle and base fluids [2].**

| Property | Water | Ethylene Glycol | Cu | $AL_2O_3$ | CuO | $TiO_2$ |
|---|---|---|---|---|---|---|
| C [J/Kg.K] | 4179 | 2415 | 385 | 765 | 535.6 | 686.2 |
| ρ [Kg/m$^3$] | 997.1 | 1111 | 8933 | 3970 | 6500 | 4250 |
| k [W/m.K] | 0.605 | 0.252 | 400 | 40 | 20 | 8.9538 |
| α [m$^2$/s] | 1.47 | 93 | 1163 | 1317 | 57.45 | 30.7 |

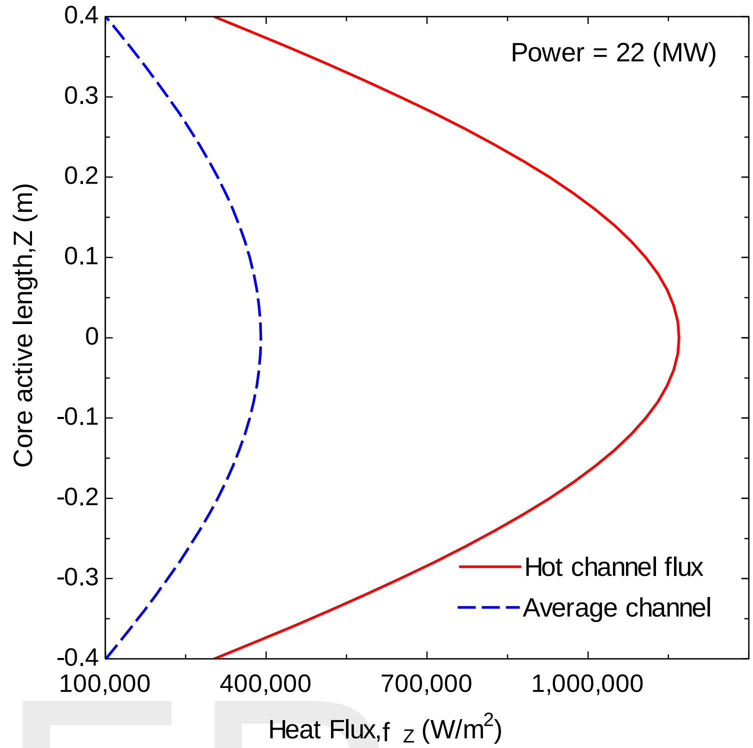


Fig.1. Heat flux distribution for hot and average channel at 22 MW. Research Reactor.

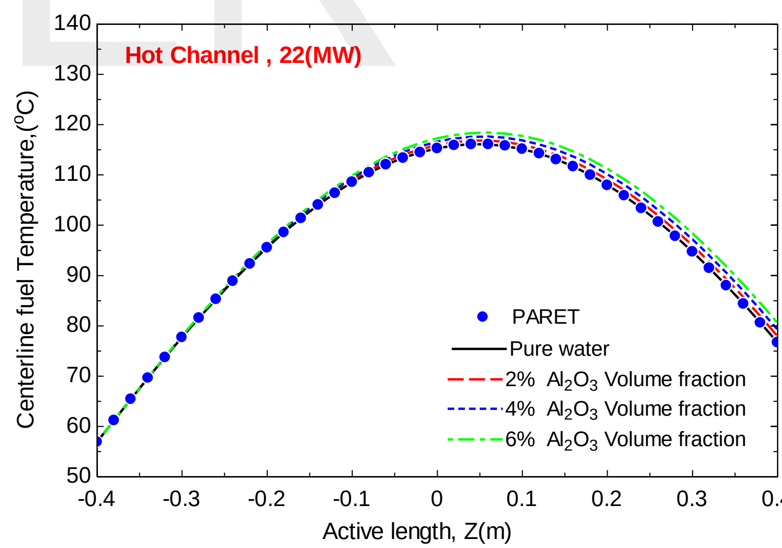


Fig.2. Hot channel centerline fuel temperature for pure water and water-Al2O3 nano-fluids at different volume fraction.

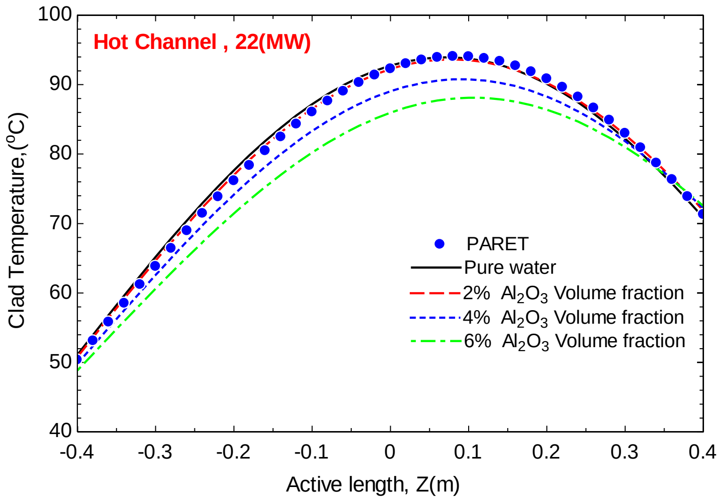


Fig.3. Hot channel clad temperature for pure water and water-Al2O3 nano-fluids at different volume fraction.

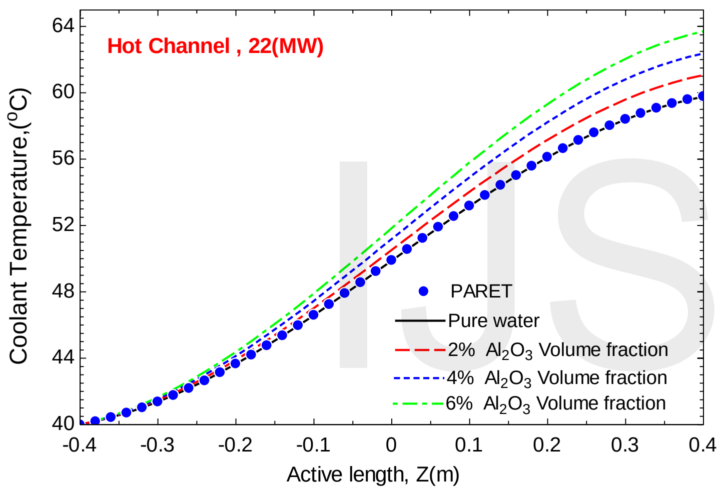


Fig.4. Hot channel coolant temperature for pure water and water-Al2O3 nano-fluids at different volume fraction.

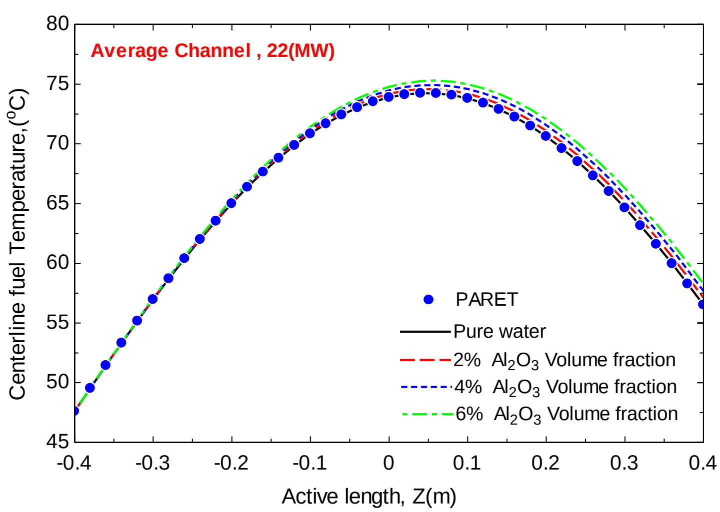


Fig.5. Average channel centerline fuel temperature for pure water and water-Al2O3 nano-fluids at different volume fraction.

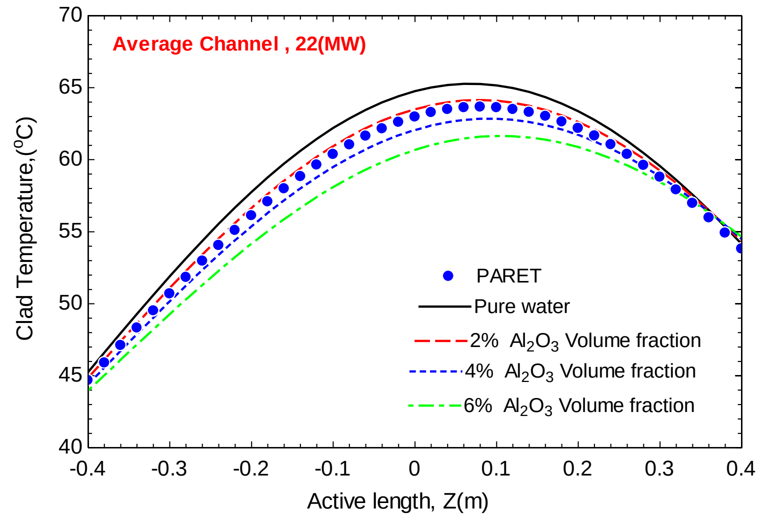


Fig.6.Average channel clad temperature for pure water and water-Al2O3 nano-fluids at different volume fraction.

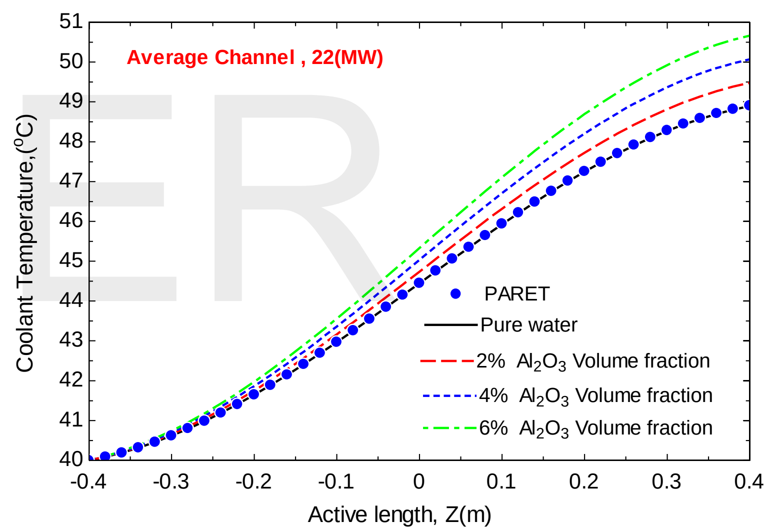


Fig.7. Average channel coolant temperature for pure water and water-Al2O3 nano-fluids at different volume fraction.

## 3. Results

Liquid molecules close to a solid surface are known to form layered structures. The layered molecules are in an intermediate physical state between a solid and bulk liquid. With these solid like liquid layers, the nano-fluid structure consists of solid nanoparticles, solid-like liquid layer, and a bulk liquid. The solid-like nanolayer acts as a thermal bridge between a solid nanoparticle and a bulk liquid and so is key to enhancing thermal conductivity.

Macroscopically, the forced convective heat transfer coefficient ,h , is given by h =( Kf /δt ), where, δt representing the local thickness of thermal boundary layer and (Kf) is the local effective thermal conductivity of nano-fluids adjacent to the wall surface. So, as (Kf) increasing and decreasing in (δt), can result in increasing of the convective heat transfer coefficient.

Figure (1) shows the relation between the heat flux distribution for hot and average channel of 22 (MW) research reactor. The maximum values of the heat fluxes was at the center of the fuel.

Figure (2) depicts the relation between the hot channel centerline fuel temperature for pure water and water- $Al_2O_3$ nano-fluid at different volume fractions. There is a good agreement between the results of the present model and PARET code. By using the nano-fluid we observed that the centerline fuel temperature almost the same for 2% , 4% and 6% volume fractions.

Figure (3) illustrate the relation between the hot channel clad temperature for pure water and water- $Al_2O_3$ nano-fluid at different volume fractions. Using water- $Al_2O_3$ nano-fluid with 2% volume fraction, we observed that the clad temperature reduced. Increasing the volume fraction of the nano-fluid the clad temperature decreased due to increases in the density and thermal conductivity of the alumina water nano-fluid, hence the heat transfer enhanced.

Figure (4) displays the relation between the coolant temperature for pure water and water- $Al_2O_3$ nano-fluid at different volume fractions in hot channel. At each position of coolant channel, the temperature of water- $Al_2O_3$ nano-fluid is higher than the pure water, i.e. water- $Al_2O_3$ nano-fluid can remove more heat than base fluids because of its higher thermal conductivity in comparison with the base fluid.

Figure (5) exhibits the relation between the average channel centerline fuel temperature for pure water and water- $Al_2O_3$ nano-fluid at different volume fractions. The figure showed that the centerline fuel temperature almost the same for 2% , 4% and 6% volume fractions.

Figure (6) displays the relation between the average channel clad temperature for pure water and water- $Al_2O_3$ nano-fluid at different volume fractions. It is obvious that as the volume fraction increases the (Pr) decreases, hence the clad temperature decrease.

Figure (7) shows the relation between the coolant temperature for pure water and water- $Al_2O_3$ nano-fluid at different volume fractions in average channel. At each position of coolant channel, the temperature of water- $Al_2O_3$ nano-fluid is higher than the pure water, i.e. it can remove more heat than base fluids because of its higher thermal conductivity in comparison with the base fluid.

## 4. Conclusions

In this paper turbulent flow of distilled water alumina water nano-fluids through research reactor 22 (MW) coolant channel is investigated. The results are presented for a distilled water and water based nano-fluid at various volume fractions (2%,4% and 6%) . The effect of nano-fluid using as a coolant on the fuel centerline, clad and coolant temperatures are studied for hot and average channel of the reactor and compared with PARET-code. The temperatures of fuel centerline and clad decreases by using nano-fluid as a coolant. The temperature of nano-fluid along the reactor coolant channel is greater than the pure distilled water.

1- For Al2O3 as Prandtl number increases ,the clad temperature decreases.
2- Nanofluids are efficient coolant because it have a higher thermal conductivity in comparison with the base liquid hence, it can remove more heat than base fluids.
3- As the volume fraction increases the density and thermal conductivity increase for alumina water nano-fluid hence, the clad surface temperature decreases.
4- As the volume fraction increases the heat transfer coefficient increase because of decreases of Nusselt Number.
5- Nanofluids stability and its production cost are major factors in using nano-fluids as a coolant in nuclear reactors.
6- Aggregation, settling and erosion problems of nanoparticle need to be examined in detail in the applications.
7- The movement of nano-particles increases turbulence of the fluids which increases the heat transfer process, also the energy transfer it could be due to the collision of higher temperature particles with the lower one.
8- By using the Al2O3 water based nano-fluid as a coolant, the clad temperature decreases with desirable value for the same reactor operating conditions.

## 5. Nomenclature

| | |
|---|---|
| Ac | total water channel cross-sectional area in the fuel element ($m^2$) |
| Af | cross-sectional area of the fueled portion of the fuel plate (m) |
| AH | channel heated area ($m^2$) |
| Ao | cross-sectional area of the end box beyond the channel exit ($m^2$) |
| Ap | surface area of the fuel plate ($m^2$) |
| Aw | coolant channel cross sectional area ($m^2$) |
| cp | specific heat of the coolant water (J/g. ºC) |
| Dhe | heated equivalent diameter of the channel (m) |
| E | Young's modulus of elasticity (bar) |
| $f$ | friction factor |
| FA | axial peaking factor |
| FE | engineering peaking factor |
| FHC | hot channel factor |
| FNUC | nuclear peaking factor |
| FR | radial peaking factor |
| g | gravity acceleration ($m/s^2$) |
| Gch | coolant mass flow rate through the channel (g/s) |
| h | coolant heat transfer coefficient ($W/m^2$. ºC) |
| H | total fuel element length - core height (m) |
| kc | clad thermal conductivity (W/m. ºC) |
| kf | fuel meat thermal conductivity (W/m .ºC) |
| kw | coolant water thermal conductivity (W/m .ºC) |
| q | total heat transferred to the coolant (W) |
| $q'_{max}$ | maximum linear power (W/m) |
| $q''_{actual}$ | actual surface heat flux ($W/m^2$) |
| $q'''_{ave}$ | average power density ($W/m^3$) |
| $q'''(z)$ | core axial power distribution ($W/m^3$) |
| $q'''_{max}$ | maximum power density ($W/m^3$) |
| Qi | integrated power in the hot channel (W) |
| Qth | reactor core thermal power (W) |
| Rh | resistance for convective heat transfer (oC/W) |
| Rt | total thermal resistance (ºC /W) |
| SVR | fuel meat surface to volume ratio ($m^{-1}$) |
| tc | clad thickness (m) |
| tf | fuel meat thickness (m) |
| tp | fuel plate thickness (m) |

| | |
|---|---|
| tw | water channel thickness (m) |
| Tb | bulk coolant temperature (°C) |
| Tci | cladding inner surface temperatures (°C) |
| Tco | cladding outer surface temperatures (°C) |
| Tfc | centerline fuel temperature (°C) |
| Tfs | fuel surface temperature (°C) |
| Tin | coolant inlet temperatures (°C) |
| Tout | coolant outlet temperatures (°C) |
| Vcore | fuel meat volume of the reactor core (m3) |
| Vf | volume of the fueled portion of the fuel plate (m3) |
| wf | fuel meat width (m) |
| wh | effective fuel plate width for heat transfer (m) |
| wp | water channel width (m) |
| z | channel axial distance (m) |

Greek letters

| | |
|---|---|
| ρ | Density, kg/m3 |
| μ | Dynamic viscosity, Pa.s |
| Φ | Nano-particles volume fraction. |
| k | Thermal conductivity,W/m.K |

Subscript

| | |
|---|---|
| nf | nano-fluid. |
| bf | base fluid. |
| P | Particle. |



## REFERENCES

[1] S.U.S Choi, Enhancing thermal conductivity of fluids with nanoparticles, Developments and Applications of Non-Newtonian Flows,FED-vol.231/MD-vol.66 (1995).

[2] Vasu VELAGAPUDI, Rama Krishna KONIJETI and Chandra Sekhara Kumar ADURU, 2008, Empirical Correlations to Predict Thermophysical and Heat Transfer Characteristics of Nano-fluids Thermal Science ,Vol.12, pp 27-37

[3] Eiyad Abu-Nada, 2009, Effect of Variable Viscosity and thermal conductivity of Al2O3-water nano-fluid on heat transfer enhancement in natural convection, International Journal of Heat and Fluid Flow.

[4] Lixin Cheng, 2009, Nano-fluid heat transfer technologies, Recent Patents on Engineering, vol.3, pp.1-7

[5] IN CHEOL BANG and JI HWAN JEONG, 2011, Nanotechnology for Advanced Nuclear Thermal-hydraulics and Safety: Boiling and Condensation, Nuclear Engineering and Technology, vol.43, no.3, pp.317-242.

[6] Gupta H.K, Agrawal GD, Mathur J., 2012, An Overview of Nanofluids: A new media towards green environment, International Journal of Environmental Sciences, vol.3, no.1, pp.433-440.

[7] Mohamed Nazififard, Mohammadreza Nematollahi, Khosrow Jafarpur and Kune Y. Suh, 2012, Numerical Simulation of Water-Based Alumina Nano-fluid in Sub channel Geometry, Hindawi Publishing Corporation, Science and Technology of Nuclear Installations, vol.2012, no.4,pp.1-12.

[8] Hisham El-Khatib , Salah El-Din El-Morshedy , Maher.G. Higazy ,Karam El-Shazly,2013. Modeling and simulation of loss of the ultimate heat sink in a typical material testing reactor. Annals of Nuclear Energy 51, 156-166.