

HEAT TRANSFER CHARACTERISTICS OF Al_2O_3 /WATER NANOFLUID IN LAMINAR FLOW CONDITIONS WITH CIRCULAR RING INSERT

by

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In this experimental investigation convective heat transfer, friction factor, and thermal enhancement characteristics of straight circular duct fitted with circular ring insert of constant heat flux boundary condition under fully developed laminar flow is presented. Tests have been conducted by using 0.1% volume concentration of Al_2O_3 nanofluid and water. Inserts of different pitch to diameter ratios of 6.25, 8.33, 12.5, and 16.67 with center core rod were used for this investigation. The circular ring insert shows a superior thermal performance than plain tube. The experimental results demonstrated that the Nusselt number, friction factor, and thermal enhancement factor increases with decrease in pitch to diameter ratio. The circular ring inserts of lower pitch to diameter ratio of 6.25 with nanofluid increases the Nusselt number by 165.38% compared to pure water and the friction factor, found to be 7.89 times higher than that of water. Empirical correlations are developed for Nusselt number and friction factor in terms of Reynolds number, volume concentration, and pitch ratio. The thermal performance factor was found to be greater than unity for all pitch to diameter ratios.

Key words: circular ring insert, Al_2O_3 nanofluid, laminar flow, pitch to diameter ratio, thermal performance factor

Introduction

Heat transfer enhancement technique had been used in several applications such as automotive cooling, petroleum industries, air conditioning and refrigerating systems, nuclear reactor, etc. Heat transfer augmentation techniques can be classified into two categories: (a) Active technique: by supplying external power source to the fluid/equipment (b) Passive technique: turbulators or swirl flow devices or fluid additive. In terms of reducing the size and cost of the devices and saving the energy, several engineering techniques had been devised to enhance the heat transfer rate. One among the method of enhancing the heat transfer is adding additives to the working fluids to change the fluid properties and insertion of swirl flow generators.

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Nanofluid, fluid containing nanometer sized particles with stability is an advanced heat transfer fluid which can overcome the poor thermophysical properties of conventional heat transfer fluids such as: pure water, ethylene glycol, paraffin, *etc.* Nanofluids have been proven advantages such as: (a) higher thermal conductivity, (b) lower dynamic viscosity, (c) excellent stability, and (d) negligible pressure drop and pipe wall corrosion. The effectiveness of nanofluids in forced convective heat transfer depends on whether thermal conductivity can outweigh the penalty in pumping power. The concept of nanofluid was proposed first by Choi and Eastman [1]. Lee *et al.* [2] observed an increase in thermal conductivity for the suspension of 4.0% volume of CuO nanoparticles (35 nm) in ethylene glycol of 20% enhancement. Das *et al.* [3] obtained 2-4 fold enhancement in the thermal conductivity of nanofluid in the temperature range of 21-510 °C using Al_2O_3 nanofluid. Wen and Ding [4] investigated that Al_2O_3 nanoparticles when dispersed in water can significantly enhances convective heat transfer in the laminar flow region and this enhancement increases with Reynolds number and particle concentration. Experiments conducted by Heris *et al.* [5] with Al_2O_3 /water nanofluid in the laminar flow range under isothermal wall boundary condition reversed that enhancement of that transfer takes place with increase of Peclet number and volume concentration. Farajollahi *et al.* [6] investigated the performance of Al_2O_3 and TiO_2 nanofluids in a shell and tube heat exchanger. They reported that for both nanofluids two different optimum concentrations exists and nanofluids have superior enhancement capabilities of heat transfer in comparison with the base fluid. The performance of nanofluids in a circular tube with constant heat flux condition been reported by Kim *et al.* [7]. They have reported 15% and 20% enhancement in the convective heat transfer coefficient of aluminum nanofluids in comparison to base fluid in laminar and turbulent flow, respectively. And also, the thermal boundary layer played a dominant role in turbulent flow regime.

Heat transfer augmentation with nanofluids in a tube has been observed with the use of tube insert for further enhancement is the objective of this study. The important group of devices used in passive method is swirl flow devices which produces secondary re-circulation on the axial flow leading to an increase of turbulent fluctuation. It allows a greater mixing of fluid inside a heat exchanger tube, subsequently reduces the thickness of hydrodynamic boundary layer thickness. It results in greater heat transfer coefficient, lengthening the flow path in consequence of turbulating fluid motion, improving fluid mixing and thinning thermal boundary layer. However, pumping power required is more when inserts are equipped inside the tube. So, measures have to be taken into account by using insert with a proper geometry. Eiamsa-ard *et al.* [8-10] investigated the heat transfer and fluid friction characteristics of twisted tape elements. They found that the geometries of twisted tape had greater impact on fluid mixing and heat transfer rate. The results showed that the heat transfer coefficient as well as friction factor increases with decrease in twist ratio. Sivashanmugam and Suresh [11, 12] compared the performance and pressure drop of full length helical twisted tape and regularly spaced helical screw-tape inserts in laminar and turbulent region. The results revealed that the tape with spacer length within 10% of the entire length could preserve heat transfer enhancement and decrease pressure drop simultaneously. Jaisankar *et al.* [13] employed typical twisted tape with different twist ratios in a solar water heater and observed that the tape with a smaller twist ratio provided higher enhancement in heat transfer due to a strong swirl flow intensity. Murugesan *et al.* [14] conducted experiments with twisted tape in conjunction with the wire nails in a double pipe heat exchanger. The results revealed that compared, to typical twisted tape, it offered higher heat transfer rate which is due to swirl flow coupled, with an extra-fluid disturbance secondary flow in the vicinity of the tube wall. Eiamsa-ard and Kiatkittipong [15] studied the effect of multiple twisted tapes in dif-

ferent arrangement with TiO_2 /water nanofluid. The results revealed that the tapes in counter arrangement provided higher thermal performance factor than that in co-arrangement and the benefit of TiO_2 nanoparticles in water was significant in improving the thermal performance. Suresh *et al.* [16, 17] conducted experiments using helical screw tape inserts and spiral rod inserts with Al_2O_3 /water nanofluid. The spiraled rod inserts with 15 mm pitch exhibited better heat transfer enhancements compared to the spiraled rod inserts having a pitch of 30 mm and authors reported that the insertion of inserts and nanofluid enhanced the heat transfer with considerable pressure drop. Chandrasekar *et al.* [18] studied the effect of wire coil insert with Al_2O_3 /water nanofluid in a circular pipe and revealed the enhancement of heat transfer. Kongkaitpaiboon *et al.* [19] investigated the effect of circular ring turbulators in heat exchanger tube under constant heat flux condition. The results revealed the effect of pitch and diameter ratio on the heat transfer rate and it is evident that the simultaneous use of nanofluid and inserts efficiently improved heat transfer rate with respect to the individual use of inserts or nanofluid. The attractive characteristics of both Al_2O_3 /water nanofluid and inserts, previously mentioned above, have motivated the present research to combine their effects. For the present study, the experiments were conducted using Al_2O_3 /water nanofluid with concentration of 0.1% by volume. Pitch to diameter ratios of insert was kept constant while Reynolds number was varied from 766 to 2300. The tests using nanofluid together with insert, insert alone were also conducted, for comparison.

Experimental set-up and procedure

Experimental set-up

The details of the experimental set-up are shown in fig. 1. It consists of a test section, calming section, pump, cooling unit, and a fluid reservoir. Both the calming section and test sections are made of straight copper tube with the dimensions of 1000 mm long, 10 mm ID, and 12 mm OD.

The calming section is used to eliminate the entrance effect and to ensure the fully developed flow in the test section. The test section tube is wound with ceramic beads coated electrical SWG Nichrome heating wire of resistance $120\ \Omega$ for uniform heating. Over the electrical winding a thick insulation is provided using glass wool to minimize heat loss from the test section to the surroundings. The terminals of the Nichrome wire are attached to an auto-transformer, by which heat flux can be varied by varying the voltage. Five calibrated RTD PT 100 type temperature sensors are placed in the thermo wells mounted on the test section at axial positions in mm of 100, 200, 400, 600, and 800 from the inlet of the test section to measure the outside wall temperatures. Two calibrated RTD PT 100 type temperature sensors immersed in the mixing chambers provided at inlet and outlet to measure the inlet and exit temperatures of the fluid. A peristaltic pump is used to circulate the fluid through the test section. The pump discharge is varied by adjusting the speed of rotation. The pump gives a maximum discharge of 1 litre per minute. A container of five litres capacity is used as the fluid reservoir. The pump was calibrated by using a glass jar. This was done by collecting the volume of water in the jar at a given interval of time and compared with the volume flow rate measured from the pump. A differential U-tube manometer is also fitted across the test

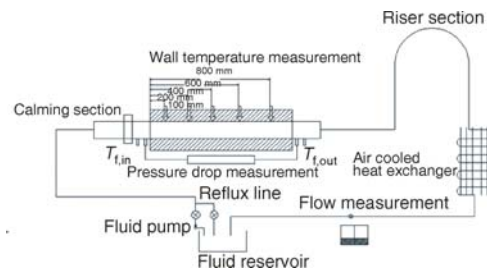


Figure 1. Schematic of the experimental set-up

section to measure the pressure drop. The fluid after passing through the heated test section flows through a riser section and then through the cooling unit which is an air cooled heat exchanger and finally it is collected in the reservoir.

Details of circular ring insert with center core rod

The details of the circular ring insert with center core rod are demonstrated in fig. 2. The circular rings of different diameters are made up of brass of 1 mm thickness with V-cuts on the periphery of the ring. Later the circular rings are pasted on to a brass rod of 2.5 mm to get various pitch to diameter ratio.

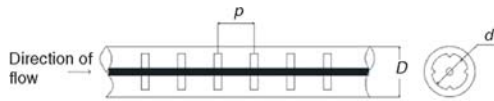


Figure 2. Geometrical configurations of circular ring insert

Table 1. Pitch to diameter ratio p/d

No.	Parameter	6.25	8.33	12.5	16.67
1	Pitch	50	50	100	100
2	Diameter	8	6	8	6

pension. The pH of the prepared nanofluids were measured by a pH meter (Sartorius PB-11) and found to be around 5 which is far from the isoelectric point for aluminum nanoparticles. This ensures the nanoparticles are well dispersed and the nanofluid is stable because of very large repulsive forces among the nanoparticles when pH is far from isoelectric point.

The thermophysical properties of nanofluids such as mass density, thermal conductivity, specific heat, and viscosity at the average bulk temperature for a volume concentration of ϕ were calculated using the regression correlations presented in the literature.

Mass density

The ratio of density of nanofluid to that of base fluid is calculated according to Pak and Cho equation [20]:

$$\frac{\rho_{nf}}{\rho} = 1 + k_{\rho}\phi \quad \text{where} \quad k_{\rho} = \left(\frac{\rho_s}{\rho} - 1 \right) \quad (1)$$

Thermal conductivity

The ratio of thermal conductivity of nanofluid to that of base fluid is given by Maxwell [21]:

$$\frac{k_{nf}}{k} = 1 + k_k\phi \quad \text{where} \quad k_k = 3 \quad (2)$$

Specific heat

The specific heat of the nanofluid is calculated using Xuan and Roetzel equation [22]:

$$\frac{Cp_{nf}}{Cp} = \frac{1 + k_c\phi}{1 + k_{\rho}\phi} \quad \text{where} \quad k_c = \frac{\rho_s Cp_s}{\rho Cp} - 1 \quad (3)$$

Four different inserts of pitch to diameter ratios 6.25, 8.33, 12.5, and 16.67 are used in this present experimentation tab. 1.

Nanofluid properties

Nanofluid with a required volume concentration of 0.1% was prepared by dispersing specified amounts of Al₂O₃ nanoparticles in deionized water. To make the nanoparticles more stable and remain more dispersed in water, ultrasonic vibrator was used. Sonication was done for one hour continuously to obtain a more stable and evenly dispersed nanoparticle sus-

Viscosity

The effective viscosity of a fluid containing spherical particle in lower volume concentration is calculated according to Einstein equation [23]:

$$\frac{\mu_{nf}}{\mu} = 1 + k_{\mu}\phi \quad \text{where} \quad k_{\mu} = 2.5 \quad (4)$$

Experimentation and data collection

Experiments were carried out to calculate the convective heat transfer and friction factor characteristics of water and nanofluid through the tube with circular ring inserts with center core rod. The storage tank is filled with the working fluid and the peristaltic pump is turned on to initiate the flow of fluid through the test section. The required flow rate to the test section was maintained by adjusting the speed of rotation. After adjusting the flow rate, the heat flux was set by adjusting the electrical voltage with the help of an auto-transformer. Initially, tests were conducted with water for validation of the experimental facility. The flow rate to the test section and heat flux was varied, and readings were taken after steady-state conditions attained. After steady-state conditions have been reached, the inlet and outlet temperature of the fluid, mass flow rate, the tube wall temperatures, and electric power input during each test run were noted down. Later by inserting the circular ring insert with center core rod of different pitch to diameter ratios, tests were conducted with water and nanofluid. In order to evaluate the friction factor characteristics of the flow, the pressure drop was measured for each mass flow rate under isothermal condition.

Data collection

The total heat supplied in to the test section was estimated by:

$$Q_1 = VI \quad (5)$$

The heat input to the fluid *i. e.* the sensible heat gained by the fluid is given by:

$$Q_2 = mC_p(T_{f,out} - T_{f,in}) \quad (6)$$

The actual heat flux is then calculated:

$$q'' = \frac{Q_1 + Q_2}{2(\pi DL)} \quad (7)$$

The local heat transfer coefficient is calculated from:

$$h_x = \frac{q''}{T_{w,x} - T_{f,x}} \quad (8)$$

The local fluid temperature is evaluated by the following energy balance equation:

$$T_f = T_{in} + \frac{q''Px}{\rho C_p v A} \quad (9)$$

The average heat transfer coefficient is calculated using:

$$h = \frac{q''}{\bar{T}_w - \bar{T}_f} \quad (10)$$

The average Nusselt number is evaluated as:

$$Nu = \frac{hD}{k} \quad (11)$$

Validation of the experimental facility

Initially experiments were conducted with distilled water in plain tube under laminar flow conditions which forms the basis for comparison of the results with nanofluids as well as for the validation of the experimental system. The experimental results are quite agreeable with the Shah equation [24].

Figure 3 shows the variation of Nusselt number along the axial direction at a Reynolds number of 766.

$$Nu = 1.953 \left(Re Pr \frac{D}{x} \right)^{\frac{1}{3}} \text{ for } Re Pr \frac{D}{x} \geq 33.33 \quad (12a)$$

$$Nu = 4.364 + 0.0722 \left(Re Pr \frac{D}{x} \right) \text{ for } Re Pr \frac{D}{x} \leq 33.33 \quad (12b)$$

Figure 4 shows the variation friction factor with Reynolds number under isothermal condition. The friction factor values calculated from the experimental results are compared with the theoretical values, which indicates it follows the Hagen-Poiseuille equation given by:

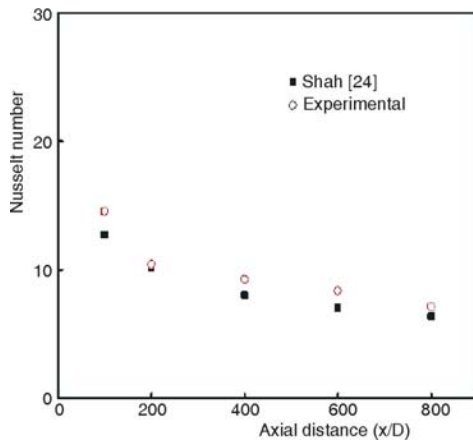


Figure 3. Comparison of Shah equation and experimental data for Nusselt number

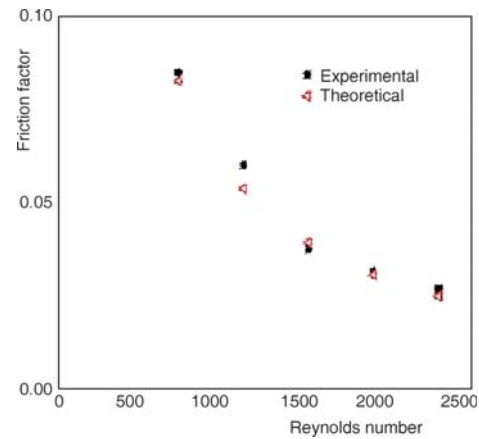


Figure 4. Comparison of theoretical and experimental friction factor of water

$$f = \frac{64}{Re} \quad (13)$$

Results and discussion

Heat transfer characteristics of nanofluids with and without inserts

Experiments were conducted to study the heat transfer enhancement of Al₂O₃/water nanofluid and circular ring insert with center core rod. The Nusselt numbers calculated from the measured values of mean wall temperature of the tube with nanofluid and circular ring, are

shown in fig. 5. It has been observed that the Nusselt number increases with Reynolds number for all the cases.

Initially, tests have been carried out by using 0.1% volume concentration of Al₂O₃/water nanofluid and water. For the given operating conditions, Nusselt number of nanofluid found to be increasing than water. The average enhancement in Nusselt number for plain tube with Al₂O₃/water nanofluid was 12.87% compared to that of water as the working fluid. This may be due to the fact that the particle laden nanofluid increases the thermal conductivity of the mixture, increase in energy exchange rate due to collision of nanoparticles as claimed by Wen and Ding [4]. Later the circular ring inserts were fitted inside the tube and readings are taken. The circular ring insert exhibits higher heat transfer rate for both nanofluids and pure water in laminar regime. The enhancement in Nusselt number increases with decrease in pitch to diameter ratio. The average enhancement in Nusselt number was 136.67, 127.16, 104.48, and 110.02% for various pitch to diameter ratios. With Al₂O₃/water nanofluid, the increase in average Nusselt number was found to be 165.38, 144.95, 121.5, and 115.86% corresponding to pitch to diameter ratios of 6.25, 8.33, 12.5, and 16.67, respectively. For given Reynolds number, the results revealed that the enhancements in Nusselt number of inserts are larger than that of plain tube. This may be due to the combined effect of nanofluids and circular ring inserts. The inserts create swirl flow coupled with an extra fluid disturbance and secondary flow in the vicinity of tube wall, resulting in superior heat transfer augmentation. The V-cuts provided in the periphery of the circular rings provide an additional turbulence and vortices behind the cuts lead to an extra augmentation.

The results of heat transfer study are used to derive the following correlation of Nusselt number using least square method of regression analysis:

$$Nu = 0.1353(Re Pr)_{nf}^{0.3115} \left(\frac{p}{d} \right)^{-0.2156} (1 + \phi)^{32} \quad (14)$$

The correlations are valid for laminar flow of 0.1% volume concentration of Al₂O₃/water nanofluid and circular ring insert of various pitch to diameter ratios ranging from 6.25 to 16.67.

The Nusselt number values predicted by the previous correlation shows reasonable agreement with the experimental data fig. 6.

Friction factor study with and without inserts

The friction factor is calculated by measuring the pressure drop across the test facility, using the following relation:

$$f_{exp} = \frac{\Delta p}{\left(\frac{L}{D} \right) \left(\frac{\rho v^2}{2} \right)} \quad (15)$$

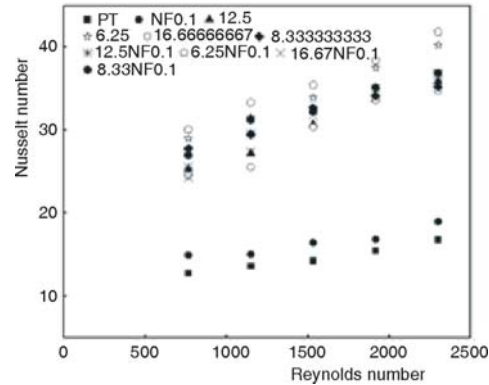


Figure 5. Variation of Nusselt number with Reynolds number

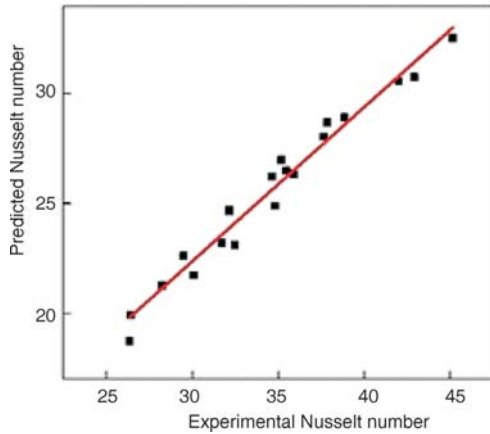


Figure 6. Comparison of experimental and predicted Nusselt number

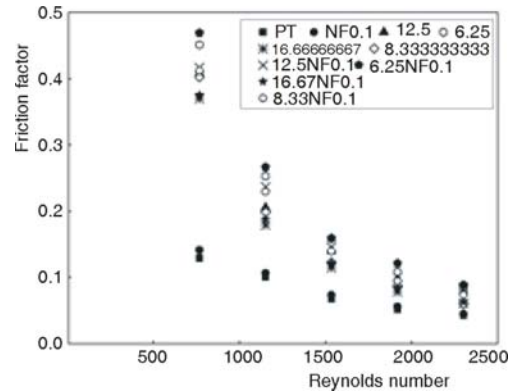


Figure 7. Variation of friction factor of water with Reynolds number

Figure 7 shows the variation of various fluids with Reynolds number for the plain tube with and without circular ring inserts. For the given operating conditions, the friction factor of nanofluid was almost equal to that of water. However, the pressure drop increases significantly with the use of circular ring inserts. The maximum value of friction factor was found to be with insert of 6.25 pitch to diameter ratio. Compared to plain tube with water, the average friction factor of Al₂O₃/water nanofluid was found to be 7.89, 6.67, 6.35, and 5.58 times higher for pitch to diameter ratios of 6.25, 8.33, 12.5, and 16.67, respectively.

The results obtained from the present investigation are used to derive the following correlation using least square method:

$$f = 2980.957(\text{Re Pr})_{\text{nf}}^{-0.3559} (1 + \phi)^{36} \quad (16)$$

The predicted values of friction factor are compared with the experimental results which are shown in fig. 8.

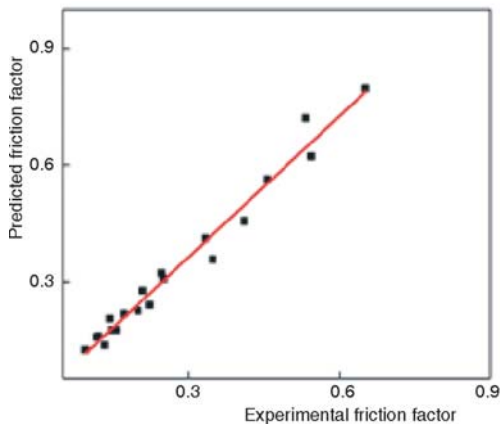


Figure 8. Comparison of experimental and predicted friction factor

Thermal performance of circular ring inserts

To evaluate the potential for real application of the enhancement device, both enhanced heat transfer and pressure drop caused by the device has to be taken in to account simultaneously. The enhanced heat transfer is defined as the ratio of Nusselt number in the tube with insert to that of the tube without insert (Nu/Nu_p). Likewise, enhanced friction factor ratio is defined as the ratio of friction factor in the tube with insert to that in the tube without the insert (f/f_p).

The ratio of both these criteria under the constraint of a constant pumping power gives the thermal performance factor:

$$\eta = \frac{\left(\frac{Nu}{Nu_p} \right)}{\left(\frac{f}{f_p} \right)^{0.333}} \quad (17)$$

The values of thermal performance factor for all inserts were found to be greater than unity. The results revealed that the circular ring insert with center core rod with various pitch to diameter ratios are considered feasible in terms of energy saving over the range studied. The maximum thermal performance factor was obtained with the insert of 6.25 pitch to diameter ratio, fig. 9.

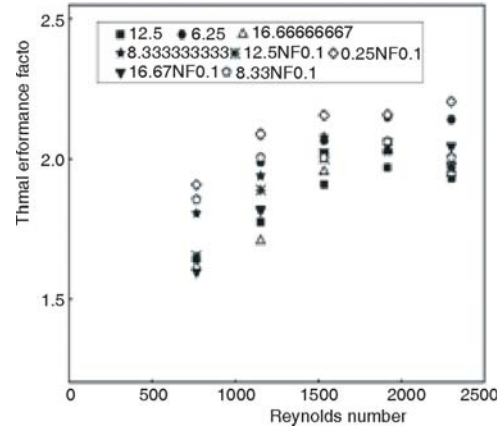


Figure 9. Variation of thermal performance factor with Reynolds number

Conclusions

In this study, investigations on convective heat transfer, friction factor, and thermal performance characteristics of Al₂O₃/water nanofluid are carried out in laminar regime with and without circular ring insert of four pitch to diameter ratios under constant heat flux condition. Experimental results obtained were compared with those obtained from the theoretical data of plain tube. The results obtained lead to the following conclusions:

- Al₂O₃/water nanofluid of very low volume concentration enhanced the average Nusselt number by 12.87% compared to that of pure water.
- For the same operating conditions convective heat transfer were further increased by the use of circular ring insert.
- The heat transfer and friction factor increases with decrease in pitch to diameter ratio and the thermal performance factor for all the cases were more than one.
- Two new empirical correlations were developed for Nusselt number and friction factor, for Al₂O₃/water nanofluid.

Nomenclature

A – cross-sectional area, [m²]
 C_p – specific heat, [Jkg⁻¹K⁻¹]
 D – test section diameter, [m]
 d – circular ring diameter, [m]
 f – friction factor, [–]
 h – convective heat transfer coefficient, [Wm⁻²K⁻¹]
 I – current, [A]
 k – thermal conductivity, [Wm⁻¹K⁻¹]
 L – length of test section, [m]
 m – mass flow rate, [kgs⁻¹]
 P – perimeter, [m]
 Δp – pressure drop, [Pa]
 p – pitch distance, [m]
 Q_1 – heat input, [W]
 Q_2 – sensible heat gained by the fluid, [W]
 q'' – actual heat flux, [Wm⁻²]
 T – local temperature, [K]
 \bar{T} – average temperature, [K]

v – fluid velocity, [ms⁻¹]
 x – axial distance from the tube entrance, [m]

Greek symbols

ρ – mass density, [kgm⁻³]
 μ – viscosity, [kgm⁻¹s⁻¹]
 ϕ – volume concentration, [%]

Subscripts

f – fluid
in – inlet
nf – nanofluid
out – outlet
s – solid phase
w – wall

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