Mechanism of Forced Convective Heat Transfer in Al$_2$O$_3$/Water Nanofluid under Laminar and Turbulent Flow

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Abstract—In this paper, fully developed laminar and turbulent flow convective heat transfer characteristics of Al$_2$O$_3$/water nanofluid flowing through a uniformly heated horizontal tube with and without wire coil inserts is presented. For this purpose, Al$_2$O$_3$ nanoparticles of 43 nm size were synthesized, characterized and dispersed in distilled water to formulate Al$_2$O$_3$/water nanofluid containing 0.1, 0.15 and 0.2% volume concentration of nanoparticles. Two wire coil inserts made of stainless steel with pitch ratios 2 and 3 were used. The results provide experimental evidence that the mechanism of thermophoresis play a pivotal role in explaining the heat transfer enhancement observed with nanofluids.

Keywords—Heat transfer enhancements, Nusselt number, Nanofluid, Wire coil insert.

I. INTRODUCTION

In heat exchangers the resistances to heat transfer increases due to fouling or scaling because of continuous operation. Moreover, the traditional heat transfer fluids used (such as water, oil, air or gas) in heat exchangers have low thermal conductivity which limits the heat transfer rate. Hence, there is a need to enhance the heat transfer rate. The heat transfer enhancement techniques that are used can be segregated into active and passive techniques. Active augmentation requires the addition of external power to bring about the desired flow modification. Examples of active augmentation include heat-transfer surface vibration, fluid vibration, and electrostatic field introduction. Passive techniques employ special surface geometries or fluid additives. Typical examples of passive augmentation are surface roughness, displaced promoters, and vortex generators [1]. But in the process of both active and passive technique of heat transfer enhancement, pumping power may increase significantly and ultimately the pumping cost becomes high. Therefore, a desired enhancement in the heat transfer rate in an existing heat exchanger must be achieved at an economic pumping power [2].

Among the various passive techniques which are effective to improve the thermohydraulic behaviour in a single-phase flow, the insert devices like wire coil inserts and twisted tapes are most frequently used in engineering applications to update an existing heat exchanger. This is mainly due to its low cost, easy installation/removal, reliability and durability [3]. To overcome the limited heat transfer capabilities of the traditional heat transfer fluids (such as water, oil, air or gas), micro/millimeter sized particles with high thermal conductivity suspended in them were considered by Ahuja [4]. Heat transfer fluids containing suspended particles of micro/millimeter sizes suffered from numerous drawbacks like erosion of the components by abrasive action, clogging in small passages, settling of particles and increased pressure drop. Hence, they were not accepted as suitable candidate for heat transfer enhancement and the search for new heat transfer fluids continued. Nanotechnology has come to rescue by providing opportunities to process and produce materials of sizes in nanometer range which can be suspended in traditional heat transfer fluids to produce a new class of engineered fluids with high thermal conductivity and elimination of the before mentioned problems associated with heat transfer fluids containing suspended particles of micro/millimeter size. This new class of heat transfer fluids with nanoparticles smaller than 100 nm in suspension is called nanofluids [5].

Though the original idea of nanofluids was to enhance the thermal conductivities of some traditional heat transfer fluids, the influence of nanoparticles has been found to alter other properties like density, viscosity, specific heat and surface properties. A large number of experiments were reported on thermal conductivity compared to other properties of nanofluids. As it is expected that the increase of thermal conductivity might be offset by the increase of viscosity, the decrease of effective specific heat or the variation of wetability, an impartial assessment of the application of nanofluids is required without focusing on the effective thermal conductivity only. A large number of inconsistent experiments were also reported for nanofluids applications under flow conditions either with or without phase change. The detailed summary of the previous studies on the thermophysical properties and convective heat transfer performance of nanofluids were well documented in the recent
reviews [6-8]. The reasons for such increase in heat transfer characteristics were attributed to reduction of boundary layer thickness by mixing effects of particles near the wall, thermal conductivity enhancement, Brownian diffusion and particle migration [9, 10].

From the literature survey, it is learnt that the bulk of the previous works on nanofluid heat transfer concentrates on only heat transfer characteristics in the laminar entrance region or developing region, transition or turbulent regime. Though Sharma et al. [11, 12] have reported the thermohydraulic performance of twisted tape with nanofluids, the thermohydraulic performance of wire coil inserts remains unstudied. As the reduction in boundary layer thickness by mixing effects of particles near the wall is expected to be one of the reasons for enhanced heat transfer performance of nanofluids, the use of wire coil inserts could be a better choice compared to twisted tape. This because wire coil inserts mainly disturb the flow near the wall while the twisted tape inserts disturb the entire flow field. In addition, wire coil inserts have the advantages of lesser pressure drop, low cost, easy installation and removal. Hence, the aim of the present experimental investigation is to estimate both the convective heat transfer and friction factor characteristics in the fully developed laminar and turbulent flow of Al$_2$O$_3$/water nanofluid under constant heat flux with and without wire coil insert. Two wire coil inserts made of stainless steel having pitch ratios of 2 and 3 respectively are used in present work. Wire coil insert is a geometrical modification and nanofluids are fluids containing nanized additives leading to fluid property modification. But, both belong to the passive technique of heat transfer enhancement and hence there is a basis for possible comparison of thermo-hydraulic behavior of these two techniques.

I. EXPERIMENTS

A. Synthesis of nanoparticle and nanofluids

Nanocrystalline alumina (Al$_2$O$_3$) powder has been prepared from an aqueous solution of aluminum chloride by microwave assisted chemical precipitation method. 0.1 M (molar solution) of aluminum chloride was taken (aqueous solution) in a round bottom flask fitted with a reflux water condenser. The solution was hydrolyzed for 20 minutes and the resulting solution was neutralized with ammonia solution. The precipitate formed is washed with distilled water and dried. The average grain size is calculated to be 43 nm using the Sherrer formula. The microstructure of the powder sample was characterized by Jeol JSM 6360 SEM which shows that the as-prepared particles are in the form of tiny agglomerates. Nanofluid with a required volume concentration of 0.1, 0.15 and 0.2% was then prepared by dispersing a specified amount of Al$_2$O$_3$ nanoparticles in water by using a ultrasonic vibrator (Toshiba, India) generating ultrasonic pulses of 100 W at 36±3 kHz. To get a uniform dispersion and stable suspension which determine the final properties of nanofluids, the nanofluids are kept under ultrasonic vibration continuously for 6 hours [13]. The pH of the prepared nanofluid was measured by a pH meter (Cyber pH-14L) and found to be around 5 which is far from the isoelectric point of 9.2 for alumina nanoparticles [14]. 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. Thus, the Al$_2$O$_3$/water nanofluid prepared in the present work was found to be very stable for several weeks without visually observable sedimentation.

B. Convective experimental setup

The experimental setup for measuring the convective heat transfer and pressure drop characteristics is shown schematically in fig. 1. The test loop consists of a pump, calming section, heated test section, cooling section, a collecting station and a reservoir. The pump used in this work was of peristaltic type (RH-P120l, Ravel Hiteks Pvt. Ltd.) in which the flow rate was controlled by the rotational speed. The pump could deliver a maximum flow rate of 2.55 liters per minute. Nanofluids were driven by the pump from the reservoir to flow through the test loop. A four liter capacity stainless steel vessel equipped by drain valve is used as fluid reservoir. In order to control the fluid flow rate, a reflux line with a valve was used. Calming section of straight copper tube 800 mm long, 4.85 mm inner diameter, and 6.3 mm outer diameter is used to eliminate the entrance effect and to ensure fully developed laminar flow in the test section. A straight copper tube with 1200 mm length, 4.85 mm inner diameter, and 6.3 mm outer diameter was used as the test section. The test section is first wound with sun mica to isolate it electrically. Then, ceramic beads coated electrical SWG Nichrome heating wire giving a maximum power of 300 W is wounded over it. Over the electrical winding, thick insulation consisting of layers of ceramic fiber, asbestos rope, glass wool and another layer of asbestos rope at the outer surface is provided to prevent the radial heat loss. The test section is isolated thermally from its upstream and downstream sections by plastic bushings to minimize the heat loss resulting from axial heat conduction. The terminals of the Nichrome wire are attached to the Auto-transformer, by which the heat flux can be varied by varying the voltage. Six calibrated RTD PT 100 type temperature sensors with 0.1 °C accuracy are placed in thermwells mounted on the test section at axial positions in mm of 110 (T$_1$), 210 (T$_2$), 410 (T$_3$), 610 (T$_4$), 760 (T$_5$) and 870 (T$_6$) from the inlet of the test section to measure the wall temperature distribution. The inlet and outlet temperatures, T$_1$ and T$_2$ respectively, were measured by two RTD PT 100 type temperature sensors immersed in the mixing chambers provided at inlet and exit. A differential pressure transducer (SGM srl, Italy) able to read up to 1 cm of water is mounted across the test section to measure the pressure drop. The fluid after passing through the heater section flows through a riser section and then through the cooling unit which is an air cooled heat exchanger and is collected in the reservoir. A three-way valve is provided in the flow pipe connecting the
cooler section and reservoir for flow rate measurements and cleaning the system between successive experimental runs. The flow rates were measured by collecting the fluid in the collecting station for a period of time with the help of a precise measuring jar and stop watch.

\[
\frac{\rho_{nf}}{\rho} = 1 + r_p \phi \tag{1}
\]

where \( r_p = \left( \frac{\rho_s}{\rho} - 1 \right) \)

From Xuan and Roetzel's equation [18], the ratio of specific heat of nanofluid to that of base fluid is given as

\[
\frac{c_{p,nf}}{c_p} = \frac{1 + r \phi}{1 + r_p \phi} \tag{2}
\]

Where \( r_c = \left( \frac{\rho_s c_{p,s}}{\rho c_p} - 1 \right) \)

Experimental uncertainty was calculated using Coleman and Steele method [15] and ANSI/ASME standards [16]. The uncertainties associated with experimental data are calculated on the basis of 95% confidence level. The calculations indicated that the uncertainties involved in the measurements is around ±3%, ±6% and ±5% for Reynolds number, Nusselt number and friction factor respectively.

II. DATA REDUCTION

A. Thermophysical properties of nanofluids

The physical and thermal properties such as density and specific heat of the nanofluid are calculated using different formulae presented in the literature as outlined below. The properties without suffix are for water. On the other hand, the thermal conductivity and viscosity of nanofluids have exhibited abnormal behavior and hence they are measured. The ratio of density of the nanofluid to that of base fluid is calculated according to Pak and Cho's equation [17] as

\[
\frac{k_{nf}}{k} = 1.007 + 3\phi \tag{3}
\]

\[
\frac{\mu_{nf}}{\mu} = 1 + 1.3\phi + 6.90\phi^2 \tag{4}
\]

B. Heat transfer calculation

The heat transfer performance was defined in terms of the Nusselt number (Nu) and heat transfer coefficient (h) as given below

\[
h = \frac{q^*}{(T_w - T_f)} \quad \text{and} \quad Nu = \frac{hd}{k} \tag{5}
\]

Here, \( T_w \) is the average temperature of the wall and \( T_f \) is the average bulk temperature of fluid. \( q^* \) is the actual heat flux, \( d \) is the tube diameter and \( k \) is the fluid thermal conductivity.

The heat losses from the test section are taken into account while calculating the actual heat flux which was taken to be average of following two evaluations. The total heat generated by the electrical heater is calculated as \( Q_t = VI \). The heat loss from the insulation (\( Q_{loss} \)) is estimated as 2.5% of the total heat from the measurements of wall temperature (\( T_w \)) and ambient temperature (\( T_{amb} \)). Therefore, the heat input from the electrical heater is

\[
Q_1 = Q_t - Q_{loss} \tag{6}
\]
Heat input was also calculated from the sensible heat gained by the fluid as

$$Q_2 = \dot{m}c_p(T_{out} - T_{in})$$  \hspace{1cm} (7)

The heat balance between the heat input from the heater ($Q_1$) and heat input to the fluid ($Q_2$) was found to be within 3.2% for all runs. The actual heat flux is then evaluated as

$$q^* = \frac{0.5(Q_1 + Q_2)}{\pi dL}$$  \hspace{1cm} (8)

### III. RESULTS AND DISCUSSIONS

#### A. Validation of the experimental system

Initially experiments are conducted with distilled water which forms the basis for comparison of results with nanofluids as well as validation of the experimental apparatus. The comparison of the experimental data with the Shah equation [20] for laminar flows and Dittus-Boelter equation [21] for turbulent flow under the constant heat flux boundary condition are in good agreement.

#### B. Heat transfer characteristics

Fig. 3 shows the variation of Nusselt number with Reynolds number under laminar flow conditions. The Nusselt numbers are calculated from the measured values of mean wall temperature and bulk mean temperature, and the heat flux. The experimental results show that the Nusselt number increases with the increase in volume concentration of the nanoparticles suspended in water and Reynolds number. For example, the Nusselt number is increased by 12.24, 22 and 39% when volume concentrations are 0.1, 0.15 and 0.2% respectively compared to water at Re=2275. If wire coil insert WC3 is used, an increase of 21.5, 24.5 and 31.5% in Nusselt number is observed when volume concentrations are 0.1, 0.15 and 0.2% respectively compared to water at Re=2275. Similarly with wire coil insert WC2, an increase of 15.9, 30.3 and 35.3% in Nusselt number is observed for volume concentrations of 0.1, 0.15 and 0.2% respectively compared to water at Re=2275. These results indicate that for a given Reynolds number, the increases in Nusselt number with increase in volume concentration are not same.

The ratio of Nusselt numbers vary from 1.1 to 1.3 with the use of nanofluids, 1.2 to 1.33 when nanofluids are used with WC3 and 1.15 to 1.27 when nanofluids are used with WC2. Thus the average Nusselt number is increased by 20% with the use of nanofluids while they are increased by only 13% and 12% when nanofluids are used with WC3 and WC2 respectively when the volume concentration is increased from 0.1 to 0.2%. A higher increase in Nusselt number observed with nanofluids suggests that the mechanism of penetration of nanoparticles into the boundary layer by thermophoresis could explain the enhancement in heat transfer characteristics of nanofluids. As the wire coil inserts destroy the boundary layer, the heat transfer enhancement by thermophoresis becomes less possible when nanofluids are used in conjunction with wire coil inserts. Hence, the increase in Nusselt numbers is less when nanofluids are used with wire coil inserts. These findings provide experimental evidence that the mechanism of thermophoresis play a pivotal role in explaining the heat transfer enhancement observed with nanofluids. It is also interesting to note that the increase in Nusselt number is almost same when nanofluids is used with wire coil inserts of different pitch ratios. This is due to the fact that the mechanism of thermophoresis is absent with the elimination of boundary layer and hence provides further supports to our conclusion that the mechanism of thermophoresis is important in explaining the heat transfer enhancement with nanofluids.

Fig. 4 shows the variation of Nusselt number with Reynolds number under turbulent flow conditions. The experimental results show that under turbulent flow also, similar to laminar flow, the Nusselt number increases with the increase in volume concentration of the nanoparticles suspended in water and Reynolds number. However, contrary to laminar flow where the increase in Nusselt number is gradual with increase in volume concentration with a trend similar to that of distilled water, the increase in Nusselt number is not gradual in turbulent region. Since the heat is primarily transferred by molecular conduction from streamline to streamline in laminar flow, it seems that the nanoparticles tend to follow fluid streamlines but in turbulent flow nanoparticles are carried by the turbulent eddies and move in a random direction resulting in enhanced heat transport. Compared to water, an increase of 48.6% in Nusselt number is observed with 0.2 NF while an increase of 32.4% is observed when 0.2 NF is used with water at Re=4500. In turbulent flow, the laminar sub layer where the turbulent eddies are absent offers more resistance to heat transfer and hence much of the temperature drop occurs in this layer. Thus, if the heat transfer has to be increased, the laminar sub layer has to be

![Fig. 3 Variation of Nusselt number with volume concentration and Reynolds number under laminar flow](image-url)
made less resistant to heat transfer which is only possible with penetration of high thermal conductivity of nanoparticles by diffusion mechanism like the thermophoresis into sub layer. As the wire coil insert is more effective in a turbulent flow due to its ability to mix the flow in the laminar sub layer near the wall quite effectively, it is expected that the laminar sub layer could be destroyed with their use and hence the effect of thermophoresis on heat transfer enhancement can be eliminated. This is the reason for low value of Nusselt numbers obtained when nanofluids are used with wire coil inserts.

IV. CONCLUSIONS

In laminar flow regime, Nusselt number of Al₂O₃/water nanofluid increases gradually with the increase in both the Reynolds number and volume concentration with a trend similar to that of distilled water. In turbulent flow regime, the increase in Nusselt number is not gradual and the enhancement becomes more pronounced at higher Reynolds number (i.e., Re ~ 5000). It is concluded that the nanoparticles tend to follow fluid streamlines in laminar flow. The movement of nanoparticles along with the turbulent eddies and the penetration of high thermal conductivity of nanoparticles by diffusion mechanisms like thermophoresis into laminar sub layer is believed to be the reasons for enhanced heat transfer in turbulent region.

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