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Investigation of Thermal Conductivity and Convective Heat Transfer of Alumina Nanofluids under Laminar Flow

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Abstract : In this research, dilute colloidal suspension alumina nanofluids were prepared by dispersing alumina nanoparticles in DI water and ethylene glycol as base fluids. Particle size analyzer and TEM test results revealed that the size of the alumina nanofluids(3wt% and 5wt%) with dispersion time 3hrs were 46nm and 60nm respectively. Thermal conductivity of these alumina nanofluids was measured by means of hot wire technique using a LAMBDA system. For water based alumina nanofluids, thermal conductivity enhancement was from 2.29% to 3.06% with 5wt% alumina at temperatures ranging from 15 to 40℃. Whereas in case of ethylene glycol based alumina nanofluids under the same temperature range, thermal conductivity enhancement was from 9.6% to 10% with 5wt% alumina. An enhancement of 37% average convective heat transfer was achieved with 5wt% alumina nanofluids at Re of 1,100.

Key Words : LAMBDA system, Thermal conductivity, Alumina, Nanofluids, TEM, Particle size analyzer

— Nomenclature —

A : Surface area of the cross section of the tube, [m^2]
C_p : Special heat, [J/KgK]
d_I : Inner diameter of Tube [mm]
d_0 : Outer diameter of Tube [mm]
h : Heat transfer coefficient [W/m^2K]
K : Thermal conductivity, [W/mK]
k_1 : Thermal Conductivity of Tube (W/mK)
n_l : Length of the test section, [m]
Nu : Nusselt number
P : cross sectional areas, [m^2]
q : Heat flux, [w/m^2]
Q_1 : Heat input from the heater [cal]
Q_2 : Heat input to the fluid [cal]
Re : Reynolds number
T : Temperature, [K]
t : Time, [s]
wt : Weight percentage, [%]
X : Axial distance from tube entrance, [m]
v : Velocity, [m/s]

Greek Symbols

α : Thermal diffusivity (mm^2/s)
γ : Shear rate (1/s)

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δ : Boundary layer thickness (mm)
η : Non-Newtonian viscosity (Pas)
μ : Viscosity (Pas)
ν : Kinematic viscosity (mm^2/s)
ρ : Density (kg/m^3)
τ : Shear stress (kg_f/mm^2)
ϕ : Volume fraction

Subscripts

m : Mixture
f : Fluid
in : Inlet
out : Out let
nf : Nanofluid
w : Tube wall

1. Introduction

Development of many industrial and new technologies is limited by existing thermal management, and need for high performance cooling. Many industrial applications need ultrahigh-performance cooling systems to miniaturize the thermal systems. Therefore modern nanotechnology has a significant application in advanced heat transfer and thermal science.

Heat transfer fluids such as water and ethylene glycol play an important role in numerous applications in many industrial sectors. Heat transfer efficiency can be improved by increasing the thermal conductivity of the working fluids. Commonly used heat transfer fluids have relatively low thermal conductivities, when compared to the thermal conductivity of solids. High thermal conductivity of solids can be used to increase the thermal conductivity of a fluid by adding small solid particles to that fluid. The feasibility of using micro sized suspensions of solids particles in base fluids in previous research had some problem like abrasion, instability and quick sedimentation of particles, clogging of channels and flow resistance[1-2]. Therefore in convective heat transfer nanoparticles less than 100nm size overcomes these obstacles. Nanofluids are suspensions of nanoparticles in base fluids, a new challenge for thermal sciences provided by nanotechnology. It has unique features in which nanometer sized particles of metals and non-metals are dispersed. Due to their excellent characteristics, nanofluids find wide applications in enhancing heat transfer and therefore are being investigated for numerous applications, including cooling process of a machine tool, manufacturing process, chemical process, pharmaceutical process and medical treatment process[3]. Maxwell[1] investigated the possibility of increasing the thermal performance in ordinary fluids by adding solid particle. From Maxwell's concept, the idea that particles size is of primary importance in developing stable and highly conductive nanofluids and thermal conductivity can be improved by increasing the particles volume fractions. Choi[4] reported that nanofluids are engineered by suspending nanoparticles with average sizes below 100 nm in traditional heat transfer fluids such as water, oil, and ethylene glycol. A very small amount of guest nanoparticles, when dispersed uniformly and suspended stably in host fluids, can provide dramatic improvements in the thermal properties of host fluids. This new class of nanotechnology based heat transfer fluids that exhibit thermal properties superior to those of their host fluids were termed as nanofluids.

Masuda et al.[5] first reported a 20% increase in the thermal conductivity of water with the addition of 3vol% Al_2O_3 nanoparticles. However, Lee et al.[6] obtained an increase of only 8% at the same volume fraction. A subsequent study by Wang et al. also examined the behavior of Al_2O_3 nanoparticles in water but observed a 12% enhancement in thermal conductivity at the same nanoparticle loading percentage. Nanoparticles may or may not exhibit size related properties that differ significantly from those observed in fine particles or bulk materials. Nanoclusters have at least one dimension between 1 and 10 nanometers and a narrow size distribution[7-8].

Thermal conductivities of nanoparticle fluid mixtures have been reported by Eastman et al.[9] and Artus[10] by adding a small volume fraction of metal or metal oxide powders in fluids increased the thermal conductivities of the particle-fluid mixtures over those of the base fluids. The thermal conductivity of nanofluid varies with the size, shape and material type of nanoparticles. For example nanofluids with metallic type nanoparticles found to have a higher thermal conductivity than nanofluid with non-metallic oxide nanoparticles. The smaller the particle size, the higher the thermal conductivity of nanofluids.[11-12]

In this research, we used alumina powder because compared with others, especially alumina nano particles have good dispersion ability. Alumina powders with sizes less than 50 nm supplied by Sigma Aldrich, Co. Chemie GmbH Austria were used. Alumina nanofluids with water and ethylene glycol as base fluids were prepared with different conditions and parameters, as shown in Table 1. The use of surfactant has some drawbacks during the application of nanofluids in thermal systems. Therefore, all alumina nanofluids samples were prepared without using any kind of surfactant or other surface stabilization additives.

The image obtained by Transmission Electron Microscope (TEM) showing alumina particles has also shown in Fig. 4.

Table 1. Conditions used to prepare water based and ethylene glycol based Al2O3 nanofluids

Alumina concentration (wt%)	Ultrasonicator dispersion time (hrs.)		
1	1	2	3
3	1	2	3
5	1	2	3

2. Thermal Properties of Alumina Nanofluids

2.1 Thermal Conductivity Measurement

Thermal conductivity of alumina nanofluids sample was measured by using F5 technology thermal conductivity measuring system (LAMBDA), capable of the continuous determination of the thermal conductivity as well as thermal diffusivity of a fluid. The most important part of the LAMBDA instrument is hot wire sensor. Modern measuring techniques and micro electron combined with an intensive mathematical and physical analysis of the system result in numerous advantages with fully automated measurement. In order to measure the thermal conductivity and not the convection in the fluid, a complete homogeneous temperature distribution in the sample has to be provided. Generally, there are two main principles for the determination of the thermal conductivity of liquids: the stationary and the in-stationary method. Only the latter one allows to determine both the thermal conductivity and the thermal coefficient of a fluid. The LAMBDA system is based on the in-stationary hot wire method. The wire is heated with a small amount of energy. The heat flow produces a time-dependent temperature field in the surrounding fluid.

With the assumption of one-dimensional heat flow this will lead to Fourier’s equation:

$$\frac{\partial v}{\partial t} = \alpha . \left(\frac{\partial v^{2}}{\partial r^{2}} + \frac{l}{r} . \frac{\partial v}{\partial r} \right) \tag{1}$$

With the temperature coefficient:

$$\alpha T = \frac{\lambda}{C_{p} . \rho} \tag{2}$$

The solution is:

$$v - v_0 = \frac{q}{4.\pi.\lambda}.E_i\left(-\frac{r^2}{4.\alpha.t}\right) \tag{3}$$

The approximation can be taken as:

$$v - v_0 = \frac{q}{4.\pi.\lambda}.\left(\ln\frac{4.\alpha.t}{r^2} - 0.5772\right) \tag{4}$$

The solution of the heat transfer on the surface of the heat-wire (r-r0) in the interval between times t1 and t2 is given by:

$$\lambda = \frac{q_1 + q_2}{8.\pi.(v_2 - v_1)}.\ln\frac{t_2}{t_1} \tag{5}$$

Another advantage of this equation is that there is no need for a correct determination of the diameter of the hot wire. With the combination of equation (4) and (5) the temperature coefficient α can be calculated as:

$$\alpha = \frac{r_0^2}{4.t}.\exp\left(\frac{4.\pi.\lambda}{q}.v + 0.56772\right) \tag{6}$$

2.2 Experimental Convective Heat Transfer

The schematic diagrams of experimental setup, used to investigate the convective het transfer of alumina naofluids is show in Fig. 1.

This experimental system was constructed by Wen and Ding[13] in their experiment as well. A straight copper tube with 1000 mm length, and 4.5 mm inner diameter, with thickness 0.85 mm was used as the test section. Eight T-type thermocouples were mounted equally spaced on the test section at axial positions. Two more T-type thermocouples were also mounted into the fluid flow at the inlet and outlet point.

And to obtain a constant heat flux boundary condition, the surface of the copper tube is uniformly bound by a silicone rubber flexible heater (Watlow, UK) and the heat testing section is heated by silicone rubber flexible heater which is fed power 300 W constant by a AC power meter, for minimizing heat loss to the surroundings, the heat testing part is isolated by a 4 cm thick adiabatic material (glass wool) as shown in Fig. 2.

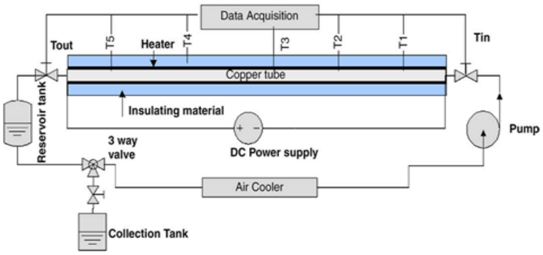

Fig. 1 Schematic Diagram of Experimental Setup for Convective Heat Transfer

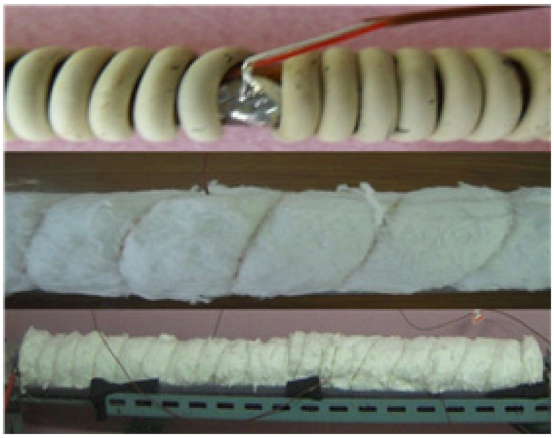

Fig. 2. Heat Testing section of copper tube with installing of silicone rubber flexible heater, thermocouple and insulation of glass wool

Performance of local heat transfer in terms of nusselt number and convective heat transfer coefficient is calculated by,

$$h(x) = \frac{q''}{(T_w - T_f)_x} \tag{7}$$

So the heat loss through the pipe is calculated by,

$$Q_{loss} = \frac{L2\pi k_1 \triangle T}{\ln\left(\frac{d_0}{d_1}\right)} \tag{8}$$

So, the actual heat flux can be calculated by the equation,

$$q'' = \frac{(Q_1 + Q_2)}{2\pi dL} \tag{9}$$

Fluid temperature profile in the test section can be calculated as,

$$T_f = T_{in} + \frac{q'' P_x}{\rho C_p v A} \tag{10}$$

2.3 Numerical Analysis of Convective Heat Transfer

The experimental results achieved from the experiment were then Fig. 3 analysis numerically. The perfect and successful application of computational fluid dynamic model depends on proper definition of computation grid suitable for the geometry being used. Hexahedral grid type was used in this model and 3-dimensional symmetry was implemented to maintain the accuracy while computational dynamic code Fluent13 was employed to solve. The mesh model has been shown in Fig 3.

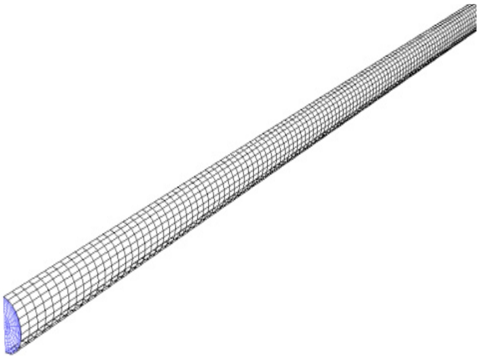

Fig. 3 Geometrical configuration under study.

The mixture multiphase model was used to model multiphase flows. For accurate simulation following boundary conditions were used.

Velocity inlet boundary condition was used to define the flow velocity, along with all relevant scalar properties of the flow, at flow inlets. The total (or stagnation) properties of the flow are not fixed, so they will rise to whatever value is necessary to provide the prescribed velocity distribution. Outflow boundary condition was used to model flow exits where the details of the flow velocity and pressure are not known prior to solution of the flow problem.

An adiabatic wall condition was used at wall surface of the tube to bound fluid and solid regions. The constant heat flux was implemented during analysis.

Table 2 Boundary condition in Fluent13

Number of Grid	48000
Heat Flux (W/m^2)	4800
Inlet	Velocity Inlet
Outlet	Outflow
Inlet Temperature (K)	293
Residual Target	10^{-6}

Energy equation for the mixture is,

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}(\phi_k \rho_k E_k) + \nabla\cdot\sum_{k=1}^{n}(\phi_k \vec{v}_k(\rho_k E_k + p)) = \nabla\cdot(k_{eff}\nabla T) + S_E \tag{11}$$

Continuity equation for the mixture is,

$$\frac{\partial}{\partial t}(\rho_m) + \nabla\cdot(\rho_m \vec{v}_m) = 0 \tag{12}$$

Mass-averaged velocity is,

$$\vec{v}_m = \frac{\sum_{k=1}^{n} \phi_k \rho_k \vec{v}_k}{\rho_m} \tag{13}$$

And mixture density is,

$$\rho_m = \sum_{k=1}^{n} \phi_k \rho_k \tag{14}$$

The momentum equation for the mixture can be obtained by summing the individual momentum equations for all phases. It can be expressed as,

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla\cdot(\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla\cdot\left[\mu_m(\nabla\vec{v}_m + \nabla\vec{v}_m^T\right] + \rho_m \vec{g} + \vec{F} + \nabla\cdot\left(\sum_{k=1}^{n}\phi_k\rho_k\vec{v}_{dr,k}\vec{v}_{dr,k}\right) \tag{15}$$

From the continuity equation for secondary phase p, the volume fraction equation for secondary phase p can be obtained as,

$$\nabla\cdot(\phi_p\rho_p\vec{v}_m) = -\nabla\cdot(\phi_p\rho_p\vec{v}_{dr,p}) \tag{16}$$

Relative velocity is given by,

$$\vec{v}_{pq} = \frac{\tau_p}{f_{drag}}\,\frac{(\rho_p-\rho_m)}{\rho_p}\,\vec{a} \tag{17}$$

3. Results and discussion

Transmission Electron Microscope (TEM) image of alumina nanofluids, prepared as per conditions mentioned in Table. 1 has been shown in Fig. 4 and the graphical result of particle size analyzer test has shown in Fig. 5.

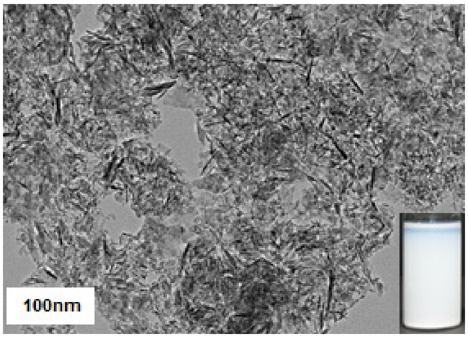

Fig. 4 TEM Image of alumina Nanofluids

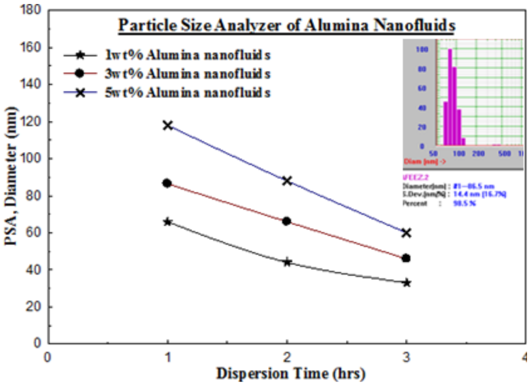

Fig. 5 Particle size analyzer graph alumina nanofluids

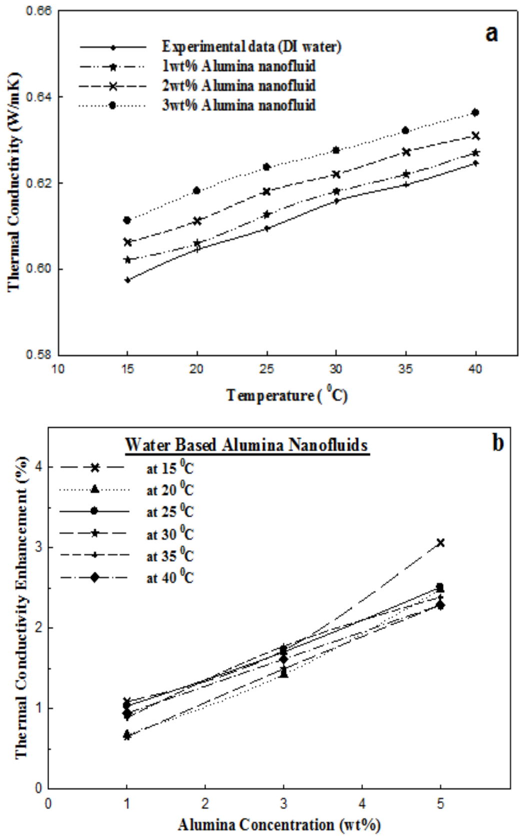

Fig. 6 a).Thermal conductivity of aqueous-alumina nanofluids b). Thermal conductivity enhancement.

The results of thermal conductivity of aqueous alumina nanofluids at different temperature zone and also the percentage enhancement in thermal conductivity due to addition of alumina nanoparticles in base fluid, has shown in Fig. 6 (a & b). As per results, enhancement in thermal conductivity in aqueous alumina nanofluids is 1.42% to1.78% with 3wt% and 2.29% to 3.06% with 5wt% alumina at temperature zone from 15 0℃ to 400℃.

Similarly Fig. 7 (a & b) illustrates the thermal conductivity of EG-based alumina nanofluids at different temperatures zone and also the percentage enhancement in thermal conductivity due to addition of alumina nanoparticles in base the fluid.

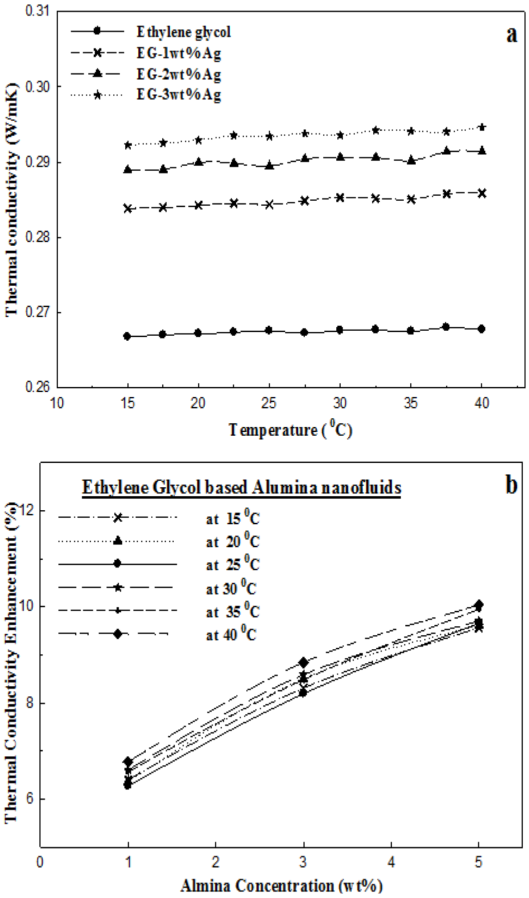

Fig. 7 a).Thermal conductivity of EG-alumina nanofluids b). Thermal conductivity enhancement.

The result reveals that, thermal conductivity enhancement is 8.2% to 8.85% with 3wt% alumina and 9.6% to 10% with 5wt% alumina nanofluids at different temperature zone.

Table 3 Thermal conductivity enhancement results of alumina/water and EG/alumina nanofluids

Temp. (°C)	Enhancement of 'K' Alumina/ water nanofluids (%)			Enhancement of 'K' Alumina/ EG nanofluids (%)		
	1wt	3wt	5wt	1wt	3wt	5wt
15	1.09	1.72	3.06	6.4	8.31	9.56
20	0.68	1.42	2.48	6.37	8.50	9.62
25	1.03	1.70	2.51	6.27	8.19	9.66
30	0.65	1.49	2.9	6.6	8.59	9.70
35	0.89	1.78	2.39	6.67	8.48	9.95
40	0.95	1.62	2.29	6.77	8.84	10.03

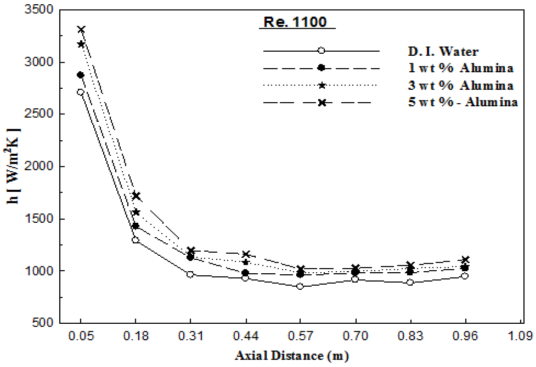

Fig. 8 Convective heat Transfer coefficient at along axial distance at Re=1,100

Detail of thermal conductivity enhancement results of alumina nanofluids with water and EG as base fluids has also been illustrated in Table 3.

Local heat transfer coefficient along the axial distance of the pipe for the alumina nanofluids at Re. number 1100 has been calculated. Fig. 8 shows the graphical results of the heat transfer coefficient along the axial distances.

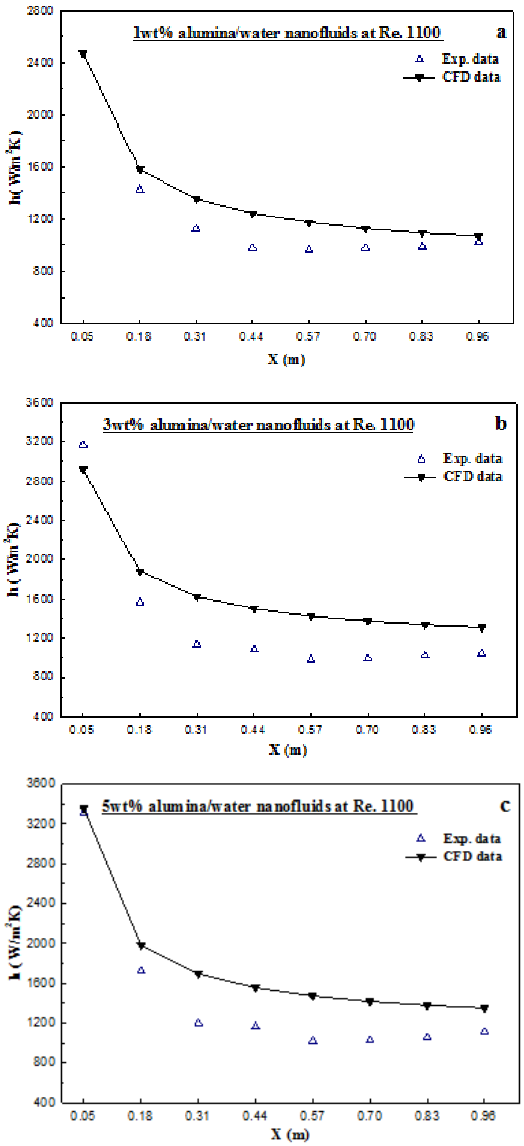

Fig. 9 Comparison results of experimental data of convective heat Transfer coefficient with CFD data at Re=1,100 a). 1wt% alumina, b). 3wt% alumina, c). 5wt% alumina nanofluids.

The comparison results of experimental data and CFD numerical data have been shown in Fig. 9 (a, b, c) in detailed for Re. 1100. Fig. 9 shows that there is a difference between the value of the results of both. Especially in 1wt% case, difference between the value of both results is about 10%. The 1wt% of results match than the concentration of 3,5wt%. Because 3,5wt% concentration have more unpredictable variables in experiment circumstance than 1wt%.

4. Conclusion

Experimental results of thermal conductivity of alumina nanofluids measured by means of hot wire technique using a LAMBDA system revealed that, for water-based alumina nanofluids, thermal conductivity has enhanced from 1.42% to 1.78% with 3 wt% alumina and from 2.29% to 3.06% with 5 wt% alumina at temperatures ranging from 15 to 40 ℃. Whereas in case of ethylene glycol-based alumina nanofluids under the same temperature range, thermal conductivity enhancement was from 8.2% to 8.85% with 3 wt% and from 9.6% to 10% with 5wt% alumina. Experimental average heat transfer coefficient for alumina nanofluids with concentration from 1wt%, 3wt% and 5wt% under laminar flow has increased considerably. An enhancement of 22% to 37 % average convective heat transfer has been achieved with 5wt% alumina concentration nanofluids at Re. 1100.

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