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Numerical and Experimental Investigation of a Packed bed Thermal Energy Storage System with Hybrid Nanofluid

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Abstract: *The results of a numerical and experimental investigation on the transient behaviour of a packed bed thermal storage system using water based nanofluid and hybrid nanofluid fluids is presented. The storage material consists of spherical particles of glass beads loosely packed in a reservoir wherein the heat transport fluid flows from the bottom to the top in the charging process..The process of charge the storage system gives rise to a typical temperature distribution along the flow direction defined "thermocline". The main objective of this work is to analyze the temperature distribution along the storage system and the formation of the thermocline for repetitive consecutive cycles, evaluating the progressive reduction in the heat capacity for energy storage in the solid material for every new cycle. The numerical investigation is based on a two-phase one-dimensional modified Schumann model, where thermodynamic properties of the fluid are temperature dependent. The temperature profiles, friction factor and Nusselt number are estimated, compared with available literature and shown graphically.*

Keywords: *packed bed; fixed bed modelling; thermal energy storage; thermocline; dynamic model; hybrid nanofluid.*

Nomenclature

A	Area of Cross Section
μ	*Viscosity*
$\emptyset$	*Volume fraction*
U	*velocity*
v	*volume*
L	*Length*
b	*Bed*
C_p	*Specific heat*
f	*Fluid*
b	*Bed*
T	*Temperature*
∞	*Boundary*
NTU	*Number of Transfer unit*
ρ	*Density*
h_{nf}	*Hybrid nano fluid*
K	*Constants*
k	*Thermal conductivity*
h	*Heat transfer coefficient*
Nu	*Nusselt number*
f	*Friction factor*
θ	*Non dimensional temperature*
ϵ	*Porosity*
N	*Number of segments*
τ	*Non dimensional heat capacities*
β	*Thermal expansion coefficient*
Rep	*Particle Reynolds number*
L	*Length of bed*
z	*Axial direction*
Z	*Nondimensional axial distance*
ψ	*Sphericity of the particle*
HTF	*Heat transfer fluid*
Subcriipts	
i	*inlet*
o	*Outlet*
f	*Fluid*
b	*Bed*
nf	*Nano fluid*
bf	*base fluid*
hnf	*Hybrid nano fluid*

I. INTRODUCTION

Conventional heat transfer fluids have been used as working fluids in most of important studies that were performed in parallel with related applications. However, conventional heat transfer fluids have lower thermal conductivity coefficients, which is the basic limitation of the heat transfer performance of the system considered. Recent studies have shown that this limitation, which is due to the lower thermal conductivity coefficient of conventional heat transfer fluids, can be overcome with the use of nanofluids. The term nanofluid is used to describe a solid and liquid mixture that consists of a base liquid and nanoparticles of less than 100 nm in size. Maxwell [1, 2] was the first to show the possibility of augmentation of thermal conductivity of a solid-liquid

mixture by increasing the volume fraction of solid particles.
However, large particles cause many troublesome problems such as sedimentation of large sized particles in base fluid. Thus, a new class of fluids for improving both thermal conductivity and suspension stability was developed that is known as nanofluid. Choi [3] presented the benefit of using the nanoparticles dispersed in a base fluid in different thermal systems to enhance the heat transfer rate. Eastman et al. [4] presented that with 0.3% volume concentration of Cu nanoparticles dispersed in ethylene glycol, its thermal conductivity increased by 40%. A. very recently, an experimental study has been carried out on nanofluid with two types of nanoparticles dispersed simultaneously in a base fluid that is called “hybrid nanofluid” Suresh et.al [5]. The most important exclusivity of hybrid nanofluid refers to composition of two variant types of dispersed nanoparticles in a base fluid.

Suresh et al. carried out an experimental study to synthesize Al2O3-Cu/water hybrid nanofluid Suresh et.al [5]. To reach the stable hybrid nanofluid, they used a thermo mechanical method (two-step method). They added Cu nanoparticles to Al2O3/water nanofluid and synthesized Al2O3-Cu/water hybrid nanofluid by different volume concentrations. According to the above mentioned benefits of hybrid nanofluids, it is clearly expected that this advanced nanofluid plays a vital role in the future of science of nanofluid and researchers show a greater tendency toward investigation of hybrid nanofluids and effect of such fluids on heat transfer and pressure drop characteristics.

Heat transfer and pressure drop characteristics were also investigated in some of the investigation carried out. In the work carried out by Suresh et.al [6] a fully developed laminar convective heat transfer and pressure drop characteristics through a uniformly heated circular tube using Al2O3 – Cu/water hybrid nanofluid were investigated. The experimental results of hybrid nanofluid for laminar flow shows the maximum enhancement of 13.56% on Nusselt number at a Reynolds number of 1730 when compared with water. the average increase in Nusselt number for Al2O3- Cu /Water hybrid nanofluid was 10.94% when compared to pure water. the enhancement obtained by 0.1% Al203 water was 6.09% when compared to pure water..This means that the mixing of a small amount of copper nanoparticles in aluminum oxide significantly enhances the Nusselt number. The average increase in friction factor of 0.1% Al2O3–Cu/water hybrid nano- fluids as16.97%whencompared to water. For the same volume concentration, Al2O3/water nanofluid showed an average of 6% increase in friction factor. This reveals that diluteAl2O3–Cu/water hybrid nanofluids will cause extra penalty in pumping power when compared to Al2O3/water nanofluid.

They have also proposed of correlations Nusselt number and friction factor particle volume fraction 0f 0.1% and the Reynolds number up to 2300, which are in good agreement with the experimental data. Suresh et.al [31] studied turbulent heat transfer and pressure drop characteristics of dilute Al2O3 –Cu/Water hybrid nanofluids and showed an average heat transfer enhancement 0f 8.02% compared with pure water Selvakumar and Suresh [8] studied the effect on heat transfer and pressure drop characteristics by using Al2O3- Cu water hybrid nanofluid of 0.1% volume fraction and observed that the convective heat transfer coefficient increases with increasing the mass flow rate of the deionized water in the thin channeled copper heat sink. They observed significant increase in convective heat transfer coefficient when Al2O3-Cu /water hybrid nanofluid was the coolant when compared with water. They reported 24% average increase in convective heat transfer coefficient for hybrid nanofluid compared with water .

Sundar et al. [8], [10] and Sharma et al.[9] undertook the experimental determination of heat transfer coefficients by measuring the viscosity and thermal conductivity, using Al_2O_3 nanofluid, for flow in a plain tube and with twisted tape insert. They concluded that nanofluids enhance heat transfer coefficients which can reduce the size of thermal storage system. Rao et. al. [11], [12],[13] have estimated pressure drop and the heat transfer coefficient in packed beds with the same nanofluid and concluded that nanofluids performed better than conventional fluids such as air and water.

In this paper, laminar forced convection flow of Al2O3/water nanofluid and Al2O3-Cu/water hybrid nanofluid in a packed bed thermal energy storage system heating the bed from the bottom is investigated for different flow rates and concentration of nanofluid and as well as hybrid nano fluid and compared the results . In fact this paper concerns the flow and heat transfer characteristics and pressure drop in the same geometry which was studied by various authors form the literature. The main objective of this study is to analyze the thermal behaviour of a sensible heat storage system characterized by a solid storage material of high volumetric thermal capacity. The solid material consists of spherical particles tightly poured into a vertical reservoir, wherein the HTF flows from the bottom to the top of the tank during the charging phase. Water+Al2o3 and Al2o3 Cuo hybrid nanofluid with three different concentrations are the HTF considered in this work and spherical particles of two different sizes glass beds are the solid material of size 6mm and 14.56mm.

II. MATHEMATICAL MODELING

The traditional Schumann [14] mode extended by Hughes et al. [15] and later by Sagara & Nakahara [16] formed the analytical framework for estimating the thermal behaviour of packed beds at high flow velocities. The energy balance for the fluid can be written as:

Energy supplied by the fluid = Energy transferred to bed by convection + Energy leaving the bed with flowing fluid + Energy loss to the atmosphere.

Assuming the heat energy to the atmosphere to be negligible, the energy balance equation can be written a

$$m_f C_{pf} T_{fi} = h_v A(T_f - T_b)dz + m_f C_{pf}\left[\left(T_{fi} - \frac{\partial T_{fi}}{\partial x}dz\right)\right]$$

$$\frac{\partial T_{fi}}{\partial (z/L_b)} = -\frac{h_v A L_b}{m_f C_{pf}}(T_f - T_b) \qquad [1]$$

Rewriting equation (5.2) one can obtain

$$\frac{\partial T_{fi}}{\partial (z/L_b)} = NTU(T_f - T_b)$$

The equation (5.3) can be integrated to obtain the following expression

$$\int_m^{m+1} \frac{\partial T_f}{T_f - T_b} = -NTU \int \partial\left(\frac{z}{L_b}\right)$$

$$In\frac{T_{f,m+1} - T_{b,m}}{T_{f,m} - T_{b,m}} - NTU\frac{\Delta z}{L_b}$$

$$\frac{T_{f,m+1} - T_{b,m}}{T_{f,m} - T_{b,m}} = e^{-NTU \times N}$$

$$\frac{T_{f,m} - T_{b,m+1}}{T_{f,m} - T_{b,m}} = 1 - e^{-NTU \times N} \qquad [2]$$

Where $NTU = \frac{h_v A L_b}{m_f C_{pf}}, N = \frac{\Delta z}{L_b}$

The Eq. (2) is considered to estimate the non-dimensional temperature for fluid, solved with the initial conditions given

$z = 0, \theta_f = 1$

For the solid phase, the equation is obtained as

$$(1 - \epsilon)\frac{\partial T_b}{\partial t} = \frac{h_v}{\rho_b C_{pb}}(T_f - T_b)$$

$$\frac{\partial T_b}{\partial t} = \frac{h_v}{\rho_b C_{pb}\,(1-\epsilon)}(T_f - T_b) = \frac{NTU}{\tau}(T_f - T_b) \qquad [3]$$

Where $\tau = \frac{m_s C_{ps}}{m_f Cp_f}$

The Eq. (3) is considered to determine the temperature variation of the solid subjected to initial condition

$z = 0, T_b = T_{bi}$

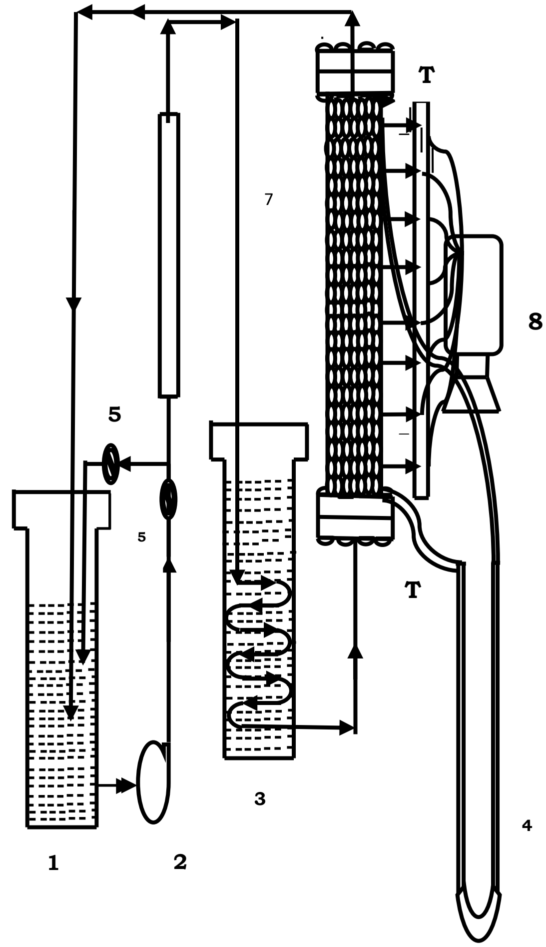

Fig 1.0 Experimental setup

Part list:

1. Supply tank. 2. Pumping device 3. Heating tank 4. Manometer 5. Gate valve 6. Rotameter7. Test section 8. Data Acquisition System Tp1, Tp2 pressure taping

A. Thermophysical Properties Of Nanofluid And Hybrid Nanofluid. :

As previously mentioned, although some literatures studied the determination of thermophysical properties, the classical models are not certain for nanofluids. The experimental results allow us to select an appropriate model for a specified property. The effective properties of the Al2O3/water nanofluid and Al2O3-Cu/water hybrid nanofluid are defined as follows:

$$\rho_{nf} = \phi_p \rho_p + (1 - \phi_p)\rho_{bf} \qquad (4)$$

Equation (4) was originally introduced in [17] for determining density and then widely employed in [18–21]. So, the density of hybrid nanofluid is specified by

$$\rho_{hnf} = \emptyset_{Al2O3}\rho_{Al2O3} + \emptyset_{Cu}\rho_{Cu}\ (1-\emptyset_p)\rho_{bf} \qquad (5)$$

Is the overall volume concentration of two different types of nano particles dispersed in hybrid nanofluid and is calculated as

$$\emptyset = \emptyset_{Al2O3} + \emptyset_{Cu} \qquad (6)$$

Equation (6) that is utilized for specifying heat capacity was first employed in [20] and then used in many articles [22, 23, 24]:

$$Cpnf = \frac{\rho_p \emptyset_p Cp_p + (1-\emptyset_p)\rho_{bf} Cp_{bf}}{\rho_{nf}} \qquad (7)$$

According to (6), heat capacity of hybrid nanofluid can be determined as follows:

$$Cp_{hnf} = \frac{\emptyset_{Al2O3}\rho_{Al2O3}C_{pAl2O3} + \emptyset_{Cu}\rho_{Cu}(1-\emptyset_p)\rho_{nf}Cp_{nf}}{\rho_{nf}} \qquad (8)$$

The thermal expansion coefficient of nanofluid can be determined by (8) employed in some literatures [23, 24]:

$$\beta_{nf} = \frac{\rho_p \emptyset_p \beta_p + (1-\emptyset_p)\rho_{bf}\beta_{bf}}{\rho_{nf}} \qquad (9)$$

Hence, for hybrid nanofluid, thermal expansion can be defined as follows:

$$\beta_{hnf} = \frac{1}{\rho_{hnf}}\left(\phi_{Al2O3}\rho_{Al2O3}\beta_{Al2O3} + \phi_{Cu}\rho_{Cu}\beta_{Cu} + (1-\phi)\rho_{bf}\beta_{bf}\right) \qquad (10)$$

In addition, for calculating Thermal conductivity of nanofluids equation (10) was proposed by Hamilton and Crosser [28].

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + (n-1)k_{bf} - (n-1)\phi_p\,(k_{bf}-k_p)}{k_p + (n-1)k_{bf} + \phi_p\,(k_{bf}-k_p)} \qquad (11)$$

Here n is the empirical shape factor in order to account the effect of particles shape and can be varied from 0.5 to 6.0. The shape factor n is given by $3/\psi$, where ψ is the particle sphericity, defined as surface area of a sphere to the surface area of the particle. Therefore for spherical nanoparticles n equals 3. This case of Hamilton and Crosser model ($n = 3$) is the same as Maxwell model [2]; see the following:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + 2k_{bf} - 2\phi_p\,(k_{bf}-k_p)}{k_p + 2k_{bf} + \phi_p\,(k_{bf}-k_p)} \qquad (12)$$

If the thermal conductivity of hybrid nanofluid is defined according to Maxwell model, (12) must be employed for this purpose:

$$\frac{k_{hnf}}{k_{bf}} = \left(\frac{(\emptyset_{Al2O3}k_{Al2O3} + \emptyset_{Cu}k_{Cu})}{\emptyset} + 2k_{bf} + 2(\emptyset_{Al2O3}k_{Al2O3} + \emptyset_{Cu}k_{Cu} - 2\emptyset k_{bf})\right) \times \left(\frac{(\emptyset_{Al2O3}k_{Al2O3} + \emptyset_{Cu}k_{Cu})}{\emptyset} + 2k_{bf} - (\emptyset_{Al2O3}k_{Al2O3} + \emptyset_{Cu}k_{Cu}) + \emptyset k_{bf}\right) - 1 \qquad (13)$$

To predict the viscosity of nanofluid, three models frequently were employed theoretically. These models are presented as follows.

$$\mu_{nf} = \mu_{bf}\left(1 + K_\mu \emptyset\right)$$

Where $K\mu = 2.5$

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\emptyset)^{2.5}}$$

$$\mu_{nf} = \mu_{bf}(1 + K_1\emptyset + K_2\emptyset)^2 \qquad (14)$$

The thermophysical properties of both Al2O3/water nanofluid and Al_2O_3-Cu/water hybrid nanofluid for all volume concentrations are available in Table1.0 proposed by Behrouz Takabi and Saeed Salehi [30] .In addition to this the volume concentrations of Al_20_3 and Cu are separately presented.

B. Experimentation:

The experimental setup as shown in the diagram. Experiments are conducted with water, Al_20_3 nanofluid and hybrid nanofluid (combination of copper oxide and aluminium two different flow rates 200 LPH and 300 LPH with two variations of temperatures 40^0 and 50^0 are considered .The heat transfer coefficient and friction factor with different parameters are estimated and compared with literature. and presented through graphs.

The friction factor and heat transfer coefficients are compared with the available equations from the literature .The friction factor is compared with Ergun Equation, and heat transfer coefficient is compared with Gnielinski [27] . the pressure drop values are compared with Ergun [28] equation

$$\Delta P = \frac{150(1-\epsilon)^2 \mu U L_B}{\epsilon^2 \Psi^2 Dp^2} + \frac{1.75\,(1-\varepsilon)^2\,\rho U^2\,L_B}{\epsilon^3\,\psi Dp} \qquad (15)$$

Gnielinski [27] equation

$$\text{Nu} = \frac{hDp}{k} = 0.664 Re_p^{0.5}\,Pr^{0.333} \qquad (16)$$

III. RESULT AND DISCUSSIONS

The experimental results are compared with theoretical equations and plotted with origin6.0. Fig 2.0 represents particle Reynolds number and friction.. At low Reynolds number the friction is very high in all fluids. The friction factor is reduces with increase in particle Reynolds number. when the flow is reaches nearly at 2000 the friction is constant in all cases of fluids. The friction is increases with increasing the volume of faction of the nanofluid. At the lower concentration i.e. at 0.02% of volume concentration the nanofluid also acts as base fluid no significant in friction factor. With increasing in volume concentration from 0.1% to 0.5% of volume faction , the friction factor is increasing with significant effect. The friction is increases with hybrid nanofluid concentration. With 0.5% of volume concentration with Al2O3 nanofluid; friction factor for hybrid nanofluid is increased by 18% when compared with nanofluid and water. Fig 3.0 Represents the effect of nanofluid concentration on heat transfer coefficient for different bed particles at 300 LPH .The heat transfer coefficient is increases with increasing the fluid inlet temperature and also increases with concentration of nanofluid.

Fig4.0 shows the effect of nanofluid concentration with different flow rates at 40^0 C. Heat Transfer coefficient is increases with increasing the flow rates and concentration . Fig 5.0 shows the effect of effect of nanofluid concentration on temperature of bed with axial distance. The temperature gradient is increases with increases the nanofluid concentration

Fig 6.0 indicates the effect of nanofluid concentration on heat transfer coefficient with bed inlet temperature. Heat transfer coefficient is increases with increasing the fluid inlet temperature and concentration of nanofluid .

IV. CONCLUSIONS

The effect fluid inlet temperature , particle size and flow rate and inclusion of Al2O3 and al2O3 –Cu nanoparticles in the base fluid ,for laminar forced convection in packed bed thermal energy storage system with given boundary conditions have been numerically investigated in this study. The experimental values are values are good agreement with available literature equations. Some important conclusion drawn from the present analyses are as follows

Heat transfer in a packed bed column filled with glass beads of 6.0 and 14.56 mm size is employed to determine heat transfer coefficient and pressure drop. The friction factor increased with decreasing particle diameter and increasing volume concentration of nanofluids compared to base fluid. The pressure drop is higher with nanofluids than with water by 10 to 15%.

The pressure drop increased with nanofluid concentration .At lower concentration, the deviation of friction factor with nanofluid and water is significant than at higher concentration. The heat transfer coefficient is higher with 6mm particles due to larger surface area and the number of particles.

Similarly, the heat transfer coefficient is greater at higher concentrations of the nanofluid. With an increase in volume concentration, the heat transfer is more and increases with the flow rate and inlet fluid temperature. The enhancement in heat transfer coefficient with nanofluids than base fluid lies between 10 to 15% due to higher values of thermal conductivity. The values from Schumann model agree with the experimental data for the two bead sizes of 6.0 and 14.56mm. The deviation between the two is less than 10%.

(i) Classical Schuman model is used to investigating the flow characteristics of packed bed thermal energy storage system numerically. The experimental values are compared with numerical solutions.

(ii) the friction factor is increases with the decreasing in the particle size. Friction factor is increases with increasing the nanofluid concentration and inclusion of Al2O3 and Cu nanofluid particle in the base fluid .The friction factor is increases nanofluid by 18% when compared with base fluid and with 21% with n hybrid fluid .

(iii) The increase of particle Reynolds number the heat transfer coefficient is increases in both nanofluid and hybrid nanofluid. The increases in the volume concentration heat transfer coefficient is increases by 12% for Al2O3 nanofluid and 15% for (Al2O3 and Cu) nanofluid when compared with base fluid.

(iii) The heat transfer rate also increases with increasing the flow rate and bed inlet temperature and concentration of nanofluid. The heat capacity of hybrid nanofluid is 10% higher than the nanofluid for all conditions

Table.1 Thermophysical properties of nanofluid and hybrid nanofluid

$\varnothing$ (%)	$\varnothing_{Cu}$ (%)	$\varnothing_{Al2O3}$ (%)	k_{nf} W/m K	μ_{nf} Kg/m-s	k_{hnf} W/m-K	μ_{hnf} (kg/m-s)
0.10	0.0038	0.0962	0.614055	0.0009041	0.6199817	0.000972
0.33	0.0125	0.3175	0.6190041	0.0009049	0.6309797	0.001098
0.75	0.0285	0.7215	0.6309797	0.0009098	0.6490042	0.001386
1.00	0.0380	0.9620	0.6437496	0.00095184	0.6570083	0.001602
2.00	0.0759	1.9241	0.6571916	0.000972	0.6849921	0.001935

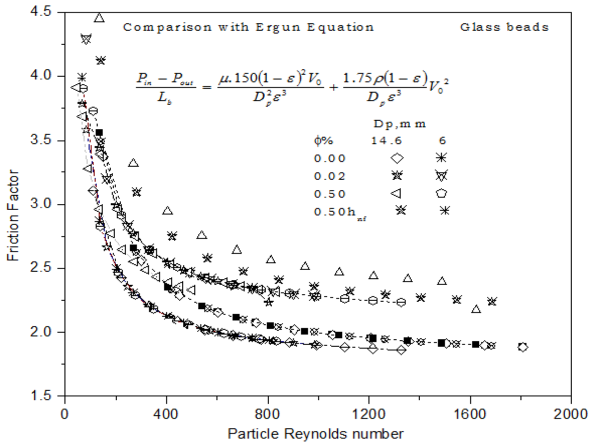

Fig 2.0 effect of nano fluid concentration on Friction factor variation with Particle Reynolds number compared with Ergun equation

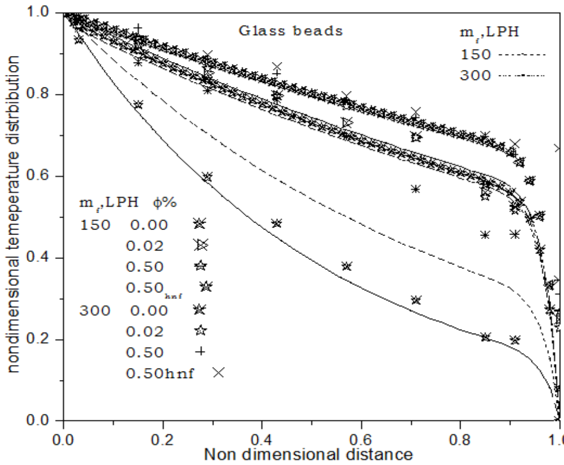

Fig 5.0 Non dimensional temperature distribution Vs Non dimensional axial distance at different flow rates with concentration of nanofluid

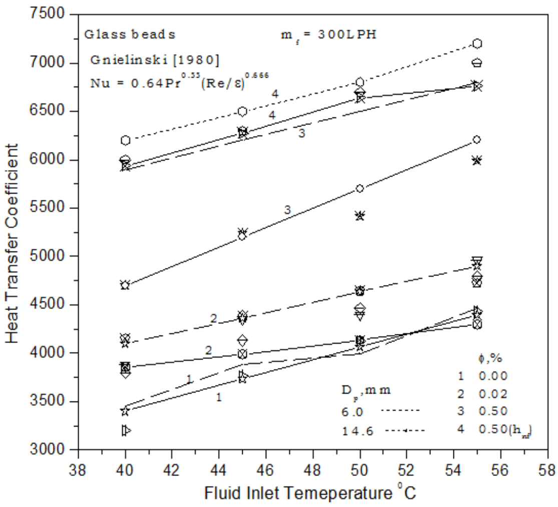

Fig 3.0 Effect of nanofluid concentration on Heat Transfer coefficient with Fluid inlet Temperature at 300 LPH

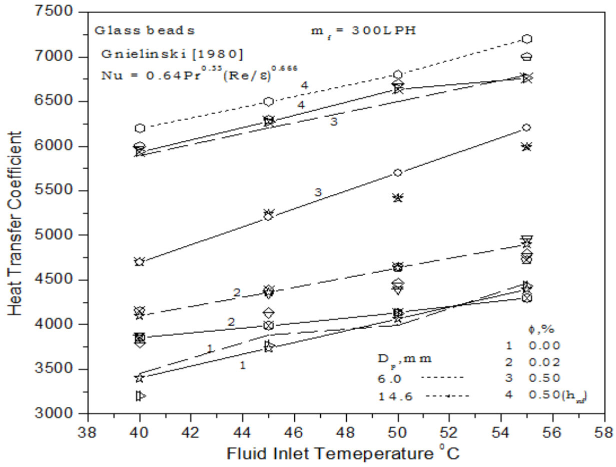

Fig6.0 Effect of nanofluid concentration Heat transfer coefficient with Fluid temperature for different particles at 300 LPH

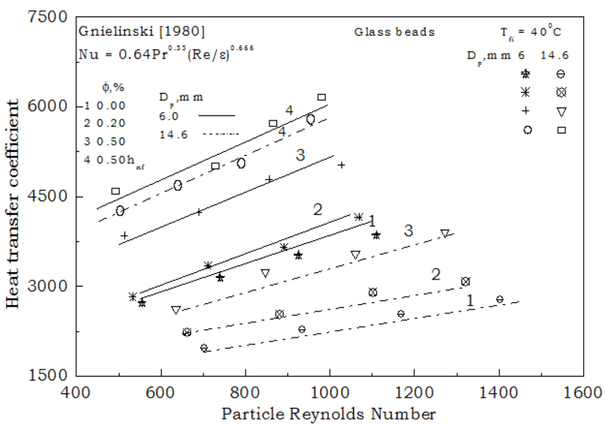

Fig 4.0 Effect nano fluid concentration on Heat transfer coefficient with Particle Reynolds number at fluid inlet temperature 40^0C

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