PERFORMANCE ANALYSIS AND OPTIMIZATION OF SHELL AND TUBE HEAT EXCHANGER USING CU-WATER NANOFLUID AS A COOLANT

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ABSTRACT

The recent development of nanotechnology have put an impact in the field of heat transfer and invented the new type of heat transfer fluids called nanofluids. Nanofluids are the stable suspension of nanosized solid particles (1-100 nm) into the base fluid or conventional fluid. Nanofluids are the potential fluids which are using for the transfer of heat in order to enhance the performance the existing heat exchanger. This recently introduced type of cooling fluids has shown the fascinating results and behavior which are superior to convention fluid. In this paper, the behavior of Cu-Water nanofluid and its effect on the performance of single pass counter-flow shell and tube type heat exchanger has been observed analytically and also the comparison is made between the Cu-Water nanofluid and conventional base fluid i.e. water. In this present paper, an analytical investigation is been carried out for the optimization of the performance of heat exchanger at different concentration of copper nanoparticles (up to 5%) and at different operating parameters. The conclusion of this paper is that the overall heat transfer coefficient and the thermal conductivity of nanofluid increases with the increase in concentration of nanoparticles and which in turn lead to higher rate of heat transfer with enhancement in the effectiveness of heat exchanger. The increase in the concentration of copper nanoparticles also increases the pumping power up to 32% at 5% concentration of copper nanoparticles.

Keyword: - *Nanotechnology, Heat Transfer, Nanofluid, Nanosized, Heat Exchanger, Cu-Water, Effectiveness, Pumping power*

1. INTRODUCTION

1.1 Heat Exchanger:

A heat exchanger is a most common and important device used to transfer heat in two or more media, in many applications. In a heat exchanger, heat is being transferred from the warmer or fluid to the colder fluid with the help of wall keeping them from mingling with each other. A heat exchanger of shell and tube type, as shown in figure 1, has wide applications and mostly used in industry process heating and cooling, power production, refrigeration and air conditioning systems, chemical processing, food industries, petroleum refineries and so on. To transfer heat effectively and at the maximum rate in a given application is the key role of heat exchanger [1]. The augmentation in heating and cooling rate in process industries promises to energy consumption, reduction in process time, thermal rating and enhances the life of equipment but also affect some processes qualitatively due to enhancement in heat transfer. The main purpose of a heat exchanger is increasing heat transfer between two fluids which reduces the required energy and helps to create a more effective process for both production and economy [2].

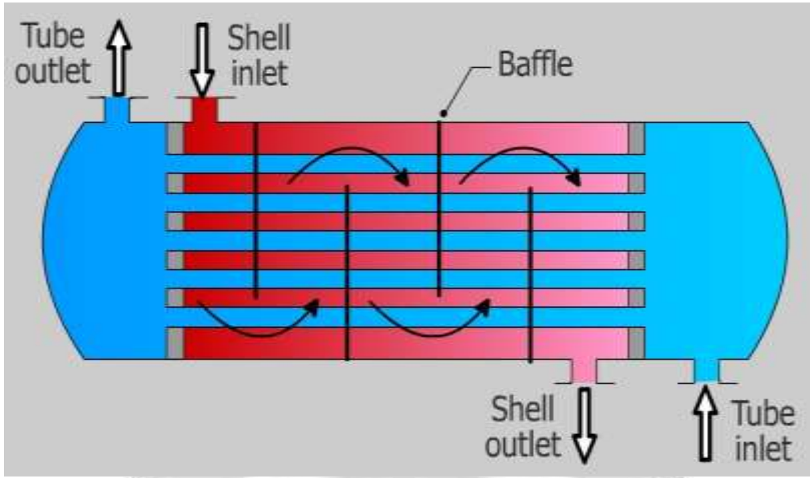

Fig -1: Shell and Tube heat exchanger [3]

A heat exchanger can be classified on the basis of the direction of two fluids as parallel flow, counter flow and cross flow type heat exchanger. In this proposed work, a counter flow shell and tube heat exchanger is been considered. A counter flow mechanism is shown in figure 2.

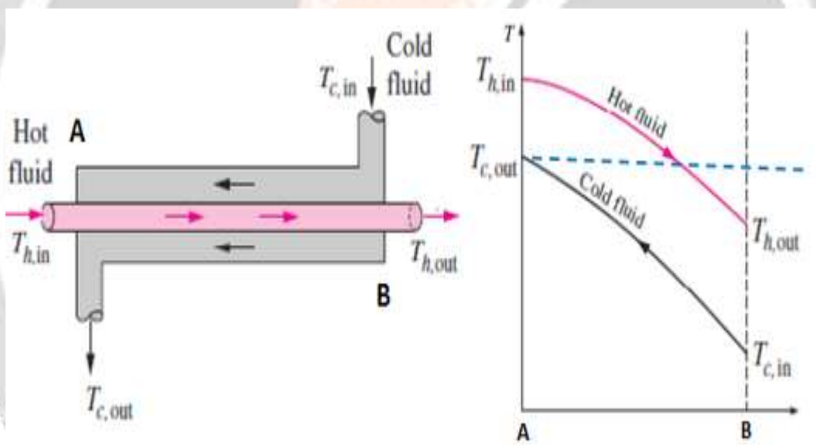

Fig -2 Counter flow mechanism [4]

1.2 Nanofluids:

The recent enhancement in nanotechnology have attracted many researchers to apply this advancement in the domain of heat transfer. The suspension of stable solid nanoparticles, of the size of 10^{-9} m, into the base fluid or conventional fluid is called 'Nanofluid'. The nanofluid shows the fascinating behaviour, over conventional fluids.

In this work, the Cu-Water nanofluid is used as a coolant fluid and the performance parameters of the heat exchanger are effectively calculated. In this analytical study of performance parameters of the heat exchanger, we observe that the enhancement in performance parameters of a heat exchanger using Cu-Water nanofluid as compared to the conventional fluid or water.

1.3 Cu-Water Nanofluid:

A decade ago, the fascinating growth and advancements in modern nanotechnology have proposed a new technique and emerging heat transfer cooling fluid called 'nanofluids'. A Cu-Water nanofluid is the stable suspension of copper nanosized (10^{-9} m) in to the water or base fluid.

A Cu-Water nanofluid, which contains the copper nanosized particles of higher thermal conductivity, has higher thermal conductivity, enhanced heat transfer coefficient and excellent stability [5].

2. METHODOLOGY

In this proposed work, the following steps are followed to calculate the performance of heat exchanger:

- Thermo-physical properties of Cu-Water nanofluid
- Flow properties of Cu-Water nanofluid
- Calculation of convective heat transfer coefficient
- Calculation of overall heat transfer coefficient
- Calculation of Number of Transfer units (NTUs)
- Calculation of effectiveness and rate of heat transfer
- Calculation of outlet temperature of both fluids and LMTD
- Calculation of pressure drop and pumping power for Cu-Water nanofluid.

The below figure 3 shows the methodology or work flow chart of this proposed work.

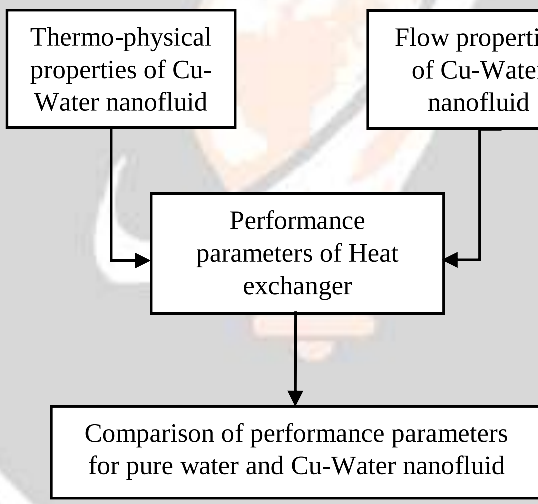

Fig -3 Work flow chart

2.1 Problem Statement:

In In this proposed work, the following problem, which is suggested by Kreith and Bohn [6], which is considered for the evaluation and comparison of performance parameters for pure water and Cu-Water nanofluid as:

It is suggested to cool the hot flue gases from the furnace of a boiler by using water as a coolant in a shell and tube type heat exchanger. The flue gases are available at the rate of 0.23 kg/s at 150°C, with a specific heat of 1000 J/kg k. The water entering the tube of the heat exchanger at 15°C at the rate of 0.06 kg/s is to be heated by flue gases. The heat exchanger is the type of one shell and four tube passes. The water flows inside the tubes, which are made of copper of 25mm inner diameter and 30mm outer diameter. The heat transfer coefficient at the gas side is 80 W/m2 k and the length of the tube is restricted to 40 m. Calculate the overall heat transfer coefficient, LMTD, effectiveness of heat exchanger, heat transfer rate, pressure drop and pumping power for coolant.

In this proposed work, the following thermo-physical properties of pure water and copper are considered as suggested in [7] as:

Table -1: Thermo-physical properties of copper and pure water

Sr. No.	Properties	Pure water	Copper
1	Thermal conductivity	0.643	386
2	Density	981.3	8930
3	Specific heat	4189	383.1
4	Viscosity	0.000598	-

2.2 Step by Step Calculation:

The step by step calculation of all parameters of the heat exchanger with empirical correlations is illustrated below.

A. Thermo-physical properties of Cu-Water nanofluid:

The thermo-physical properties of Cu-Water nanofluid differ from either of the parent material and these properties are calculated as discussed below.

I. Thermal conductivity:

The thermal conductivity of Cu-Water nanofluid can be calculated by using the correlation suggested by the Mushtaq I. Hasan and A. Rageb, 2000 [7] as:

$$k_{nf} = k_f \left[\frac{k_p + (\mathrm{SH}-1)\mathrm{k}_f - (\mathrm{SH}-1)\mathrm{c}(\mathrm{k}_f - \mathrm{k}_p)}{k_p + (\mathrm{SH}-1)\mathrm{k}_f + c(\mathrm{k}_f - \mathrm{k}_p)}\right] \quad (2.1)$$

Where,

SH = solid particle shape factor and it is given by:

$$SH = \frac{3}{\psi}$$

Where,

Ψ is the sphericity and its value is unity for spherical particles.

II. Density of Nanofluid:

In this paper, the density of Cu-Water nanofluid is been calculated by using the relation suggested by Ramiar and colleagues [8] and Y. Xuan, W. Roetzel, [9] as:

$$\rho_{nf} = c\rho_p + (1-\mathrm{c})\rho_f \quad (2.2)$$

III. Specific Heat of Nanofluid:

The specific heat is the amount of heat which is necessary to rise the unit temperature of unit mass of nanofluid and it is calculated by using the relation suggested by T.sai & R. Chein [10], J. Lee & I. Mudawar [11] and Khanafer and Vafai [12] as:

$$C_{P_{nf}} = cC_{P_p} + (1-c)\,C_{P_f} \tag{2.3}$$

IV. Viscosity of Nanofluid:

In this study, the viscosity of nanofluid is calculated by using the correlation suggested by Wen and Ding [13] as:

$$\mu_{nf} = \mu_f\,(1+2.5c) \tag{2.4}$$

B. Flow properties of Cu-Water nanofluid:

The following parameters which are discussed below give the shows and flow properties of Cu-Water nanofluid.

I. Mass flow rate of nanofluid:

The mass flow rate of nanofluid is calculated by using the following relation as:

$$m_{nf} = \rho_{nf} \times v_{nf} \tag{2.5}$$

II. Thermal heat capacity of nanofluid:

The thermal heat capacity of nanofluid is calculated as [14]:

$$C_{nf} = m_{nf} \times c_{pnf} \tag{2.6}$$

III. Prandtl number for nanofluid:

The Prandtl number for Cu-Water nanofluid is calculated by using the relation suggested in [6] & [14] as:

$$\Pr = \frac{\mu_{nf} \times c_{pnf}}{k_{nf}} \tag{2.7}$$

IV. Reynolds number for nanofluid:

The Reynolds number for nanofluid is calculated as [15]:

$$\mathrm{Re} = \frac{\rho v x}{\mu}]_{nf} \tag{2.8}$$

V. Nusselt number for nanofluid:

The Nusselt number for nanofluid is been calculated as [14]:

$$Nu_{nf} = \frac{h \times d}{k}]_{nf} \tag{2.9}$$

The Nusselt number can also be written as the function of Reynolds number and Prandtl number as suggested by Dittus and Boelter [16] as:

$$Nu_{nf} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n} \tag{2.10}$$

Where, n = 0.4, for heating

n = 0.3, for cooling

C. Performance parameters for heat exchanger:

The parameters which are used for the computation of performance of the heat exchanger are discussed below as:

I. Overall heat transfer coefficient:

The overall heat transfer coefficient is been calculated as [14]:

$$U_o = \frac{1}{\dfrac{r_i}{r_o \times h_{nf}} + \dfrac{\ln(r_o/r_i)}{k_{tm}} \times r_o + \dfrac{1}{h_o}} \tag{2.11}$$

II. Number of Transfer Units (NTUs):

The NTUs for the heat exchanger is calculated as [6]:

$$NTU = \frac{UA}{C_{\min}} \tag{2.12}$$

III. Effectiveness of heat exchanger:

The effectiveness of heat exchanger is calculated using the following relations as:

$$\varepsilon = \frac{Q_{actual}}{Q_{\max imum}}$$

Where,

$$Q_{\max} = C_{\min} \times (\mathrm{T}_{hi} - \mathrm{T}_{ci})$$

For counter flow heat exchanger the effectiveness is also given by [6] & [14]:

$$\varepsilon_{cf} = \frac{1 - \exp[-NTU(1 - c_r)]}{1 - c_r \exp[-NTU(1 - c_r)]} \tag{2.13}$$

Where,

$c_r = \dfrac{C_{\min}}{C_{\max}}$, heat capacity ratio

IV. Outlet temperature of both fluids:

The outlet temperature of both hot and cold fluids is calculated by using energy equation as:

$$Q = m_c \times c_{pc} \times [\mathrm{T}_{c_o} - \mathrm{T}_{c_i}]$$
$$Q = m_h \times c_{ph} \times [\mathrm{T}_{h_i} - \mathrm{T}_{h_o}] \quad (2.14)$$

V. LMTD for heat exchanger:

The LMTD of heat exchanger is calculated as [16]:

$$Q = U \times A \times \theta_m \quad (2.15)$$

VI. Head loss due to friction:

The loss of head due to friction between the particles and tube wall is calculated by using the relation suggested by Darcy Weisbach [17] & [18] as:

$$h_f = \frac{4fLV^2}{2gd} \quad (2.16)$$

Where, $f = \frac{0.0791}{\mathrm{Re}^{(1/4)}}$, for turbulent flow

VI. Pressure drop and pumping power for nanofluid:

The pressure drop and pumping power for Cu-Water nanofluid is calculated by using the relations suggested in [19] & [17] respectively as:

Pressure drop, $$\frac{\Delta p}{\rho g} = h_f = \frac{4fLV^2}{2gd} \quad (2.17)$$

Pumping power, $$\Delta P_p = \rho \times g \times Q \times h_f \quad (2.18)$$

3. Results and Discussion:

The following results which are obtained by using water and Cu-Water nanofluid as a coolant, are discussed below.

From the above chart-1, it can be concluded that the thermal conductivity of Cu-Water nanofluid is higher than pure water. The conductivity of Cu-Water nanofluid increases with the increase in volume fraction or concentration of copper nanoparticles into the base fluid i.e. water. This is so because of the conductivity of copper nanoparticles is higher than pure water.

The chart-2 shows the variation in Reynolds number with the volume fraction of copper nanoparticles. From this, we can understand that the Reynolds number for Cu-Water nanofluid is higher than pure water and it increases with the volume fraction of nanoparticles into the base fluid.

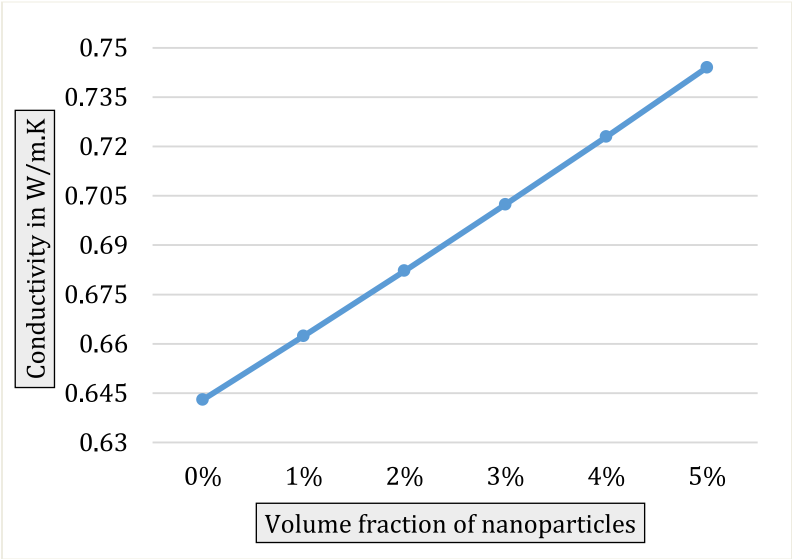

Chart -1: Conductivity of Cu-Water nanofluid at the different concentration of nanoparticle

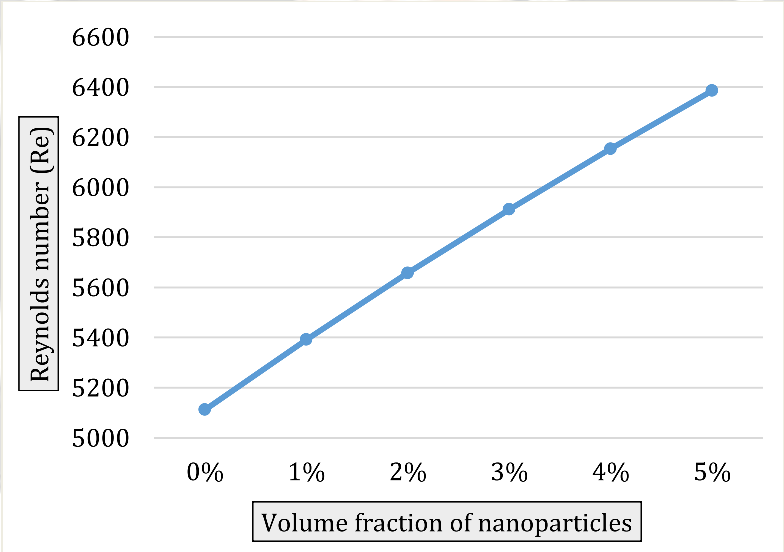

Chart -2: Reynolds number for Cu-Water nanofluid at the different concentration of nanoparticles

For Cu-Water nanofluid, the percentage increase in density is higher than the percentage increase in viscosity, at a particular concentration of the nanoparticles, which leads the higher Reynolds number of Cu-Water nanofluid. Here, the Reynolds number is higher than 2300 which indicates that the flow is turbulent.

The convective heat transfer coefficient between the Cu-Water nanofluid and tube wall is shown in chart-3. From this chart, it can be concluded that the convective heat transfer coefficient increases with the suspension of copper nanoparticles into the base fluid. This convective heat transfer coefficient further increases with the increase in the concentration of the copper nanoparticles into water. The increase in convective heat transfer coefficient, at 5% volume fraction of copper nanoparticles, is approximately 32% as compared to pure water. The convective heat transfer coefficient plays an important role for the enhancement in heat transfer rate.

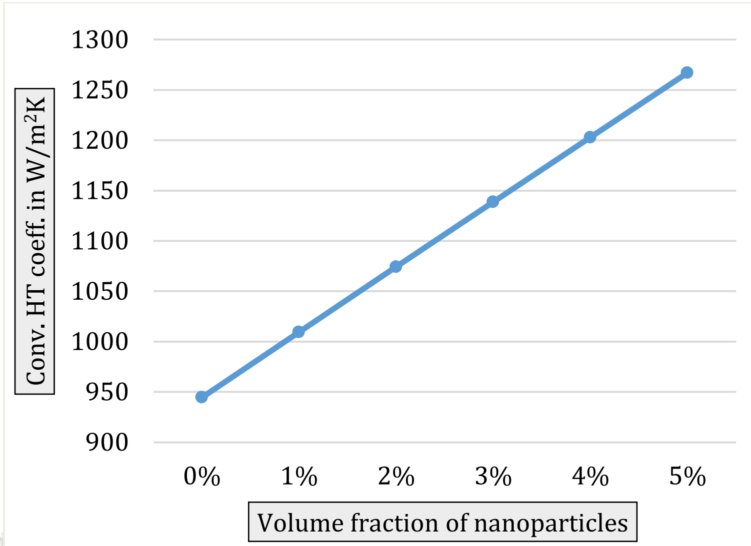

Chart-3: Convective heat transfer coefficient b/w Cu-Water nanofluid and tube wall, at the different concentration of nanoparticles

The below chart-4 shows that the overall heat transfer coefficient of heat exchanger increases with the volume fraction or concentration of copper nanoparticles. The increase in overall heat transfer coefficient, at 5% volume fraction of copper nanoparticles, is approximately 2.5% as compared to pure water alone. This increase in overall heat transfer coefficient is because of the increase in thermal conductivity and convective heat transfer coefficient of nanofluid.

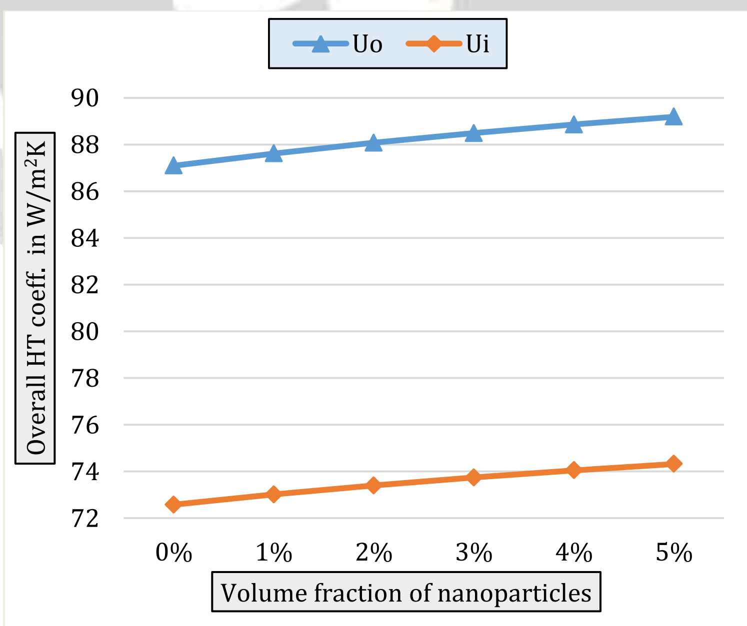

Chart-4: Overall heat transfer coefficient of heat exchanger with Cu-Water nanofluid, at the different concentration of nanoparticles

From chart-5, it is clear that the effectiveness of heat exchanger increases by suspending the copper nanoparticles into pure water. This effectiveness of heat exchanger further increases with the increase in volume fraction or concentration of copper nanoparticles into the base fluid.

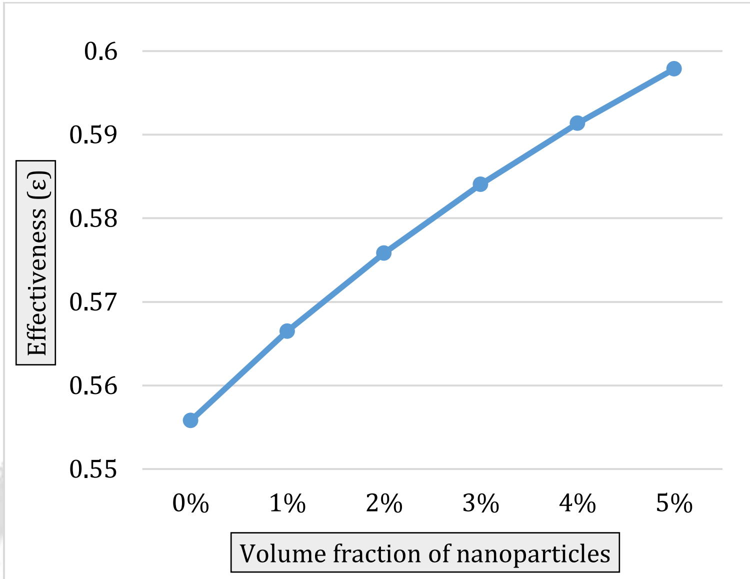

Chart-5: Effectiveness of heat exchanger at different concentration of copper nanoparticles

The percentage increase in effectiveness, at 5% concentration of copper nanoparticles, is approximately 7.7% as compared the effectiveness with pure water alone. The increase in effectiveness is always desirable for a heat exchanger and Cu-Water nanofluid shows the attractive characteristics.

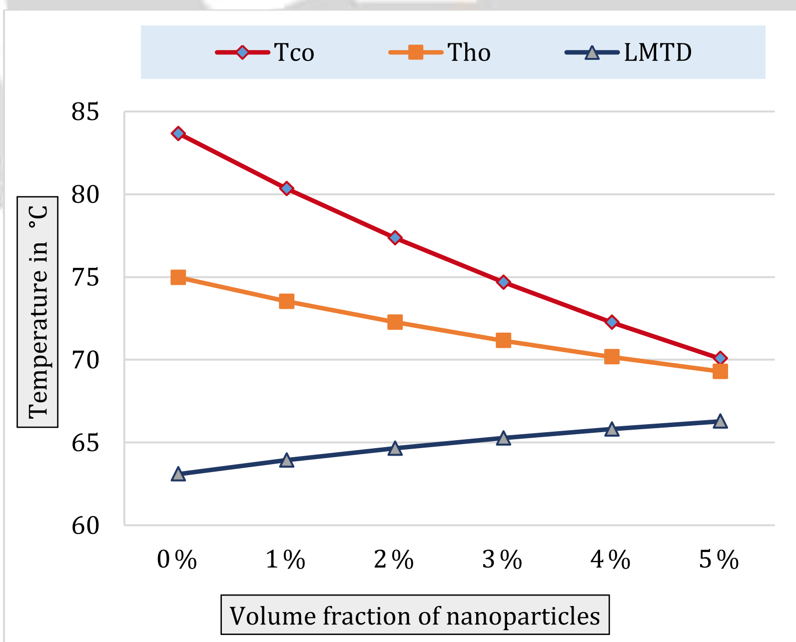

Chart-6: Outlet temperature of Cu-Water nanofluid, hot flue gases and LMTD of HE, at different concentration of copper nanoparticles

The above chrat-6 indicates that the outlet temperature of Cu-Water nanofluid is lower than that of for pure water. The outlet temperature of Cu-Water nanofluid decreases with the increase in volume fraction of copper nanoparticles. This is because of the reason that the specific heat of Cu-Water nanofluid increases with the increase in volume fraction of copper nanoparticles. The increase in specific heat indicates that the higher amount of heat required to rise the unit temperature of unit mass of Cu-Water nanofluid.

The outlet temperature of hot flue gases also decreases with the increase in volume fraction or concentration of copper nanoparticles into the base fluid. This happens so because the higher amount of heat is extracted from the hot flue gases by Cu-Water nanofluid having higher specific heat. The higher specific heat of Cu-Water nanofluid leads the larger temperature difference between Cu-Water nanofluid and hot flue gases which in turn promotes the decrease in outlet temperature of flue gases. At 5% concentration of copper nanoparticles, the decrease in outlet temperature of flue gases is approximately 7.5% as compared with pure water. According to the problem, as specified, the lower outlet temperature of hot flue gases is desirable and the Cu-Water nanofluid shows the positive results.

The chart-6 also shows the variation in Logarithmic Mean Temperature Difference (LMTD) with the volume fraction of copper nanoparticles into the base fluid. From the above chart, we can conclude that the LMTD increases with the volume fraction of copper nanoparticles. The increase in Logarithmic Mean Temperature Difference of heat exchanger is approximately 5.1%, at 5% concentration of copper nanoparticles, as compared the LMTD with pure water. The increase in LMTD of the heat exchanger is always desirable and it promotes the increase in heat transfer rate because the rate of heat transfer is directly proportional to the LMTD.

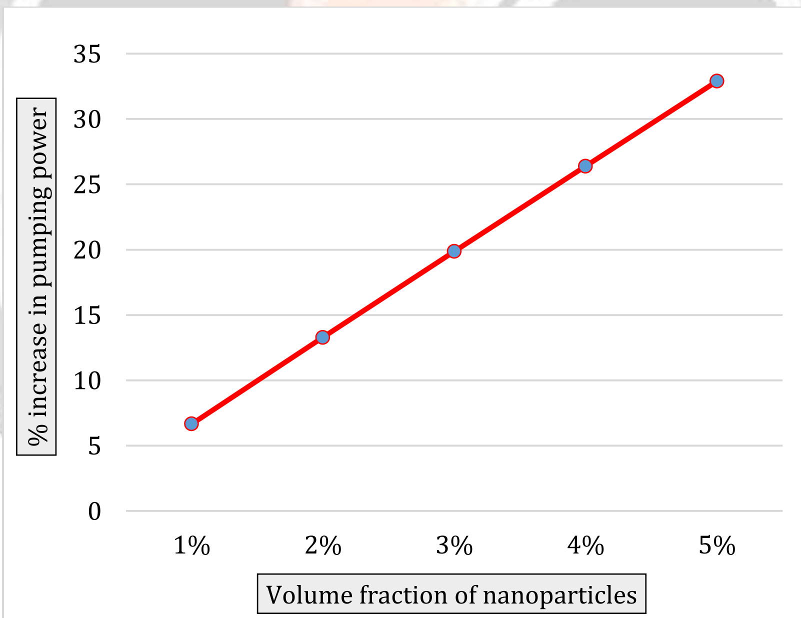

Chart-7: %increase in pumping power for Cu-Water nanofluid at different concentration of copper nanoparticles

The chart-7 shows the plot between pumping power for Cu-Water nanofluid versus volume fraction of copper nanoparticles. From this chart, it can be concluded that the pumping power for Cu-Water nanofluid is higher than that for pure water. The pumping power for Cu-Water further increases with the increase in volume fraction of copper nanoparticles into the base fluid. The increase in pumping power is because of the increase in density of Cu-Water nanofluid as compared with pure water. The increase in pumping power is approximately 33%, at 5% volume fraction of copper nanoparticles, as compared with the pumping power for pure water. This large increment in pumping power limits the increase of volume fraction of copper nanoparticles into the base fluid.

4. CONCLUSIONS

From this proposed work, we can conclude that the thermo-physical properties of the nanofluids differ from the parent materials. The conductivity of the nanofluids, nanoparticles of higher thermal conductivity, is higher as compared with the conventional fluids when used as a coolant. The convective heat transfer coefficient is also improved at nanofluid side. This increase in thermal conductivity and convective heat transfer coefficient would give the higher overall heat transfer coefficient and which in turn increases the rate of heat transfer and effectiveness of the heat exchanger. At the same time, the nanofluids, having the higher density as compared to the conventional fluids, required higher pumping power. The pumping power of nanofluids increases with the volume fraction or concentration of nanoparticles which limits the large concentration of nanoparticles into the conventional fluid.

5. FUTURE SCOPE

The more research is required for better understanding the behavior of nanofluids and its effect on operating parameters. An important area for future research is that the thermal conductivity of nanoparticles or nanofluids can be a function of geometrical parameters such as particle shape, particles size, particle agglomeration etc. Therefore, future researches should be focused on finding out the critical parameters which affect the thermal conductivity of nanofluids. Another challenging issue is to obtain the desirable nanoparticle product according to requirement. The recent development in the technology of production of nanosized particles will be helpful for the nanofluids research.

We have to also concern about public safety both in use and in production. Nanofluids engineers are required to introduce green designs by choosing the eco-friendly nanoparticles production techniques with nontoxic and biodegradable nanoparticles. Another and most challenging direction for future applied research is to produce the large volume of stable nanoparticles at low cost.

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