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Enhancement of Heat Exchanger Effectiveness by Using Water- Al2O3 as a working substance

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Abstract — *In this research, the performance of counter flow double tube heat exchanger of 1m length, 19.0 mm outer diameter, and 9.5 mm inner diameter made from copper has been studied numerically using nano-water as a cold fluid. Al2O3 nanoparticles of 40 nm diameter with a volume concentration of 0.5% have been used with water as base fluid. The cold nano-water flows inside the inner tube at a volume flow rate of 3 Liter/min and 7 Liter/min, which enters the heat exchanger at 15 °C, whereas hot water flows in an annular space of the heat exchanger at a volume flow rate of 5 Liter/min. and enters the heat exchanger at a temperature of 50 C°. ANSYS FLUENT (2020 R1) was used to solve the governing differential equations and to estimate the heat exchanger effectiveness. The results obtained revealed an enhancement in the performance by using nano-water as a working fluid. The maximum heat exchanger effectiveness obtained when using nano - water is 31%, for a volume flow rate of 7 Liter/min.*

Keywords — *Double tube heat exchanger, nano-water, overall heat transfer coefficient, the effectiveness of heat exchanger.*

I. INTRODUCTION

A heat exchanger is a heat transfer device that exchanges heat between two or more fluids. Heat exchangers have widespread in industrial and domestic applications, and many types of heat exchangers have been developed to use in steam power plants, chemical processing plants, refrigeration, and air conditioning systems, and transportation power systems. Heat exchangers have played a very important role in the engineer's awareness of energy and their desire to find optimal design not only in terms of thermal analysis and economic returns but in terms of returns of rationalizing energy consumption [1].

To improve the heat transfer process, a change is required in the physical-thermodynamic properties of the fluids used. The conventional liquids have somewhat low thermal conductivity if compared to non-metallic solids such as copper oxide, alumina, and metallic solids such as copper and aluminum. Therefore, it is necessary to find ways and ideas to enhance the properties of the fluids used by adding solid particles to these fluids. As a result of the development taking place at present, it has become possible to manufacture particles of nanoscale sizes easily disperse and suspend in the basic liquid such as water or oil. The new fluids showed better thermal properties without any deposits that may block the channels that run through them because of its small size particles [2].

Yimin and Qiang [3] conducted a study to calculate the coefficient of thermal conductivity of nanofluids and relied on some samples of nanofluids prepared by mixing nanoparticles in the base liquid. It was found that the nanoparticles gave a clear improvement to the heat transfer process and that the coefficient of thermal conductivity is affected by the shape, size, and concentration of nanoparticles.

Mehrabian M. A. and Hemmat M. [4] performed an experimental study to examine the thermal performance of a double-pipe heat exchanger that used water at atmospheric pressure as a working liquid. The temperature measurements were taken at the inlet and outlet of the two streams, as well as at halfway between the inlet and outlet. They concluded that the values of heat transfer coefficients obtained from the experiments are more than that calculated theoretically.

An experimental study was done by Ravi Kumar N.T. et al. [5] to see the effect of nanofluids consisting of Fe3O4 particles mixed with water as a base liquid for variable concentrations by volume ranging between 0.005% to 0.06% and Reynolds's number ranges from 14000 to 30000, on the performance of a U-shaped double-tube heat exchanger under turbulent flow conditions. They noted an improvement in the number of Nesselt about 15.6% for a volume concentration of 0.06%, when compared with the basic water, an improvement in the annular space heat transfer coefficient by 3.44%, inner tube side improved by 3.26%, and the effectiveness of the heat exchanger by 1.008 times larger than that of water at a concentration of 0.06 % and Reynolds number of 28984.

Sarit Das et al. [6] in their reviewed study focused on nanoparticles added to conventional liquids such as water

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and oil, which are known as nanofluids, concluded that nanofluids are a new technology that will show a significant improvement when used in the field of refrigeration, and it appears that small metallic nanoparticles in size enhance abnormally thermal conductivity and new properties that differ from the base material.

Praveen K. Namburu et al. [7] performed a numerical analysis of turbulent flow and thermal transfer of three different types of nanoparticles (CuO, Al2O3, and SiO2) in a mixture of ethylene glycol and water as the basic fluid passing through a circular tube under constant heat transfer rate conditions. they obtained an experimental relationship of the nanofluid viscosity at a concentration of 10 % and found that nanofluids containing particles of smaller diameter have a higher viscosity and a greater number of Nusselt. A comparison of the heat transfer coefficient of the three nanomaterials mentioned above was made. CuO nano-liquid has convective heat transfer coefficients higher than that for base liquid. Also, they observed that the smaller the particle diameter, the greater viscosity of the nano-liquid.

A reviewed study conducted by Sadik and Anchasa [8] included theoretical and experimental research and articles that focused on heat transfer analysis of nanofluids. They concluded that adding nanoparticles to the base liquid improves the thermal conductivity of new fluids and creates a new substance with conducting properties that differ from the base liquid.

Maysam Molana [9] made a comprehensive review of the research that concerned with the use of nanofluids in different types of heat exchangers. She noted that, the use of water as a base liquid represents 87%, followed by ethylene cyclol 8%, and that the most widely used nanoparticles are alumina and copper oxide, and carbon by 52%, 20%, and 11%, respectively. Most researchers concluded that there is a significant improvement in the number of Nusselt with any increase in the number of Reynolds, and the use of nanofluids in heat exchangers increased the required pumping energy. The maximum improvement in heat transfer was at the highest volumetric concentration in most studied cases. It was observed that the maximum improvement in heat transfer is 325%, 411%, and 85% in shell and tube, double tube, and coiled exchanger, respectively.

Mohammed Jibory, Ahmad Sabah Al-hilaly [10] conducted a theoretical and experimental study of heat transfer for a turbulent flow of fully developed within a double-tube heat exchanger using one type of nanoparticle (γ-AL2O3) mixed with pure water. Four concentrations (0.5%, 1%, 1.5%, and 1%) were used, and the Reynolds number are (6196.92-38669.54). In the experimental study, a test system was built which contains the measuring devices and machines necessary to calculate the percentage improvement in heat transfer, with a similar condition for theoretical and experimental work. The velocity of the hot liquid in the inner tube was ((0.176, 0.352, 0.529, 0.705, 0.881, 81.05) m/s, with the constant velocity of the fluid in an annular space which is (0.529) m/s. The results showed that the improvement of heat transfer is related to an increase in the volumetric concentration and the number of Reynolds. The best enhancement in the rate of heat transfer was obtained for the practical and theoretical results are (48.93) % and (46.63) % respectively.

II. THERMOPHYSICAL PROPERTIES

Thermal conductivity:

The thermal conductivity is a very important factor in promoting heat transfer. The thermal conductivity of nanofluids can be calculated from the following equation [11]:

$$k_{nf} = \frac{k_p + 2k_{bf} + 2(k_p - k_{bf})\emptyset}{k_p + 2k_{bf} - 2(k_p - k_{bf})\emptyset} k_{bf} \qquad (1)$$

Dynamic viscosity:

The dynamic viscosity of the nanofluids is calculated from the following equation [12] :

$$\mu_{nf} = (1 + 2.5 * \emptyset) * \mu_{bf} \qquad (2)$$

Density:

To calculate the density of the nanofluid, the following equation was used [7]:

$$\rho_{nf} = (1 - \emptyset)\rho_{bf} + \emptyset\rho_p \qquad (3)$$

Specific heat:

The specific heat of the nanofluids is formulated by the following equation[12] :

$$C_{p_{nf}} = \frac{(1 - \emptyset)C_{p_{bf}} \times \rho_{bf} + \emptyset \times \rho_p \times C_{P_P}}{\rho_{nf}} \qquad (4)$$

III. Calculation of heat exchanger

In the present study, a nano – water consists of Al_2O_3 nanoparticles dispersed in water was used to investigate the overall heat transfer coefficient and heat exchanger effectiveness. The rate of heat transfer from the hot fluid to the nano-water can be calculated from [13]:

$$Qactual = mCp(Thi - Tho) \qquad (5)$$

Since the heat exchanger is well insulated, so the heat transfer from the hot water is equal to that transfer to cold nano-water, and calculated from [13]:

$$Qactual = mCp(Tco - Tci) \qquad (6)$$

The heat transfer coefficients at either surface of the inner tube can be evaluated from the following equation [13], based on the equivalent diameter :

$$Nu = \frac{h \times d}{k} = 0.023\, Re^{0.8} Pr^{n} \qquad (6000 \leq Re \leq 14000) \qquad (7)$$

n = 0.3 , for colling

n= 0.4 , for heating

The overall heat transfer coefficients, U_i, based on the internal surface area of the inner tube:[13]

$$\frac{1}{Ui} = \frac{1}{hi} + \frac{Ai \ln Do/Di}{2\pi kL} + \frac{Ai}{Ao}\frac{1}{ho} \qquad (8)$$

Where A_i and A_o are the internal and external surface area of the inner tube:

The heat exchanger effectiveness can be computed from [13]:

$$\varepsilon = \frac{Qacual}{Qmax} \qquad (9)$$

Where Q_{max} is the maximum possible heat for the heat exchanger and expressed as [13]:

$$Q = \left(mC_p\right)_{min}\left(T_{hi} - T_{ci}\right) \qquad (10)$$

Numerical Analysis

A numerical simulation was performed to analyze the thermal performance of a horizontal tube in the counter-flow heat exchanger, using finite volume methods (FVM) which is one of the most techniques of the computation fluid dynamic (CFD) software ANSYS FLUENT 2020 has been used. The domine of the tube wall and both cold and hot fluids was divided into some Hexa small size cells. the 2D model consists of 166000 elements with 167167 nodes. The governing equations of continuity, momentum, and energy and turbulent quantities are solved using a control volume technique. k - ε turbulent model is chosen. The following assumptions are assumed:

1- Steady, incompressible, and turbulent flow.
2- There is a thermal equilibrium between the non-particles and water.
3- The properties of both hot and cold liquids are constant along with the heat exchanger.
4- The heat exchanger is well insulated so that heat loss to the surrounding is negligible**.**

Governing Equations

a-
b- Continuity equation [10]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (11)$$

c- Momentum Equations:
d-

1- Momentum equation in the X-direction:

$$\frac{\partial \rho u}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} + \frac{\partial(\rho wu)}{\partial z} = -\frac{\partial p}{\partial x} + \rho g_x + \mu\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \qquad (12)$$

2-

Momentum equation in the Y-direction:

$$\frac{\partial \rho v}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho wv)}{\partial z} = -\frac{\partial p}{\partial y} + \rho g_y + \mu\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right] \qquad (13)$$

Momentum equation in the Z-direction:

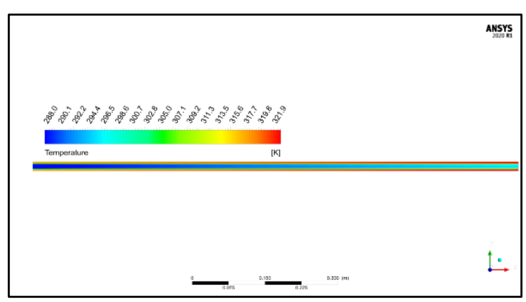
$$\frac{\partial \rho w}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = -\frac{\partial p}{\partial z} + \rho g_z + \mu\left[\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right] \qquad (14)$$

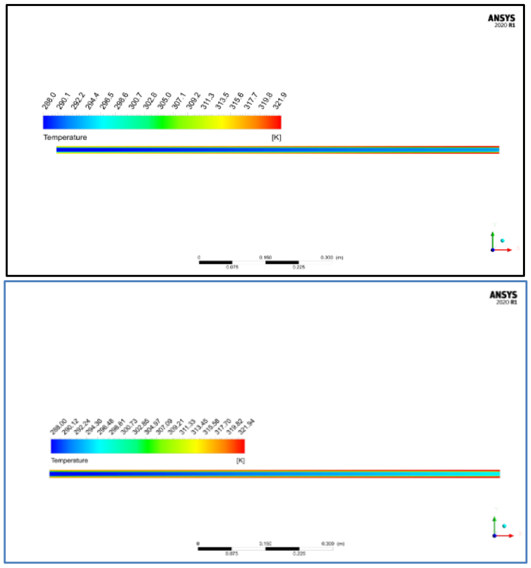
Energy equation:

$$\frac{\partial}{\partial x}\left(\rho uh - \frac{\mu}{pr}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(\rho vh - \frac{\mu}{pr}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial x}\left(\rho wh - \frac{\mu}{pr}\frac{\partial h}{\partial z}\right) \qquad (15)$$

VI. RESULTS AND DISCUSSION

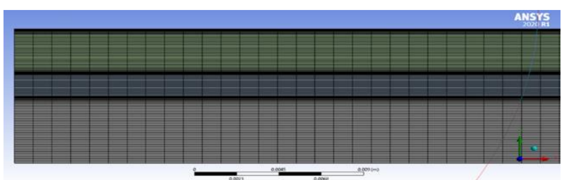
The temperature contours along the inner and outer tube of the heat exchanger are shown in Fig (1) for volume flow rates of 3LPM and 7LPM. It can be noted that the addition of nanoparticles to cold water that flows inside the inner tube caused to increase in the temperature difference between the inlet and outlet of the heat exchanger for both hot and cold fluids.



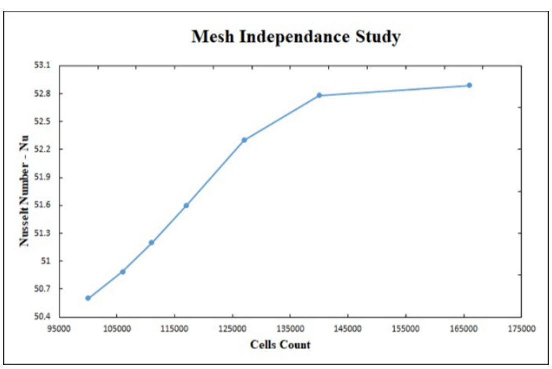


Fig(1) contour of temperature.

This is indicated in Fig. (2) which represents the variation of temperature difference of cold fluid for pure water and nano water. It can be seen that the temperature difference is decreased with increasing the flow rate.



(a) Meshing



(b) Grid independent test.

Fig (2) optimum mesh.

Fig. (3) shows the enhancement in the overall heat transfer coefficient when adding the nanoparticles to water for both values of volume flow rates. This is due to the improvement of thermophysical properties of fluid by adding nanoparticles as compared to pure water.

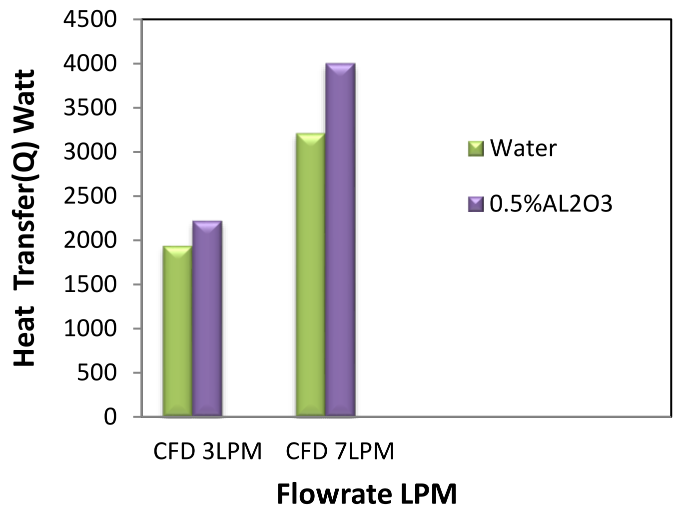


Fig (3) heat transfer with volume flow rates.

Fig. (4) indicates the same trend of the overall heat transfer coefficient for the heat transfer rate. This is because heat transfer is directly proportional to the overall heat transfer coefficient. the percentage enhancement in heat transfer rate, when a volume flow rate of 3LPM was used reached 18%, while the percentage enhancement was 24% for 7 LPM.

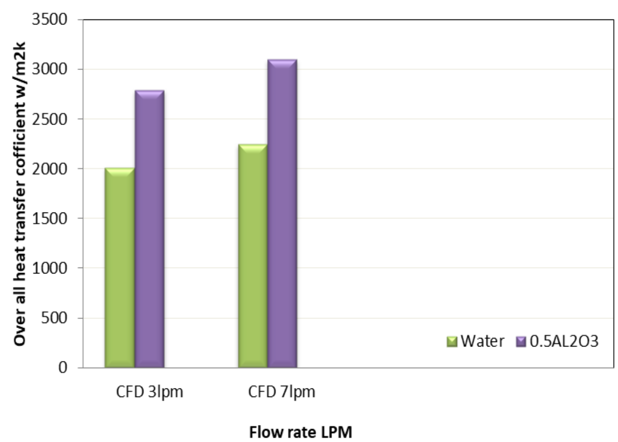


Fig (4) overall heat transfer coefficient with volume flow rates.

The effectiveness of the heat exchanger with the two values of volume flow rate for pure water and nano water has been calculated. Figure (5) shows that the effectiveness of both of them increases with the increase in volume flow rate, and there is an enhancement ineffectiveness of heat exchanger when using the nano water as working fluid. The maximum enhancement ineffectiveness was 31%, for a volume flow rate of 7 LPM.

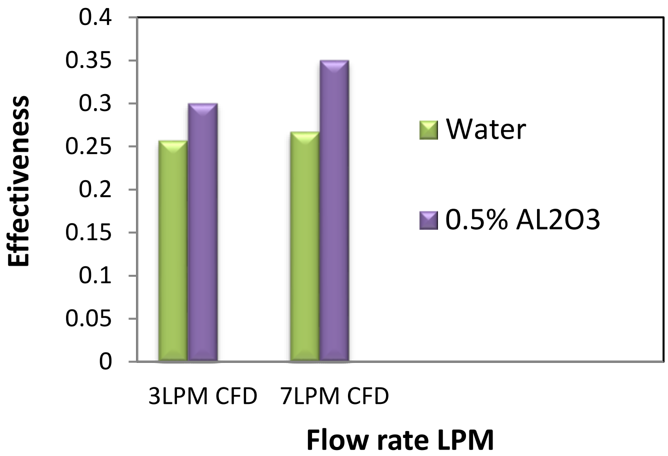


Fig (5) effectiveness with flowrates.

V. CONCLUSION

The following conclusions were obtained:

1- The overall heat transfer coefficient increased when using nano- water instead of pure water.

2- The overall heat transfer coefficient increased with an increase in the volume flow rate.

3- The maximum percentage enhancement in heat transfer rate when using nano- water was 24%, for a volume flow rate of (7) LPM.

4- The maximum heat exchanger effectiveness obtained, when using nano- water was 31%, for a volume flow rate of 7 LPM.

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