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Navid Bozorgan

Using Four Model for Predicting the Thermal Conductivity in the Analysis of the Efficacy of Nanofluid in a Double-Tube Heat Exchanger

In the present paper, CuO/Ethylene-Glycol (EG) nanofluid with d_p=29 nm and volume fractions of nanoparticles ($\phi = 1-10\%$) as coolant has been used in a double-tube heat exchanger to optimize its heat transfer performance under laminar flow conditions. The hot solvent inlet heat exchanger must be cooled down with a specified amount. At first, the heat transfer relations between hot solvent and nanofluid as coolant in the heat exchanger have been investigated theoretically. Subsequently, the heat transfer coefficient, overall heat transfer coefficient, friction factor, pressure drop and pumping power for CuO/EG nanofluid calculated based on four experimental models presented to predict the thermal conductivity of the CuO/EG nanofluid. Moreover, the heat transfer area is optimized by using the CuO/EG as coolant in the heat exchanger to reject this same amount of heat.

Keywords: *Nanofluid, Double-tube heat exchanger, thermal conductivity coefficient, Heat transfer performance.*

1. Introduction

Improving the heat transfer characteristics of a coolant liquid had been in research for decades. The heat transfer conventional fluids as coolants such as water and ethylene glycol are often limited due to their low thermal conductivities. To overcome this limited heat transfer capabilities of these fluids, the use of nonosized metals and metal oxides as an additive suspended into the base fluid is a technique for the heat transfer enhancement [1-7]. Fluids with suspended particles of nanometer dimensions are called nanofluids, which this term proposed by Choi [8] in 1995 at the Argonne National Laboratory, U.S.A. Compared with traditional solid-liquid suspensions containing millimeter or micrometer sized particles, nanofluids as coolants in the heat exchangers have shown better heat transfer performance because of small size of suspend solid particles. It causes that nanofluids have a behavior similar to base liquid molecules. Faulkner et al. [9] indicated that by using the nanofluids as coolants in cooling system of flow channel could achieve a significant cooling effect. Nguyen et al. [10] applied Al_2O_3 nanofluid to an electronic cooling system. Their results showed that the convective heat transfer coefficient was enhanced by 40% maximum with a volume fraction of

6.8%. Pantzali et al. [11] applied 4% CuO nanofluid to a commercial herringbone-type PHE. This study indicates that fluid viscosity has an important role in the performance of a heat exchanger. Aminossadati et al. [12] investigated numerically natural convection in a two dimensional square cavity filled with a CuO/water nanofluid. They observed that the heat transfer rate increases with an increase of the Rayleigh number and the solid volume fraction. Mohammed et al. [13] numerically studied the effects of using nanofluid on the performance of a square shaped microchannel heat exchanger (MCHE). They concluded that the benefits of nanofluids such as enhancement in heat transfer coefficient are dominant over the shortcomings such as increasing in pressure drop. Saeedinia et al. [14] applied CuO-Base oil vary in the range of 0.2-2% inside a circular tube. Their results showed that the CuO nanoparticles suspended in Base-oil increases the heat transfer coefficient even for a very low particle concentration of 0.2% volume concentration. Moreover, the maximum heat transfer coefficient enhancement of 12.7% is obtained for a 2% CuO nanofluid. One of the commercially available nanoparticles is CuO nanoparticle. In the present paper, 29 nm-CuO/EG nanofluid vary in the range of 1-10% has been numerically studied as a coolant in a typical double-tube heat exchanger. It shall be noted that metal oxides such as CuO nanoparticles are chemically more stable than their metallic counterparts [15-18].

Table 1. Thermophysical properties of nanoparticles and base fluid.

Material Properties	CuO	EG
c_p (J/kgK)	540	2323
ρ (kg/m^3)	6510	1125
k (W/mK)	18	0.244
T_{fr} (°C)	_	-12

2. Prediction of Thermophysical Properties

As mentioned previously, investigating the efficiency of CuO/EG nanofluid as coolant in double-tube heat exchangers is the aim of this study. At the first step, the heat characteristics of the nanofluid have been evaluated and at the next step the application of nanofluid as coolant have been considered for increasing the heat transfer performance of a double-tube heat exchanger. Some of the properties of nanoparticles and base fluid are listed in Table 1 that useful for assessing the nanofluid properties. The necessary thermophysical properties in this paper are density, viscosity, specific heat and thermal conductivity. The commonly used models for these properties are given as follows.

For density [19]

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \tag{1}$$

Viscosity [20]:

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^{2.5}} \tag{2}$$

Specific heat [21]:

$$c_{p,nf} = \frac{(1-\phi)\rho_{bf} c_{p,bf} + \phi\rho_p c_{p,p}}{\rho_{nf}} \tag{3}$$

where ϕ is volume concentration of nanoparticle and ρ_p , ρ_{bf} and $c_{p,p}$, $c_{p,bf}$ are the densities and the heat specifics of the nanoparticles and base fluid, respectively.

2.1. Modeling Thermal Conductivity

Thermal conductivity is an important parameter in the field of nanofluid heat transfer. In the present paper, four experimental models are presented to predict the thermal conductivity of the CuO/EG nanofluid that the calculations are based on these models. The first model is model presented by Ya and Choi (Y-C) as follows [22]:

$$k_{nf,Y-C} = \left[\frac{k_p + 2k_{bf} + 2(k_p - k_{bf})(1+\beta)^3\phi}{k_p + 2k_{bf} - (k_p - k_{bf})(1+\beta)^3\phi}\right] k_{bf} \tag{4}$$

where k_{nf} is the thermal conductivity of the nanofluid, k_p is the thermal conductivity of the nanoparticles, k_{bf} is the thermal conductivity of the base fluid and β is the ratio of the nanolayer thickness to the original particle radius, β=0.1 is used normally for calculating of thermal conductivity of the nanofluids. In this model, the effect of a liquid nanolayer on the surface of the nanoparticle is considered. The second model is Hamilton-Crosser (H-C) model that this model presented for particles uniformly dispersed in a continuum medium as follows [23]:

$$k_{nf,H-C} = \left[\frac{k_p + (n-1)k_{bf} - (n-1)\phi(k_{bf} - k_p)}{k_p + (n-1)k_{bf} + \phi(k_{bf} - k_p)}\right] k_{bf} \tag{5}$$

where n is the shape factor given by $n = 3/\psi$ and ψ is the sphericity defined as the ratio of the surface area of a sphere, having a volume equal to that of the particle, to the surface area of the particle ($\psi = 1$ for spherical particles for $\phi < 30\%$). The third model is Corcione model which is expressed as follows [24]:

$$k_{nf,Corcione} = \left[1 + 4.4\mathrm{Re}^{0.4}\mathrm{Pr}^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_{bf}}\right)^{0.03}\phi^{0.66}\right] k_{bf} \tag{6}$$

where Pr is the Prandtl number of the base fluid, T is the nanofluid temperature, T_{fr} is the freezing point of the base fluid and Re is the nanoparticle Reynolds number which is defined as:

$$\mathrm{Re} = \frac{\rho_{bf} u_p d_p}{\mu_{bf}} \tag{7}$$

where u_p is the nanoparticle Brownian velocity as:

$$u_p = \frac{2k_b T}{\pi\mu_{bf} d_p^2} \tag{8}$$

where k_p=1.38065×10^{-23} J/k is the Boltzmann constant and by substitution of Eq. (8) in Eq. (7), the following equation will be obtained:

$$\mathrm{Re} = \frac{2\rho_{bf} k_b T}{\pi \mu_{bf}^2 d_p} \tag{9}$$

In the present study, the fourth model used to predict the thermal conductivity of nanofluid is Patel model which is presented as follows [25]:

$$k_{nf,Patel} = \left[1 + \frac{k_p A_p}{k_{bf} A_{bf}} + c k_p \mathrm{Pe} \frac{A_p}{k_{bf} A_{bf}}\right] k_{bf} \tag{10}$$

where c=25000 is a constant determined experimentally, A_p/A_{bf} and Pe here is defined as

$$\frac{A_p}{A_{bf}} = \frac{d_p}{d_{bf}} \frac{\phi}{(1-\phi)}, \ \mathrm{Pe} = \frac{u_p d_p}{\alpha_{bf}} \tag{11}$$

where α_{bf} is the thermal diffusivity of the base fluid and d_{bf} is can be obtained as [24]:

$$d_{bf} = 0.1\left(\frac{6M}{N \pi \rho_{bf0}}\right)^{1/3} \tag{12}$$

in which M is the molecular weight of the base fluid, N is the Avogadro number and ρ_{bf0} is the mass density of the base fluid calculated at T_0=293 K which d_{bf}=0.505 nm calculated for the ethylene glycol in this study.

3. Heat Transfer and Pressure Drop Modeling

As mentioned former, evaluating the heat transfer performance of nanofluid as a coolant in a double-tube heat exchanger is the aim of present work.

3.1. Heat Transfer Modeling

The rate of heat transferred to the cooling hot solvent in a double-tube heat exchanger can be written as follows:

$$Q = \dot{m}_h c_{p,h} (T_1 - T_2) \cong \dot{m}_{nf} c_{p,nf} (t_2 - t_1) \tag{13}$$

where h and nf pertain to the hot solvent and nanofluids as coolants, respectively. The total heat transfer area of a double-tube heat exchanger (A) is computed from the following equation:

$$A = \frac{Q}{U \times F \times LMTD} \tag{14}$$

$$LMTD = \frac{(T_1 - t_1) - (T_2 - t_2)}{ln \frac{(T_1 - t_1)}{(T_2 - t_2)}} \tag{15}$$

where U is the total heat transfer coefficient and F is the temperature correction factor, which in the case of the countercurrent flow can be taken equal to 1.

The total heat transfer coefficient (U) can be calculated by Eq. (16) as follows:

$$U = \left(\frac{1}{h_{h,o}} + \frac{1}{h_{nf}} + Rf\right)^{-1} \tag{16}$$

where Rf is the fouling resistance, $h_{h,o}$ is heat transfer coefficient of hot solvent that referred to the external area and h_{nf} is the heat transfer coefficient of the nanofluid as coolant. By considering of the Eq. (16), the heat transfer coefficients of hot solvent and nanofluid must be calculated. The heat transfer coefficient of the hot solvent flowing inside the tube under a turbulent regime (*Re*>10000) can be calculated as follows [26]:

$$h_h = 0.023 Re_h^{\,0.8} Pr_h^{\,0.33} \left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.14} \frac{k_h}{D_i} \tag{17}$$

where D_i is the internal diameter of the internal tube, $(\frac{\mu_{nf}}{\mu_{wnf}})^{0.14}$ is the viscosity correction factor. In the above equation the Reynolds and Prandtl numbers are calculated with considering the hot solvent properties as follows:

$$\mathrm{Re}_h = \frac{\rho_h u_h D_i}{\mu_h} \tag{18}$$

$$\mathrm{Pr}_h = \frac{c_{p,h}\mu_h}{k_h} \tag{19}$$

Consequently, heat transfer coefficient of hot solvent that referred to the external area, $h_{h,o}$, is defined as: (For further studying, see [26])

$$h_{h,o} = h_h \left(\frac{D_i}{D_o}\right) \tag{20}$$

where D_o is the external diameter of the internal tube.

The heat transfer coefficient of the nanofluid as coolant flowing for *Re*<2100 in the annular can be calculated as follows:

$$h_{nf} = 1.86 \left(Re_{nf}\, Pr_{nf} \frac{D_{eq}}{L} \right)^{0.33} \left(\frac{\mu_{nf}}{\mu_{wnf}} \right)^{0.14} \frac{k_{nf}}{D_{eq}} \tag{21}$$

where L is the heat transfer length and D_{eq} is the equivalent diameter which is expressed in the following form:

$$D_{eq} = \frac{4 \times \text{flow area}}{\text{internal tube perimeter}} = \frac{(D_s^2 - D_o^2)}{D_o} \tag{22}$$

where D_s is the internal diameter of the external tube. In the Eq. (21), the Reynolds and Prandtl numbers are calculated with considering the nanofluid properties as follows:

$$\mathrm{Re}_{nf} = \frac{\rho_{nf} u_{nf} D_{eq}}{\mu_{nf}} \tag{23}$$

$$\mathrm{Pr}_{nf} = \frac{c_{p,nf}\mu_{nf}}{k_{nf}} \tag{24}$$

It is important to note that the physical properties appeared in Eqs. (17) and (21) must be evaluated at average temperature (mean between inlet and outlet temperatures). In addition, the viscosity correction factor is the ratio of nanofluid viscosity at the mean fluid temperature to viscosity of nanflouid at the mean tube wall temperature. This factor must be exactly calculated for computing the heat transfer coefficients for both hot solvent and coolant nanofluid. But the viscosity of the nanofluid at the wall temperature cannot be calculated explicitly because this temperature is unknown. Therefore, as a first approximation, it is assumed to be equal to 1. With this simplification, a first value for the coefficients $h_{h,o}$ and h_{nf} is obtained. Then, T_w is calculated by equating the heat transfer rates at both sides of the tube wall as follows:

$$q_{conv} = h_{nf}(T_w - t_{ave}) = h_{h,o}(T_{ave} - T_w) \tag{25}$$

By using the above equation, T_w can be obtained. By having T_w, it is possible to calculate the viscosity correction factor and therefore, the previous values for $h_{h,o}$ and h_{nf} are modified.

3.2. Pressure Drop Modeling

The fraction factor of CuO /EG nanofluid in laminar flow regime can be calculated using the formula presented as follows:

$$f_{nf} = 16 / \mathrm{Re}_{nf} \tag{26}$$

In this paper, the pressure drop (Δp_{nf}) and pumping power (*PP*) for CuO/EG nanofluid used as a coolant in a double-tube heat exchanger are calculated as follows [26]:

$$\Delta p_{nf} = 2\frac{f_{nf} L \rho_{nf} u_{nf}^2}{D'_{eq}}\left(\frac{\mu_{nf}}{\mu_{wnf}}\right)^{0.25} \tag{27}$$

$$PP = u_{nf} a_s \Delta p_{nf} \tag{28}$$

where D'_{eq} is the equivalent diameter of an annulus given by $D'_{eq} = D_s - D_o$ and a_s is the annular flow area.

4. Simulation Results and Discussion

As mentioned previously, four experimental models have been applied to predict the thermal conductivity of the CuO/EG nanofluid. As shown in Fig. 1, the thermal conductivi-ty of nanofluid vary in the range of 1-10% has been calculated by using these models. These results are important for evaluating the heat transfer performance of the coolant. As can be seen, thermal conductivity increases with increasing the nanoparticle volume concentration. Moreover, compression of the thermal conductivity CuO nanofluid predicted by cited 4 models showed that (Y-C) and (H-C) models and also Corcione and Patel models are nearly close to each other as it can seen from Fig. 1.

Fig. 2 shows the effect of nanoparticle on the heat transfer coefficient. Results show that the heat transfer coefficient can be enhanced by adding nanoparticles to the base fluid. It is important to note that the increase in particle concentration increases the fluid viscosity and decreases the Reynolds number whereby the heat transfer coefficient decreases. But Fig. 2 shows that the increase in particle concentration increases the heat transfer coefficient. This indicates that thermal conduction enhancement plays a more significant role in the convective heat transfer compared with the viscosity increase under the conditions of this study. Enhancement of heat transfer by the nanofluid may be resulted from the following two aspects: first one is the suspended particles that increase the thermal conductivity of the mixture; the other one is that chaotic movement of ultrafine particles accelerates energy exchange process between the fluid and the wall. For example, a further inspection of Fig. 1 and 2 shows that for CuO/EG nanofluid in ϕ =4%, k_{nf}=0.2834, 0.2732, 0.263, 0.2583 and h_{nf}=305, 297.82, 290.5, 284.15 calculated using models of (Y-C) and (H-C) and Corcione and Patel, respectively. Therefore, the deviations between the predicted values of k_{nf} using four experimental models lower than the predicted values of h_{nf}. In the present paper, the overall heat transfer coefficient for CuO nanofluid in $\phi = 1-10\%$ calculated to estimate the efficacy of using the nanofluid as coolant in the double-tube heat exchanger.

According to Fig. 3, the overall heat transfer coefficient increases with increasing the probability of collision between nanoparticles and the wall of the heat exchanger under higher concentration. Accordingly, from the results shown in Fig. 3 it is evident that CuO nanofluid has considerable potential for the use in the double-tube heat exchanger. For example, an inspection of Fig. 3 shows that the overall heat transfer coefficients of the CuO/EG nanofluid with different concentrations (1-10% volume fraction) have increased by ~ (1.82-18%), (1.4-13.8%), (1.47-6.91%) and (0.72-7.5%) using models of (Y-C) and (H-C) and Corcione and Patel, respectively.

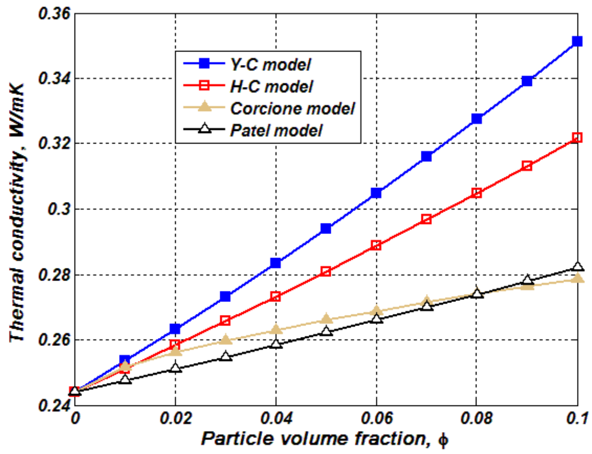

Figure 1. Variation of thermal conductivity with particle volume fraction for CuO/EG nanofluid.

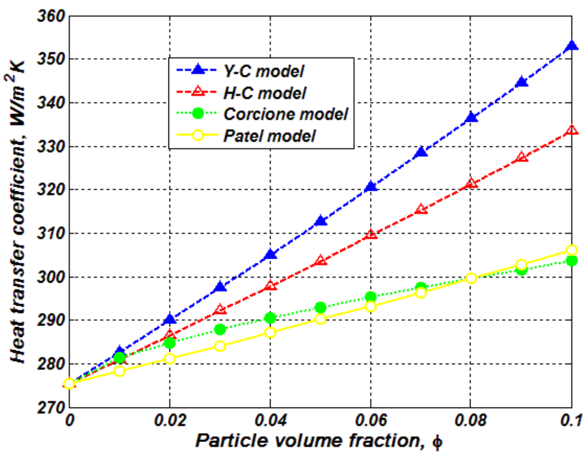

Figure 2. Heat transfer coefficient of the CuO/EG nanofluid as coolant in a double-tube heat exchanger

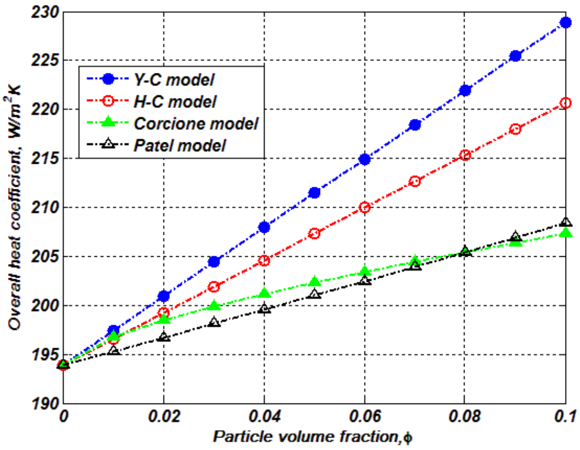

Figure 3. Overall heat transfer coefficient of the CuO/EG nanofluid as coolant in a double-tube heat exchanger

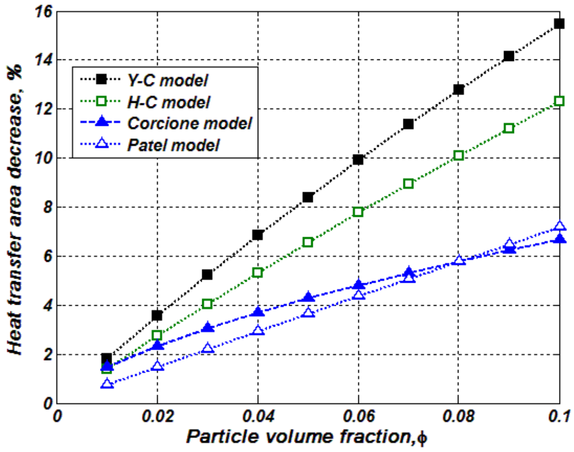

Figure 4. Percent heat transfer area reduction in a double-tube heat exchanger by using the CuO/EG nanofluid as coolant

As can be seen in Fig. 4, the heat transfer area is optimized by using the CuO/EG nanofluid as coolant to reject 15.4 kW of heat from a double-tube heat exchanger. It can be seen that by using the CuO/EG nanofluid with different concentrations (1-10%), the heat transfer area decreased by~ (1.8-15.5%), (1.4-12.3%), (1.47-6.66%) and (0.74-7.2%) using models of (Y-C) and (H-C) and Corcione and Patel, respectively.

In order to apply the nanofluids for practical application, in addition to the heat transfer performance of the nanofluids it is necessary to study the nanofluids pressure drop developed during the flow of the coolant. Therefore, the effect of CuO/EG nanofluid in $\phi = 1 - 10\%$ on pressure drop and pumping power studied in this paper. With increasing the volume concentrations of the nanoparticles increases the viscosity and density in nanofluids whereby friction factor and pressure drop also increases. Hence, nanofluids generally require greater pumping power than their base fluid. In this study, the effect of CuO/EG nanofluid with different concentrations (1-10% volume fraction) on the pressure drop and pumping power is shown in Figs. 5–6. For example, when CuO/EG nanofluid with concentrations of 10% used as coolant in a double-tube heat exchanger, pumping power increased about by 9.17%, 13.47%, 21% and 20.4% using models of (Y-C) and (H-C) and Corcione and Patel, respectively.

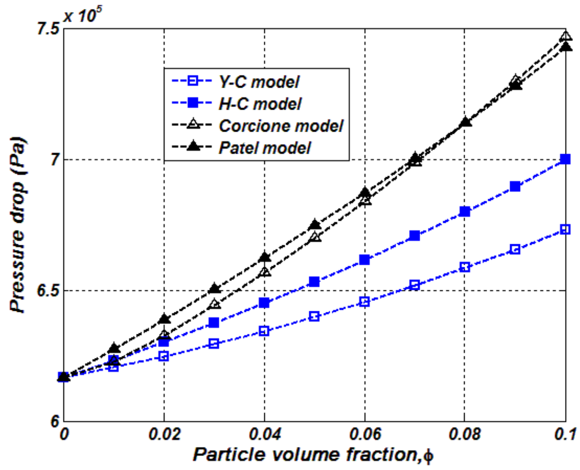

Figure 5. Pressure drop for CuO/EG nanofluid as coolant in a double-tube heat exchanger

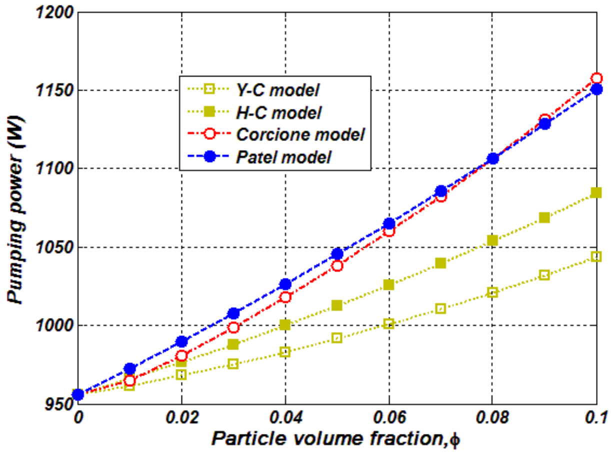

Figure 6. Pumping power of CuO/EG nanofluid in a double-tube heat exchanger

5. Conclusions

In the present study, the use of CuO nanofluid as coolant in $\phi = 1-10\%$ for optimization of the heat transfer performance of the double-tube heat exchanger in laminar flow was investigated. Models of (Y-C) and (H-C) and Corcione and Patel applied to predict the thermal conductivity of CuO/EG nanofluid that the calculations have been carried out based on these models. For example, the results showed that using the CuO/EG nanofluid in $\phi = 10\%$, the heat transfer area decreased by~ 15.5%, 12.3%, 6.66% and 7.2% while the pumping power increased about by 9.17%, 13.47%, 21% and 20.4% using models of (Y-C) and (H-C) and Corcione and Patel, respectively.

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Address:

- Navid Bozorgan, Department of Mechanical Engineering, Abadan Branch, Islamic Azad University, Abadan, Iran, n.Bozorgan@gmail.com