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Research Paper

Computational Analysis of Hybrid Nanofluid Flow in a Double-Tube Heat Exchanger: A Numerical Study

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Abstract. The heat transfer improvement and the increase of heat exchangers' efficiency represent a very important issue in the energy field. Many research projects have focused on the use of fluids with high thermal conductivity such as nanofluids. In this case, hybrid nanofluids, are a new class of nanofluids with good heat transfer characteristics. The present work falls within this framework and involves a numerical study to examine the influence of two oil-based hybrid nanofluids, Al_2O_3-MWCNT and MgO-MWCNT, with different volume concentrations and inlet flow rates. More to the point, the impact of different nanoparticle ratio and the location of hybrid nanofluid in a laminar flow of two-pipe counter-current heat exchanger have been investigated. In virtue of which, the results illustrate that increasing the volume concentration of nanoparticles and the flow rate of the hybrid nanofluid has a positive impact on improving the heat transfer rate. Therefore, the improvement in heat transfer rate reached 77.8% for Al_2O_3-MWCNT/oil hybrid nanofluid and 59.5% for MgO-MWCNT/oil hybrid nanofluid. Similarly, the study has also revealed that the preferred nanoparticles ratio for Al_2O_3-MWCNT/oil hybrid nanofluid is in the order of (25:75) and its circulation in the inner tube as a hot fluid makes it possible to improve the thermal performance of the considered two-tube heat exchanger to a greater advantage.

Keywords: Two-pipe heat exchanger; Hybrid nanofluid; Computational Fluid Dynamics (CFD); Heat transfer rate.

1. Introduction

The enhancement of heat transfer in heat exchangers has attracted a large number of researchers over the last two decades. More than a few researches have focused on the use of nanofluids to improve the performance of heat exchangers. Besides, the term nanofluid was introduced by Choi and Eastman [1] who had the idea of adding nanoparticles to conventional fluids to increase their thermal conductivity, based on this idea, Eastman et al. [2] have increased the thermal conductivity of ethylene glycol by 40% through adding 0.3% copper nanoparticles less than 10 nm in diameter. Then, several numerical [3, 4] and experimental works [5, 6] have been developed, the majority of studies was carried out to discover the most efficient nanofluid for improvement purpose of the heat transfer in various fields such as the cooling of electronic components [7, 8], photovoltaic panels [9, 10], insulation and cooling oils of electricity transformers [11], automobile radiator cooling [12], pool boiling [13]. In order to maximize the heat transfer rate of nanofluids, a number of parameters have been investigated. The dynamic viscosity and thermal conductivity model of Koo and Kleinstreuer [14] has been implemented in a micro-channel by Almeida, Gireesha, et al. [15] in the presence of buoyancy forces, a magnetic field, and nonlinear thermal radiation effects. Kumar, Nagaraja, et al. [16] investigated the buoyancy impact of a transported nanofluid on a curved stretched sheet driven by a magnetic dipole. In order to maximize the Nusselt number for a nanofluid flow on a curved surface, Nagaraja, Almeida, et al. [17] using both Taguchi and ANOVA tools, these two methods were also applied by Nagaraja, Gireesha, et al. [18] using the Darcy-Forchheimer model. Almeida, Kumar, et al. [19] studied the effect of differens other parameter such as the radiation, Prandtl number, and compression parameter on the entropy optimization for a hybrid nanofluid located between two parallel plates of the stretching. Using the grey relational analysis, Kumar, Ajaykumar, et al. [20] studied the impact of linear radiation and thermo-diffusion on the enhancement of the heat transfer rate. Since the tubular heat exchanger is one of the most common heat exchangers used in industry thanks to the simple geometry thereof. Ismael Hasan et al. [21] experimentally studied the performance of a concentric double-tube heat exchanger using water-based nanofluids containing Al_2O_3 and TiO_2 nanoparticles in different concentrations. On the other hand, the results illustrate that the heat transfer rate increases with the increase of nanoparticle volume concentration. As consequence, they obtained an increase in the maximum heat transfer coefficient of 18.25% for the nanofluid (Al_2O_3 – water) and 15.5% for the nanofluid (TiO_2 – water) for a concentration of 0.3%. In light of which, they concluded that the nanofluid (Al_2O_3 – water) has a higher heat transfer rate than that of (TiO_2 – water).

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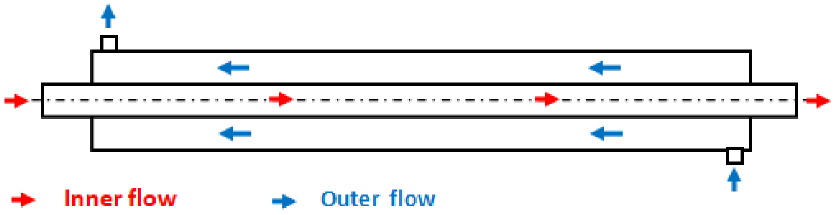

Fig. 1. The studied geometric configuration.

Above and beyond, Ali et al. [22] have experimentally and numerically investigated the effect of oil-based magnesium oxide nanofluids at different concentrations and for different values of internal fluid inlet flow rate on the performance of a double-tube counter flow heat exchanger in laminar regime. Hence, the obtained results illustrate that the injection of magnesium oxide nanoparticles into the oil leads to an improvement in its heat transfer. Likewise, the volume fraction of the nanoparticles and the nanofluid inlet flow rate had a positive effect on heat transfer in this exchanger. In this respect, hybrid nanofluids stand for a new category of nanofluid, composed of two or more types of nanoparticles. Nevertheless, these have thermal properties, in respect such as thermal conductivity and viscosity that are much higher than those of simple nanofluids [23, 24]. In virtue of which, the evolution of this class of nanofluids, as well as their characteristics and areas of use, are well detailed in several works, [25, 26].

In recent times, hybridization of Al_2O_3 and TiO_2 nanoparticles has experimentally been studied by Wanatasanappan and Abdullah [27] for the purpose of increasing the thermal conductivity of various vegetable oils. Similarly, this hybridisation of nanoparticles has alike been used by Murtadha [28] to cool photovoltaic panels. Lately, Bouselsal et al. [29] have obtained a heat transfer rate improvement of 103.07% in a tubular heat exchanger by use of the water-based Al_2O_3-MWCNT hybrid nanofluid with a concentration of 2%.

For the purpose of optimizing the heat transfer rate of a double-tube heat exchanger using hybrid nanofluids, the present work is part of this scope and conducted a numerical study for different nanofluid compositions. Besides, two oil-based hybrid nanofluids Al_2O_3-MWCNT and MgO-MWCNT with different volume concentrations were studied and compared for different inlet flow rates. In addition, the impact of the best selected hybrid nanofluid fraction and location on improving the heat transfer rate in a laminar flow two-tube counter-current heat exchanger has alike been studied and analysed in details.

2. Mathematical Formulation

The present work is based on the study of heat transfer and flow behaviour of hybrid nanofluids in a two-pipe heat exchanger made of 316 stainless steel, as seen in Fig. 1. Subsequently, the dimensions used are demonstrated in Table 1 and are consistent with those used by Ali et al. [22].

The single-phase model is used to analyse the thermal and dynamic structure of the hybrid nanofluids. In this model, the nanofluid is considered as a Newtonian and incompressible fluid, but with enhanced properties thanks to the integration of nanoparticles [30, 31].

Given these assumptions, the governing convective phenomena within the heat exchanger, namely those pertaining to continuity, momentum and energy, can be written as follows:

Conservation of mass:

$$\nabla.(\rho\nu) = 0 \tag{1}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2}$$

Conservation of momentum:

$$\nabla.(\rho\nu) = -\nabla P + \nabla.(\mu.\nabla\nu) \tag{3}$$

According to x:

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf}}\left[-\frac{\partial P}{\partial x} + \mu_{nf}(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2})\right] \tag{4}$$

According to y:

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf}}\left[-\frac{\partial P}{\partial y} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)\right] \tag{5}$$

Energy conservation:

$$\nabla.(\rho\nu C_p T) = \nabla.(k\nabla T) \tag{6}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k_{nf}}{C_P\rho_{nf}}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{7}$$

Table 1. Heat exchanger dimensions [22].

	External Diameter (mm)	Internal Diameter (mm)	Length (mm)
Inner tube	5.95	6.35	500
Outer tube	7.9	12.7	500

The rate of heat transfer Q can be expressed by Eq. (8). Assuming that the system is insulated; the heat lost by the hot fluid is absorbed by the cold fluid, neglecting head losses:

$$Q = Q_c = Q_h = m.C_p.\Delta T \tag{8}$$

in which Q_h and Q_c represent the heat transfer rates for the hot and cold fluids, respectively.

The overall heat transfer coefficient U is calculated using the following relationship:

$$U = \frac{Q}{A_i \Delta T_{LMTD}} \tag{9}$$

where A_i is the internal surface area of the inner tube and ΔT_{LMTD} is the logarithmic mean temperature difference given by Eq. (10):

$$\Delta T_{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{10}$$

where $\Delta T_1 = \Delta T_{h,in} - \Delta T_{c,out}$ and $\Delta T_2 = \Delta T_{h,out} - \Delta T_{c,in}$.

3. Boundary Conditions

The double-tube, counter-current, laminar flow heat exchanger used is manufactured from 316 stainless steel. Moreover, hot corn oil flows through the inner tube, whilst cold distilled water flows through the annular tube. Further; the hot oil was pumped at a temperature of 90°C with different volume flow rates (100, 200, 300 and 400 ml/min), while the distilled water entered at a temperature of 25°C and a constant flow rate of 150 ml/min. Nevertheless, two types of oil-based Al_2O_3-MWCNT and MgO-MWCNT hybrid nanofluid in different concentrations and proportions were injected to improve the heat transfer rate.

4. Thermo-Physical Properties of Hybrid Nanofluids

The thermo-physical properties of hybrid nanofluids are calculated by models and correlations already proposed. Besides, density, specific heat and thermal conductivity, respectively, are calculated by Eq. (11) and Eq. (12) [32]:

$$\rho_{nf} = \varphi_1 \rho_1 + \varphi_2 \rho_2 + (1-\varphi)\rho_{bf} \tag{11}$$

$$\rho_{nf}.C_{P_{nf}} = \varphi_1.\rho_1.C_{P_1} + \varphi_2.\rho_2.C_{P_2} + (1-\varphi).\rho_{bf}.C_{P_{bf}} \tag{12}$$

Such that $\varphi = \varphi_1 + \varphi_2$.

The expression for the thermal conductivity of the hybrid nanofluid is presented in Eq. (13) [32]:

$$\frac{k_{nf}}{k_{bf}} = \frac{\frac{\varphi_1 k_1 + \varphi_2.k_2}{\varphi} + 2(1-\varphi)k_{bf} + 2(\varphi_1 k_1 + \varphi_2.k_2)}{\frac{\varphi_1 k_1 + \varphi_2.k_2}{\varphi} + (2+\varphi)k_{bf} - (\varphi_1 k_1 + \varphi_2.k_2)} \tag{13}$$

For dynamic viscosity, Einstein's model [33] defined by Eq. (14) is chosen:

$$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi) \tag{14}$$

Table 2 demonstrates the values of the different thermo-physical properties of the fluids used, namely: water at T = 293 K, pure corn oil, Al_2O_3-MWCNT/oil and MgO-MWCNT/oil at T = 363 K.

5. Mesh Sensitivity Analysis

For the numerical modelling of our two-dimensional computational domain, a structured, non-uniform, variable mesh refined near the wall and annular space was used Fig. 2. Hence, the grid composed of quadrilateral elements was chosen for all simulations.

The domain discretization has shown to be a very important phase in CFD simulation. In such a numerical simulation, the accuracy of the results depends on the density and refinement of the mesh. For such purpose, a mesh independence study was conducted by testing a series of grid densities with different numbers of cells on the total heat transfer rate.

Table 2. Thermo-physical properties of working fluids and nanoparticles.

		Thermal conductivity (W/m.K)	Viscosity (Kg/m.s)	Specific heat (J/Kg.K)	Density (Kg/m^3)
Water		0.6	1.003	4182	998.2
Corn oil [22]		0.167	8.368	2154	916.4
MgO [22]		50.10	-	980	3580
Al_2O_3 [34]		36	-	880	3890
MWCNT [34]		1500	-	710	2100
Al_2O_3-MWCNT/oil	φ = 0.125%	0.317	10.98	2147.66	919.78
	φ = 0.25%	0.457	13.60	2141.37	923.16
	φ = 0.5%	0.736	18.8	2128.89	929.93
MgO-MWCNT/oil	φ = 0.125%	0.294	17.08	2148.60	919.36
	φ = 0.25%	0.38	18.22	2143.24	922.32
	φ = 0.5%	0.55	19.44	2132.62	928.24

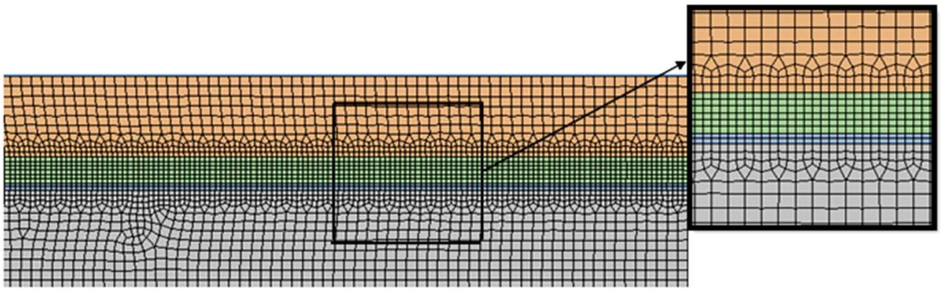

Fig. 2. Mesh generated for the system under study.

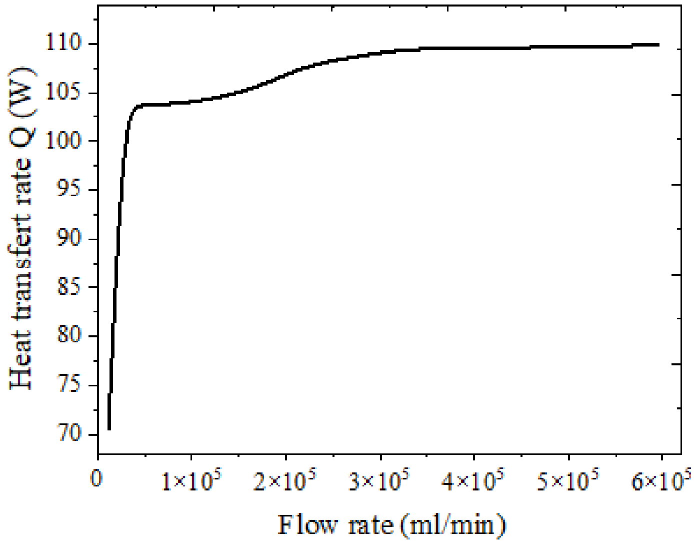

Fig. 3. Effect of mesh density on heat transfer rate.

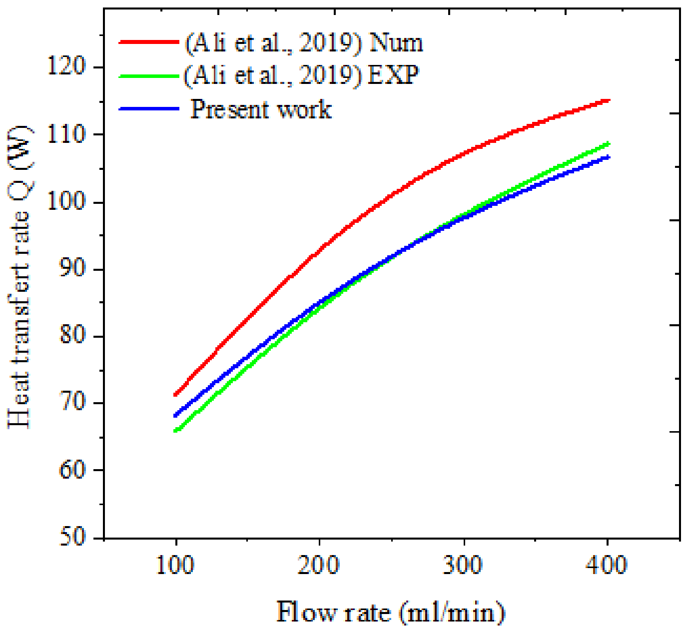

Fig. 4. Heat transfer rate as a function of the oil volume flow rate: Comparison with Ali et al. [22].

Figure 3 demonstrates that the number and size of elements influence the results, up to a value of 350000 elements, whereat stability is observed. Besides, we can see that the mesh grid with 393790 nodes gives a good compromise between accuracy and mesh density.

6. Model Validation

In order to prove the validity of our numerical results obtained with the Ansys fluent calculation code, we compared our results with those in the literature. Further, we compared our results with the heat transfer rate and the overall heat transfer coefficient which have experimentally and numerically been obtained by Ali et al. [22] as a function of the volume flow rate of pure oil circulating in a two-dimensional heat exchanger.

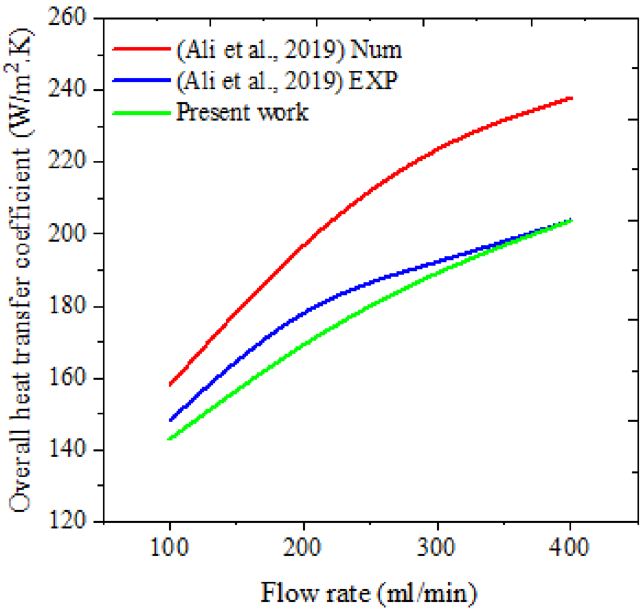

Fig. 5. Overall heat transfer coefficient as a function of the oil volume flow rate: Comparison with Ali et al. [22].

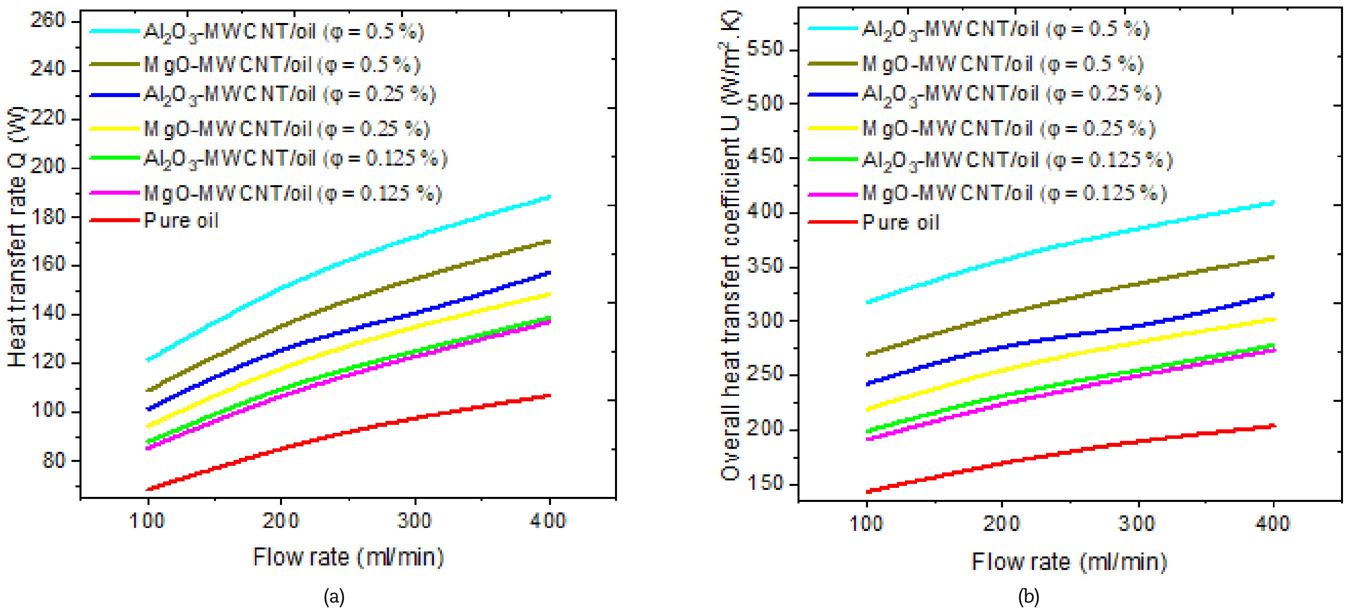

Fig. 6. Effect of nanoparticle type and volume concentration on the improvement in (a) heat transfer rate Q and (b) overall heat transfer coefficient *U*.

According to Fig. 4 and Fig. 5, it can be noticed that our results are very close, particularly with those experimentally obtained by Ali et al. [22]. In addition, a relative error of less than 3% for Q and less than 6% for *U*, which is acceptable and shows good agreement between our results and those obtained by Ali et al. [22].

7. Results and Discussion

a) Effect of volume concentration and type of hybrid nanofluid

This numerical study was conducted in three main points, firstly two types of hybrid nanofluids Al_2O_3-MWCNT and MgO-MWCNT with a fraction of (80:20) oil-based with different volume concentrations of nanoparticles (0.125% – 0.25% and 0.5%), are considered as hot fluid that passes through the inner tube of the twin-tube heat exchanger, which is used to heat water.

Figures 6(a) and 6(b) demonstrate the effect of the volume concentration of the two types of hybrid nanofluid mentioned above for different hybrid nanofluid input flow rates. Besides, it can be noticed that the heat transfer rate, as well as the overall heat transfer coefficient, increase with the increase in the hybrid nanofluid input volume flow rate. In light of which, the results demonstrate also that increasing the volume concentration of different nanoparticles has a positive effect on increasing the heat transfer rate and the overall heat transfer coefficient. Likewise, the nanofluid containing Al_2O_3-MWCNT shows a greater effect than that containing MgO-MWCNT for each concentration. In light of which, the heat transfer rate was improved by 77.8% for the case of the Al_2O_3-MWCNT/oil hybrid nanofluid with a concentration of 0.5%, whereas for the same concentration the MgO-MWCNT/oil hybrid nanofluid gave an improvement of 59.5%. On the other hand, the overall heat transfer coefficient has been improved by 76.26% and 100.82% for the two preceding hybrid nanofluids, respectively.

Similarly, it should be noted that the pure oil illustrated the lowest heat exchange rates compared with the other two cases.

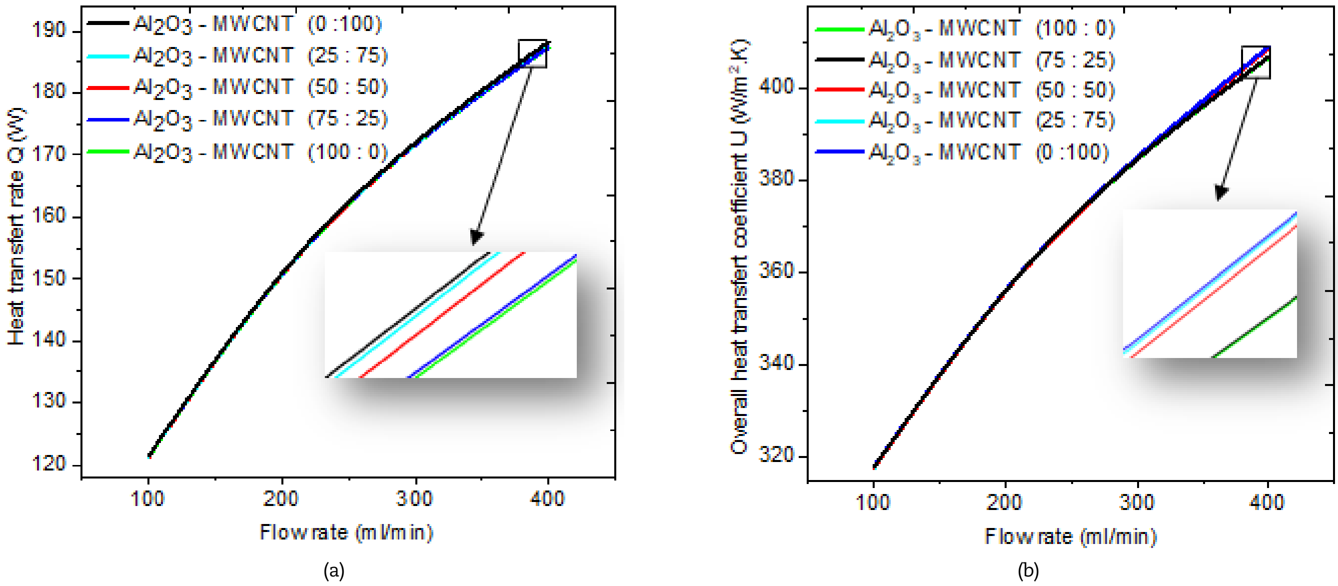

Fig. 7. Effect of nanoparticles ratio on increase in (a) heat transfer rate and (b) overall heat transfer coefficient *U*.

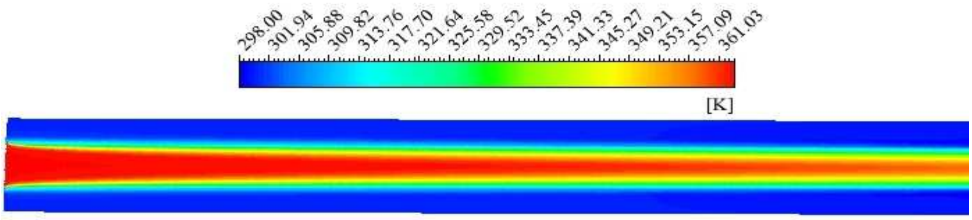

Fig. 8. Temperature contour during hybrid nanofluid flow.

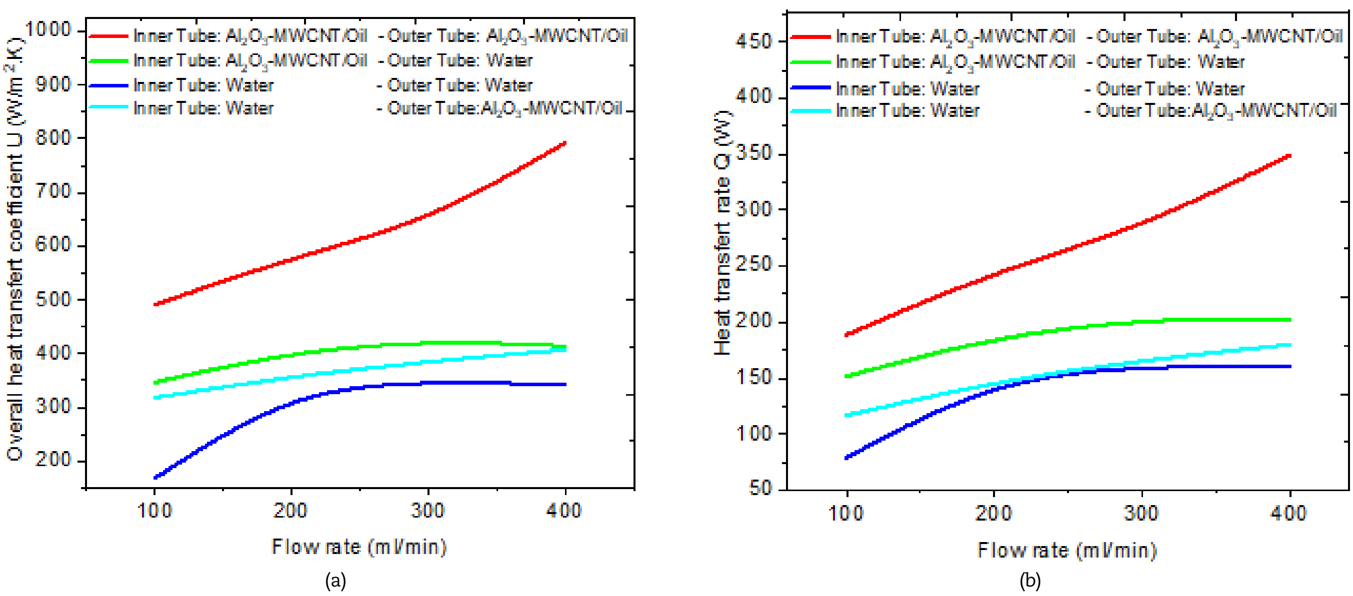

Fig. 9. Effect of hybrid nanofluid location in the two-pipe heat exchanger.

b) Nanoparticles' ratio effect

The first stage of this study revealed that the Al_2O_3-MWCNT/oil hybrid nanofluid with a total volume concentration of 0.5% performed best and showed good heat transfer efficiency. Although the mixing ratio of hybrid nanofluids has an effect on improving the heat transfer rate of the latter [36], this type and concentration of nanofluid were chosen to be studied in this second step, by comparing the performance of five different nanoparticles ratios (0 : 100), (25 : 75), (50 : 50), (75 : 25) and (100 : 0).

Although the multiwalled carbon nanotubes have a much higher thermal conductivity than alumina nanoparticles, the MWCNT/oil mono nanofluid has a significant influence on increasing the heat transfer rate and the overall heat transfer coefficient than the Al_2O_3/oil mono nanofluid, in the case of hybridization of these two nanoparticles. Besides, Figs. 7(a) and 7(b) demonstrate that the effect of the nanoparticles ratio of the Al_2O_3-MWCNT/oil hybrid nanofluid appears more with the increase in the volume flow rate of the nanofluid; subsequent to which, the results are zoomed in for the flow rate of 400 ml/min, the heat transfer rate as well as the overall heat transfer coefficient are considerably improved by increasing the proportion of multiwall carbon nanotubes, in such a manner that the most effective nanoparticles ratio is (25 : 75), then (50 : 50), and finally (75 : 25), the three particle ratios of which are more efficient than the mono-nanofluid Al_2O_3/oil.

The thermal behaviour of the hybrid nanofluid in the two-pipe heat exchanger studied is illustrated in Fig. 8, besides, it can be noticed that the nanofluid enters the heat exchanger and gradually loses heat along the way thereof.

c) Effect of hybrid nanofluid location

The two previous stages of this study have proved that a heat exchanger with Al_2O_3-MWCNT/oil with particle ratio of (25 : 75) and with a total volume concentration of 0.5% illustrates better thermal performance. Furthermore, the present step is devoted to study the impact of using this hybrid nanofluid model in the inner tube, in the annular section, or in both tubes of the twin-tube heat exchanger.

Figures 9(a) and 9(b) illustrate that the location of the hybrid nanofluid in the two-pipe heat exchanger has a very significant effect on the efficiency of the exchanger, the heat transfer rate as well as the overall heat transfer coefficient are higher in the case whereat the hybrid nanofluid circulates in both tubes "inner and annular" of the exchanger, whilst these two factors are lower when using water in both tubes of the exchanger. On the other hand, using the hybrid nanofluid in the inner tube as a hot fluid and the water as a cold fluid circulating in the annular tube makes it possible to obtain a good heat transfer rate compared with the opposite case.

8. Conclusion

In this work, a numerical study focusing on different hybrid nanofluids, such as MgO-MWCNT and Al_2O_3-MWCNT, based on oil under different volume concentrations (0.125 – 0.25 and 0.5%) and nanoparticles ratios (0 : 100), (25 : 75), (50 : 50), (75 : 25), (100 : 0) was carried out. Besides, these hybrid nanofluids were used in different locations in the twin-tube heat exchanger to increase their heat transfer efficiency. In virtue of which, the obtained results illustrated that the use of hybrid nanofluids considerably increases the heat transfer rate and the overall heat transfer coefficient compared to a single fluid. Likewise, the rate of transfer increased as well with any increase in the flow rate and the volume concentration of the nanoparticles. Additionally, an increase in the estimated maximum heat transfer rate of 77.8% was obtained when using Al_2O_3-MWCNT hybrid nanofluids/oil for a concentration of 0.5% and 59.5% and in the case of MgO-MWCNT hybrid nanofluids/oil for the same concentration, concerning the overall heat transfer coefficient, we had an increase of 76.26% and 100.82% for the two preceding hybrid nanofluids, respectively. More to the point, the best particle ratio for Al_2O_3-MWCNT hybrid nanofluid/oil is in the order of (25 : 75) and its use in the inner tube as a hot fluid and cold water in the annular tube made it possible to maximise the heat transfer and improve the performance of the studied two-tube heat exchanger. Finally, the use of Al_2O_3-MWCNT/oil nanofluid hybrid with a nanoparticle volume concentration of 0.5% and nanoparticle ratio of (25 : 75) in the inner tube of a twin-tube heat exchanger greatly improved its efficiency for heating water or other fluids, and can be used in a variety of industrial fields.

Author Contributions

D.A. BRAKNA developed the numerical model, conducted the simulations, wrote the manuscript, and prepared all the figures under the co-author's guidance. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Nomenclature

T	Temperature [K]	Q_c	Heat transfer rate of cold fluid [W]
Q	Heat transfer rate [W]	Q_h	Heat transfer rate of hot fluid [W
U	Overall heat transfer rate [W/m^{2}K]	k_{bf}	Base fluid thermal conductivity
φ	Volume concentrations of nanoparticles	k_{nf}	Nanofluid thermal conductivity
ρ	Density [Kg/m^3]	μ_{nf}	Nanofluid viscosity
k	Thermal conductivity [W/m.K]	μ_{bf}	Base fluid viscosity
C_P	Specific heat [J/Kg.K]	MWCNT	Multi-Walled Carbone Nanotube
μ	Dynamic viscosity [Kg/m.s]	Al_2O_3	Aluminum Oxide
m	Mass [kg]	MgO	Magnesium Oxide
υ	Velocity component along x-direction [m/s]	CFD	Computational Fluid Dynamic
u	Velocity component along y-direction [m/s]	φ_1	First nanoparticles volume concentrations
$\Delta T_{\Lambda MT\Delta}$	Logarithmic mean temperature difference	φ_2	Second nanoparticles volume concentrations

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