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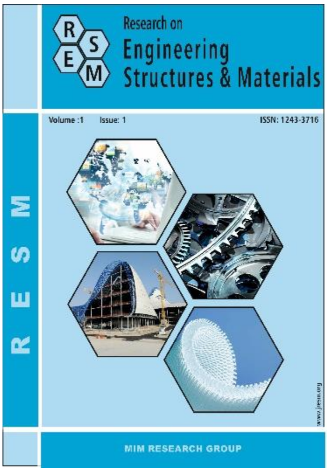

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Research Article

Thermo-hydraulic performance analyses of water based CuO-SiO_2 hybrid nanofluid flow in a horizontal straight tube

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Abstract

This study presents a numerical investigation of volume fraction effect of water based hybrid CuO-SiO_2 nanofluid in a horizontal tube on thermal performance. Uniform heat flux was applied onto the outer surface of the test tube. Fully developed turbulent flow was ensured with adjusting solution domain. k-epsilon turbulent model was chosen to simulate turbulent flow, and analyses were implemented for Reynolds number ranging from 10,000 to 50,000. The nanofluid flow was assumed as single phase, and properties of nanoparticles and water are concerned as independent in temperature. Thermo-physical properties of nanofluid were calculated with commonly used equations and correlations in literature. Nanoparticle volume fractions in water were employed as 5, 4, 3, and 2% in which each volume fraction is different value of CuO and SiO_2. As a result, since CuO is more effective thermal properties than SiO_2, it is observed that greater volume fraction of CuO than SiO_2 shows better heat transfer performance. Moreover, the highest Nusselt number is obtained for 1%CuO-4%SiO_2 water based nanofluid for Reynolds number of 50,000. However, due to better hydraulic properties of SiO_2 than CuO, the higher volume fraction of SiO_2 compared to CuO, the higher thermo-hydraulic performance was obtained.

1. Introduction

Heat transfer is an important phenomenon in many engineering systems such as cooling and heating applications; therefore, thermo-physical properties of used heat transfer fluids have particular importance in these applications. Thermo-hydraulic analyses of heat exchangers were generally in terms of physical design in previous. The physical design of heat exchangers are adding pins, inserting turbulator, coiling the tube and increasing the heat transfer surface area. However; since development in nano technology at last decade has been improved, novel applications and investigation areas come out. A branch of these developments is on heat exchangers working fluid. Conventional heat transfer fluids such as water and oil have low thermal conductivity, and it is a primary factor that limits increasing heat transfer performance. In order to increase heat transfer performance, nanofluids have been interested by many researchers [1, 2] in recent years, because they have shown better thermal performance than conventional fluids such as water and oil. The main aim of using nanofluid is to increase thermal conductivity of the conventional fluid, since the conventional fluids have low thermal conductivity in comparison with most of solids. The other advantage of nano-particles in comparison with micro-particles is of higher surface area per volume and behavior of easier suspending in base fluid. Many experimental and numerical studies in both laminar and turbulent regimes have shown that adding nanoparticle to a base fluid increases heat transfer enhancement.

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Duangthongsuk and Wongwises [3] experimentally investigated that effect of TiO_2-water nanofluid on heat transfer coefficient and friction factor in a double tube counter flow heat exchanger under turbulent flow conditions. The study is concerned about volume fraction of TiO_2 is ranging from 0.2 % to 2 %, and Reynolds number ranging from 4,000 to 14,000. They concluded that maximum heat transfer coefficient is obtained 26% higher than base fluid for 1.0 % volume fraction, and pressure drop slightly increases by increasing particle volume fraction. Sahin et al. [4] experimentally investigated the effect of Al_2O_3-water nanofluid on convective heat transfer and pressure drop characteristic inside a circular tube. They concluded that heat transfer increased with the increase of Reynolds number. They also observed that the highest thermal efficiency is obtained about 1.1 times higher than base fluid for 0.5 % volume fraction and Reynolds number of 8,000. In addition to experimental studies about nanofluids, many researches numerically conducted by using CFD programs, in recent years, due to challenges of preparing experimental setup and costs. Celen et al. [5] numerically carried out an investigation for TiO_2-water nanofluids in order to observe average temperature, pressure and velocity distribution inside pipe. They used an experimental study data to validate accuracy of numerical methodology. Their results were tolerably as similar as experimental results. Moghadassi et al. [6] investigated the effect of water based Al_2O_3 and Al_2O_3-CuO hybrid nanofluid on forced convective heat transfer. The nanofluid volume fraction of 0.1 % and average particle size of 15nm was considered. Their results showed that higher convective heat transfer coefficient was obtained for Al_2O_3-CuO nanofluid. And they reported that average Nusselt number increase was 4.73% and 13.46% in comparison with Al_2O_3-water and distilled water, respectively. Dawood et al. [7] conducted a numerical study in order to see the effect of different nanoparticles (Al_2O_3, CuO, SiO_2 and ZnO), different volume fractions (0.5-4%) and diameters (25-80nm) under constant heat flux at both laminar flow ($200 \le Re \le 1500$) and turbulent flow ($4{,}000 \le Re \le 10{,}000$). Their results showed that SiO_2-water nanofluid has the highest Nusselt number, followed by ZnO-water, CuO-water, Al_2O_3-water and lastly distilled water. In this research, forced convective heat transfer of water based CuO-SiO_2 hybrid nanofluid under constant heat flux and fully developed turbulent flow is numerically investigated. Volume fraction of hybrid nanofluid is ranging from 2% to 5%, and Reynolds number is ranging from 10,000 to 50,000. Akbari et al. [8] investigated the nanofluid heat transfer in a 3-D curved micro tube with using mixture model. They investigated that the heat transfer and fluid flow behavior in a curved micro tube. They concluded that with the increment of nanoparticle amount, isotherms get to the intended temperature more rapidly. In addition to smooth tube studies, some researcher investigated the effect of some inserts in the tube or channel. In another study, Alipour et al [9] investigated the silver-water nanofluid with different volume fractions in a three-dimensional trapezoidal microchannel. They concluded that as the Reynolds number increased, the average Nusselt number and average convection heat transfer coefficient increased. Nikkah et al. [10] concluded that similar results with their study which is about on forced convection heat transfer of water/functionalized multi-walled carbon nanotube nanofluids in a microchannel.

In this study the effect of using water based hybrid CuO-SiO_2 nanofluid in a horizontal straight tube on heat transfer and hydraulic performance is investigated numerically. However, the previous studies are generally considered about using of one type nanoparticle. In order to ensure accuracy of numerical analyses, both distilled water and CuO nanofluid flow is validated for Nusselt number and friction factor with commonly used correlations in literature and a study of Rostamani et al's, respectively[11].

The main aims of the present study are:

- To observe the effect of ratio of hybrid nanofluid properties on Nusselt number criteria

- To find optimal volume fraction depends on Reynolds number in terms of thermo-hydraulic performance

2. Numerical Study

CFD (Computational Fluid Dynamics) simulations have been commonly used to predict, solve and analyze the problems which involve fluid flows, heat and momentum transfer, by using equations and algorithms of fluid mechanics. The advantage of CFD simulations is to optimize variations of systems with shorter time and cheaper than experimental setup, with acceptable deviations.

The CFD program uses the control volume technique to convert governing equations (conversation of mass, momentum and energy equations) to algebraic equations. A careful check for grid independence is required for ensuring the validity and accuracy of numerical methodology. For this purpose, different grid structures were tested, and one of them (as illustrated in Fig 1.), having minimum cell size of 0.57 mm and cell number of 1.18 million is selected for all cases, because the water results in terms of both Nu number and friction factor does not change more than approximately 2%.

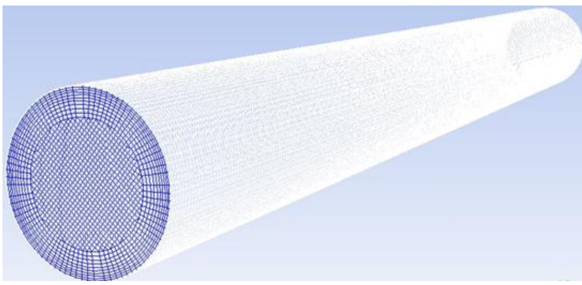

Fig. 1. Grid structure of used circular tube

Furthermore, CFD program needs to a compatible turbulence model to simulate turbulent flow in the tube. k - ε standard turbulent model was employed to simulate turbulent flow by using CFD program. The three-dimensional continuity, momentum and energy of Navier-Stokes equations are solved by using finite volume method (FVM) and the Semi Implicit Method for Pressure Linked Equations (SIMPLE) algorithm scheme is applied to examine the effects of turbulent flow on heat transfer and friction characteristics. The CFD program uses a point implicit (Gauss-seidel) linear equation solver in conjunction with an algebraic multigrid method [12]. Second order upwind discretization schemes were chosen on all the transport equations. The convergence criteria were assumed 10^{-6} for continuity, x-y velocity, energy, k and ε. The values of pressure drop (ΔP) and temperature difference were acquired from surface integrals form the program.

2.1. Computational domain

As depicted in Fig.2, a 3D geometry is generated to describe both distilled water and nanofluid flow characteristic in a straight circular tube under constant heat flux of 50 kW/m^2 and velocity inlet (m/s) based on Reynolds numbers in a turbulent flow regime. The computational domain is used for the purpose of simulate a part of a heat exchanger.

The investigated part of the heat exchanger is assumed as horizontal and the test tube material is aluminum and diameter of the tube of 10 mm. Length of entrance section (L_1) is considered as a 10D to supply fully developed flow in front of the test section. Length of test section (L_2) is considered as 1m. Length of exit section (L_3) is considered as 5D to defect the reverse flow effect.

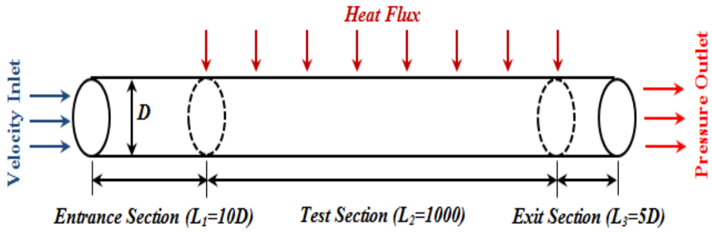

Fig. 2. Schematic diagram of the solution domain

2.2. Validation of numerical study for distilled water and nanofluid

In order to choose reality turbulence model, calculated average Nusselt number (Eq. 1) and friction factor (Eq. 4) are respectively compared with Gnielinski Eq. (3) [13] and Blasius Eq. (5) [14] in Fig. 3. Results showed that k-ε standard model is more compatible than the other turbulence models according to both Nusselt number and friction factor in terms of distilled water, as recommended by Sadeghinezhad et al. [15].

Nusselt number:

$$Nu = \frac{hD}{k} \tag{1}$$

Heat transfer coefficient:

$$h = \frac{q}{T_s - T_b} \tag{2}$$

Gnielinski Equation [13]:

$$Nu = 0.012(Re^{0.8} - 280)\,Pr^{0.4} \quad for \quad 1.5 \leq Pr \leq 500 \quad 3x10^3 < Re < 10^6 \tag{3}$$

Friction factor:

$$f = \frac{\Delta P}{\frac{1}{2}\rho V^2 \frac{L}{D}} \tag{4}$$

Blasius Equation [14]:

$$f = 0.316 Re^{-0.25} \tag{5}$$

Thermo-Hydraulic Performance:

$$THP = \frac{Nu_{nf}/Nu_{bf}}{\left(f_{nf}/f_{bf}\right)^{1/3}} \tag{6}$$

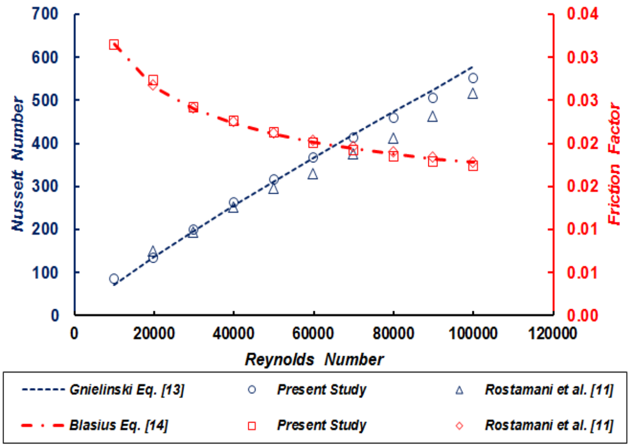

Fig. 3. Validation of numerical results for water in terms of average Nusselt number and friction factor

A single-phase approach is employed to model nanofluids, and properties of fluid are applied as independent in temperature. Studies by Rostamani et al. [11], was used to validate to prove accuracy of numerical solution method for nanofluid flow. Validation of nanofluid with volume fraction (φ=0.03) of CuO-water nanofluid is illustrated in Fig 4. Good agreement is observed between the result of present study and Rostamani et al [11].

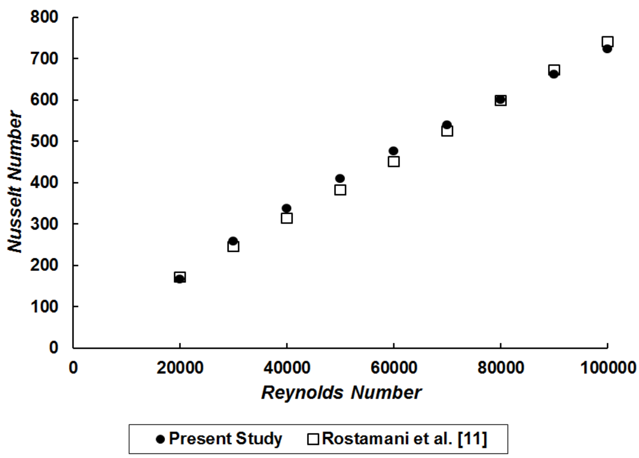

Fig. 4. Validation of numerical results for 3% CuO in terms of average Nusselt number with study by Rostamani et al. [11]

3. Numerical Analyses

There are many researches in the literature on heat transfer enhancement by using nanofluid with one nanoparticle type. However, there is no sufficient works on the investigation of the effect of hybrid nanofluid mixture (two different nanoparticle mixture together). So, in present study, in order to observe the effect of the hybrid CuO-SiO_2 mixture is conducted by using various fraction combinations ranging from 2% to 5% (Table 1) at Reynolds number ranging from 10,000 to 50,000.

Table 1. Combinations of the hybrid CuO-SiO_2 mixture volume fractions

Total volume fractions (%)	Combinations (%)						
5	CuO	0	1	2	3	4	5
	SiO_2	5	4	3	2	1	0
4	CuO	0	1	2	3	4	-
	SiO_2	4	3	2	1	0	-
3	CuO	0	1	2	3	-	-
	SiO_2	3	2	1	0	-	-
2	CuO	0	1	2	-	-	-
	SiO_2	2	1	0	-	-	-

3.1. Thermal and physical properties of nanofluid

Water is conventional heat transfer fluid due to easily being supplied and prepared. However, in order to achieve better heat transfer performance, nanofluids have been used in many engineering applications, in recent years. But, preparation of nanofluids is a challenging process for getting homogeny mixture fluid and avoiding sedimentation. So ultrasonic homogenizers are used to get homogenous nanofluid mixture. Furthermore, determining thermo physical properties (density, thermal conductivity and specific heat capacity) of nanofluids is another challenge in experimental setups. Duangthongsuk and Wongwises [3] studied on three methods of preparation of nanofluid for experimental setup. The methods which are control of Ph value of the suspensions, addition of surface activators or surfactants and use of ultrasonic vibrations [3]. However, some simple formulas are used for determining these properties in numerical study field. Used formulas in the work are given as below;

Density of nanofluid:

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_{np} \tag{7}$$

Density of Hybrid mixture:

$$\rho_{nf,hybrid} = \frac{\varphi_{CuO}\rho_{nf-CuO} + \varphi_{SiO2}\rho_{nf-SiO2}}{\varphi_T} \tag{8}$$

Specific heat of nanofluid:

$$Cp_{nf} = \frac{(1-\varphi)\rho_{bf}Cp_{bf} + \varphi\rho_{np}Cp_{np}}{\rho_{nf}} \tag{9}$$

Specific heat of Hybrid mixture:

$$Cp_{nf,hybrid} = \frac{\varphi_{CuO}Cp_{nf-CuO}+\varphi_{SiO2}Cp_{nf-SiO2}}{\varphi_{total}} \tag{10}$$

Thermal conductivity:

One of most used formula (Eq. 11) for calculation the thermal conductivity of nanofluid is developed by Hamilton and Crosser [16], in 1962.

$$k_{nf} = k_{bf}\frac{[k_{np}+(n-1)k_{bf}-(n-1)\varphi(k_{bf}-k_{np})]}{[k_{np}+(n-1)k_{bf}+\varphi(k_{bf}-k_{np})]} \tag{11}$$

$$n = 3/\psi \tag{12}$$

where n is the empirical shape factor and ψ is the sphericity, defined as the ratio of the surface area of the particle (Eq. 12), as stated by Duangthongsuk and Wongwises [3]. The sphericity value assumed as 1. Expressions of k_{nf}, k_{np} and k_{bf} are the thermal conductivity of nanofluid, nanoparticle and base fluid, respectively.

Thermal conductivity of hybrid mixture:

$$k_{nf,hybrid} = \frac{\varphi_{CuO}k_{nf-CuO}+\varphi_{SiO2}k_{nf-SiO2}}{\varphi_{total}} \tag{13}$$

Dynamic viscosity:

$$\mu_{nf} = \mu_{bf}(123\varphi^2 + 7.3\varphi + 1) \tag{14}$$

Dynamic viscosity of hybrid nanofluid does not need to calculate again due not to including expect of volume fraction (φ) in the formula. Main thermo and physical properties of base fluid and nanoparticles are in constant temperature and summarized as in Table 2. Main aim of using nanofluid is to raise thermal conductivity value and Pr (Prandtl number) as well, and it causes to increase viscous diffusion rate of base fluid.

Table 2. Properties of water and nanoparticles

	Water	**CuO**	**SiO_2**
ρ [kg/m³]	998.2	6510	2550
Cp [j/kgK]	4182	540	710
μ [kg/ms]	0.001003	-	-
k [W/mK]	0.6	18	1.4

4. Results and Discussion

As a first step in this study, numerical procedure is validated to ensure accuracy of analyses both distilled water and nanofluid with some correlations in literature and another study [11], respectively. And after that, volume fraction combinations of hybrid CuO-SiO_2 water based nanofluid are investigated at turbulent regime (10,000 ≤ Re ≤ 50,000). The numerical analyze for nanofluid is assumed as a single phase, and thermo-physical properties of nanofluid are calculated as independent in temperature with commonly used equations in literature. Nusselt distribution of all combinations of volume fractions at

Reynolds number ranging from 10,000 to 50,000 is illustrated in Fig. 5. Nusselt number for nanofluid combinations is slightly higher than distilled water for Reynolds number of 10,000. However, with the increment of Reynolds number, the effect of nanofluid on heat transfer increases. In the other hand, different combinations of hybrid CuO-SiO_2 nanofluid have different behavior on the Nusselt number. Results show that higher volume fraction of SiO_2 in comparison with CuO in the mixture, more positively effect on Nusselt number. The main reason of that CuO has better performance in terms of convective heat transfer coefficient rather than SiO_2, due to greater thermal conductivity. Because the Nusselt number depends on convective heat transfer coefficient and thermal conductivity, increase-decrease ratio between them occurs this result. In other words, the increase ratio of convective heat transfer coefficient is better than the increase ratio of conductive heat transfer of hybrid nanofluid with the increasing SiO_2 volume fraction.

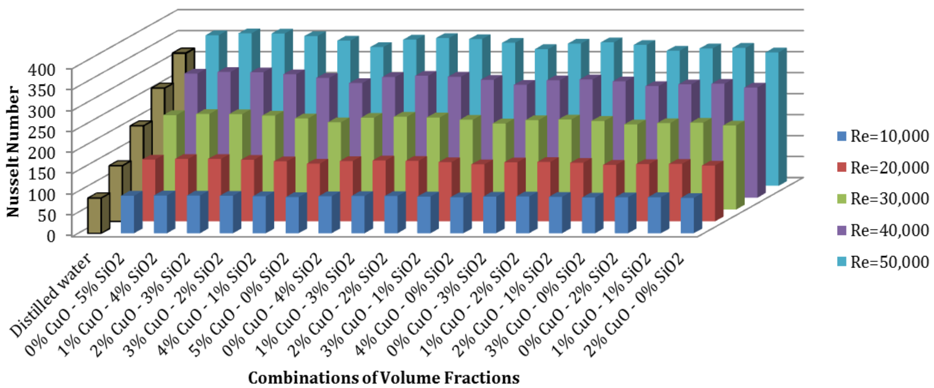

Fig. 5. Nusselt number versus Reynolds number for combinations of volume fractions

The relationship of convective heat transfer coefficient between nanofluid and water (h_{nf}/h_{bf}) is given in Fig 6. It is clearly seen that amount of CuO nanoparticle is dominant on that of SiO_2 on convective heat transfer coefficient performance. The second reason of this result is about increasing Prandtl (Pr) number of hybrid nanofluid. Therefore, heat transfer working fluids having more Prandtl number such as water and ethylene glycol (e.g. $Pr_{air}\cong0.7$, $Pr_{water}\cong7.0$ and $Pr_{ethylene}$ glycol$\cong150$) are preferred in many engineering applications.

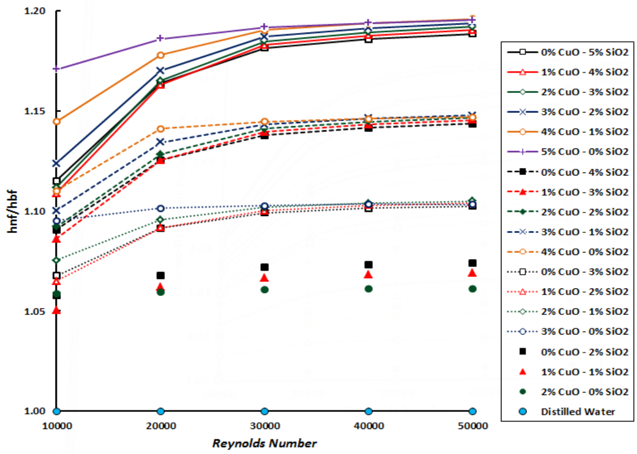

Fig. 6. Heat trasnfer coefficient versus Reynolds number for combinations of volume fractions

In addition to heat transfer enhancement, friction factor have to be considered by designers in the hydraulic systems. The results showed that friction factor slightly increases by increasing nanofluid volume fraction, as reported by many researchers [1, 3, 10 and 11]. However, pressure drop increases, as Reynolds number and volume fraction of nanoparticle increases (Fig 7). The highest pressure drop is observed for 1% CuO – 4% SiO_2 nanofluid mixture. When this results is examined, it is observed that the minimum density of the hybrid nanofluid is 1% CuO – 4% SiO_2. Furthermore, thermo-hydraulic performance (THP) distribution on all investigated cases is illustrated in Fig. 8. As can be seen in this figure, all cases have THP value of greater than 1.0. The THP increases as Reynolds number increase, but increasing tendency decreases after Reynolds number of 30,000.

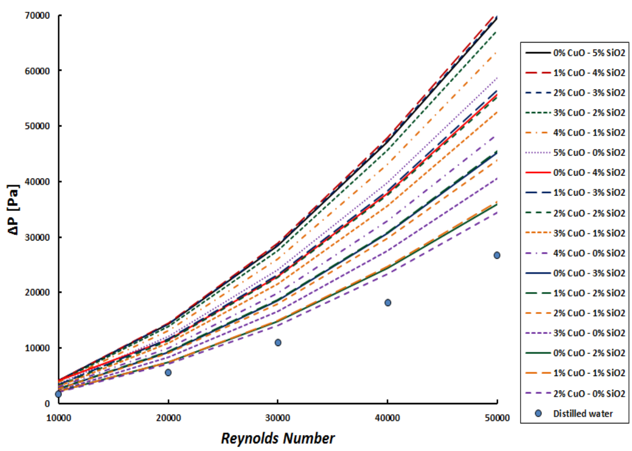

Fig. 7. Pressure drop criteria versus Reynolds number for combinations of volume fractions

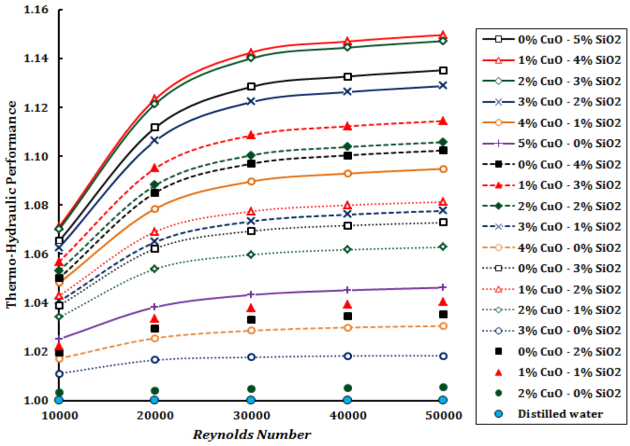

Fig. 8. Thermo-hydraulic performance criteria versus Reynolds number for combinations of volume fractions

5. Conclusions

In this study, the effect of water based hybrid nanofluid CuO-SiO_2 on heat transfer enhancement through the horizontal tube under turbulent condition is numerically investigated by using a CFD program. Results showed that Nusselt number increases by increasing both volume fraction and Reynolds number. In the other hand, when considered combinations of volume fraction for CuO-SiO_2, SiO_2 has better effect on Nusselt number in comparison with CuO. The highest Nusselt number is obtained as 363.63 (i.e. 1.15 times higher than distilled water) for 1% CuO – 4% SiO_2 at Reynolds number of 50,000.However, CuO has greater thermal conductivity than SiO_2, and this situation causes the increase convective heat transfer coefficient, because the conductive heat transfer between the molecules more effectively occurs. Another reason of this situation is related with Prandtl number. For the fluids having greater Prandtl number, thermal diffusivity developing is speeder than hydraulic developing. Therefore, the fluids having greater Prandtl number have positive effect on heat transfer performance. The main cause of this result is that higher volume fractions of SiO_2 have more Prandtl number in comparison with CuO. And the highest Prandtl number of 10.5 is belongs to 1% CuO – 4% SiO_2.

For friction factor characteristic, volume fractions between 1-5% slightly increases friction factor compared with distilled water. Therefore, thermo-hydraulic performance can be directly related with increasing on Nusselt number. The highest thermo-hydraulic performance is obtained as 1.149 for 1% CuO – 4% SiO_2 at Reynolds number of 50,000.

NOMENCLATURE

Symbol	*Unit*	*Definition*
D	[m]	diameter of the tube
f	[-]	friction factor
h	[W/m^{2}K]	convective heat transfer coefficient
k	[W/mK]	thermal conductivity
L	[m]	length of the tube
n	[-]	empirical shape factor

Nu	[-]	Nusselt number
ΔP	[Pa]	pressure drop
Re	[-]	Reynolds number
T	[K]	temperature
THP	[-]	Thermo-Hydraulic performance criteria
V	[m/s]	velocity magnitude of the fluid

Greek symbols

ρ	[kg/m³]	density
φ	[-]	volume fraction of nanoparticle
Cp	[kj/kgK]	specific heat capacity
μ	[kg/ms]	dynamic viscosity
ψ	[-]	sphericity of the nanoparticle

Subscripts

bf	base fluid
nf	nanofluid
np	nanoparticle
T	total
s	surface
b	bulk

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