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Thermal Performance of Four-Lobe Swirl Generator and its Transition Parts Under a Different Type of Nanofluids

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ABSTRACT

Due to the importance of promoting the thermal performance of heat exchangers, innovating a new technique is the main goal of many researchers. In swirl flow techniques, keeping the pressure drop at the practical level still requires more and more attention. In the current paper, a numerical study is conducted to explore the impact of a novel lobe swirl generator and its transition parts on forced convective heat transfer and friction factor in a circular pipe subjected to constant heat flux. The swirl mechanism is investigated at the pitch to a diameter of $P/D = 8$ as the optimum design. The transition part under several parameters of variable beta (β), transition multiplier ($n = 0.5$) and variable helix ($t = 1$) have been adopted. The effect of SiO_2, Al_2O_3, and CuO volume concentrations (*1 to 5%*) in water under various Reynolds numbers (*Re*) from *15,000 to 35,000* have been carried out. The turbulent swirling flow was modelled using the applicable shear-stress transport (*SST*) *k-ω*. The outcome demonstrated an enhancement in heat transfer value ranging from *1.35 to 1.87* with an increased pressure drop value from *1.23 to 1.67*. It was also found that using SiO_2/water at 5% volume concentration and *Re 15000* created the highest thermal performance, with a significant factor of *1.67*.

1. Introduction

The need for energy is rapidly growing as the world economy and population rise. Therefore, building an ecologically friendly and reliable energy source is critical and necessary. Due to the significance of promoting heat transfer in the field of thermal application, many researchers are focusing on developing a novel technique. One of the new technology recently created is the lobed swirl generator. Swirl flow provides tangential velocity noticeable on the fluid flow downstream. Swirl flow played a vital role in producing secondary flow, which is the main factor for improving heat transfer in many thermal performance applications [1–3]. When the target outcome is to improve

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heat transfer, keeping the pressure drop at the appropriate level is still a significant challenge. Therefore, the novel swirl flow has been proposed to overcome this problem.

Jafari *et al.,* [4] studied the impact of a 4-lobe swirl generator on thermal performance numerically and experimentally under constant length and various angles. The result revealed that the lobed swirl under the angle of 360^0 presented the highest thermal performance from 1.24 to 1.60. The comparison between the tri-lobe and oval tube cross-sections has been performed by Tang *et al*., [5]. The result demonstrated the heat transfer enhancement of up to 5.4% by using a tri-lobe instead of an oval tube. Yan *et al*. [6] studied the effect of a different pitch to diameter (*P:D*) and lobe number on the effectiveness of the lobe swirl generator. The result proved that the optimum design of lobe swirl generator was attained at a lobe number of four (*n = 4*) and (*P:D = 8*). The transition parts of the lobe swirl have been designed by Ariyaratne and Jones [7] to overcome the increase in the pressure drop which occurs by the swirl pipe's constant geometry. The outcome showed that the transition parts under gradual changing from circular shape to lobe and vis versa led to reducing the pressure drop, increased the generated swirl intensity and a decrease in swirl decay.

Increasing the thermal conductivity and heat transfer rate of transporting liquids by adding nanotechnology particles is a feasible alternative. Several researchers have recognised the dispersion of nanoparticles in conventional heat transfer fluids as a way to enhance heat transfer capabilities [8–10]. Nanofluids, which have high thermal conductivity, have been incorporated with conventional fluids to promote heat transfer rates [11-13] and reduce overheating in heating and cooling applications [14]. The mass flow rate, the concentration of nanoparticles, and, most significantly, the thermal conductivity of nanoparticles have vital steps in the thermal conductivity improvement of nanofluids [15-17].

Extensive work have been conducted to improve the heat transfer using nanofluids in various channels such as corrugated facing step [18], backward facing-step [19], combined corrugated with facing-step [20, 21]. Nfawa *et al*., [22] investigated the heat transfer enhancement in a corrugated-trapezoidal channel using winglet vortex generators. Hybrid nanofluids have been used to enhance heat transfer and thermal conductivity through corrugated facing step channels [23,24] and backward/ forward steps channel [25]. Nfawa *et al*., [26] has introduced a novel use of MgO nanoparticle additive for enhancing the thermal conductivity of CuO/water nanofluid.

Khairul *et al.,* [27] studied the effect of CuO, Al_2O_3, SiO_2, and ZnO with pure water as base fluid on heat transfer enhancement of heat exchanger application. The study proved that the CuO/water nanofluid presented a tremendous increase in heat transfer coefficient and lowest friction factor compared to the four nanofluids investigated when applied in a helically coiled mechanism. Rejvani *et al.,*[28] studied the effect of adding SiO_2-nanoparticle at different volume concentrations from 0% to 1.5% to the water as base fluid under various temperatures on the thermal conductivity enhancement. The study clarified that the thermal conductivity of SiO_2 /water considerably increases at the temperature water value of 40°C. Torki & Etesami [29] examine the effect of SiO_2/water under different concentrations on heat transfer enhancement in the rectangular enclosure geometry. The result evidenced that the SiO_2/water at low volume concentrations has an insignificant effect on thermal conductivity enhancement. Therefore, to promote the capability of silicon dioxide (SiO_2), an increase in volume concentration is highly required. Prasad *et al.,* [30] studied the effect of different glycerol ratios with water and SiO_2-nanofluid on thermal conductivity, dynamic viscosity and stability. The result showed that the SiO_2-nanofluid continued to be stable for one month. Also, the high temperature has the most influential factor in thermal conductivity improvement.

According to the overmentioned literature review and to the best of our knowledge, it has been highlighted; (i) that the implemented lobe swirl generator presents a remarkable thermal performance. (ii) Transition parts are more efficient at the swirl intensity than the lobe swirl itself due to its gradual change from circular to lobe and vis versa, which is the main reason for decreased frictional pressure loss [7]. (iii) The use of oxide nanoparticles in many thermal techniques led to a substantial increase in heat transfer combined with a rising pressure drop. It can be pointed out that there is no study performed on the effect of lobe swirl generator and its appealing transition parts combined with nanofluids in the field of thermal application. Therefore, the outcome target of this study is to address the challenge of pressure drop penalty by proposing a unique study on the effect of lobe swirl device with its attractive transition parts together with nanofluids on thermal performance efficiency improvement.

2. Methodology

The geometrical shape used in the current study is known as a lobe swirl generator. Ganeshalingam [31] suggested a 4-lobed swirl generator with a *P:D* = 8, a length of 400 mm, and equivalent diameter of 50 mm as the optimum design. Therefore, this modelling was used in the present work to examine its influence on heat transfer and thermal performance. As shown in Figure 1, the length of the entry section, transition parts, lobed swirl device and test section at 800, 100, 200 and 800 mm, respectively, were adopted. The aluminium tube (test section) was subjected to constant heat flux. The working fluid of water, SiO_2/water, Al_2O_3/water and CuO/water were generated at several Reynolds numbers from (15,000 to 35,000). The Nusselt number (*Nu*), friction factor (*f*) and thermal performance criteria (*PEC*) are taken place to figure out the targeted outcome. Therefore, the related equations used are illustrated as follows:

$$Nu = \frac{(h_{avr} \times D)}{K} \tag{1}$$

$$f = \frac{\Delta P}{\left(\frac{L}{D}\right) \times \left(\frac{\left(\rho u_{in}^2\right)}{2}\right)} \tag{2}$$

$$\eta = \frac{\left(Nu / N_{up}\right)}{\left(f / f_p\right)^{1/3}} \tag{3}$$

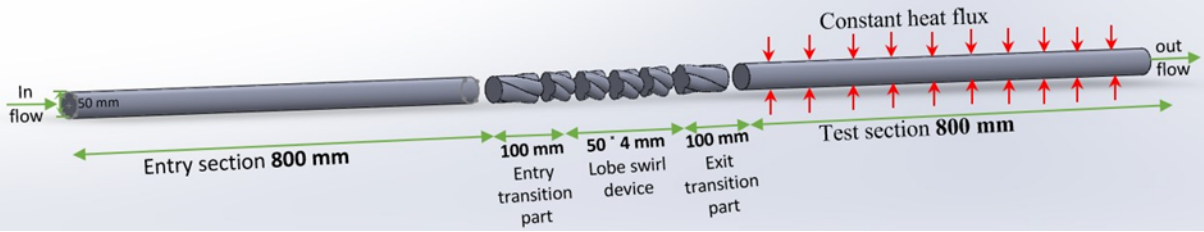

Fig. 1. 3D Representation schematic of the lobed swirl generator

2.1 The Benefit of Transition Parts

Ariyaratne and Jones [7] confirmed that the transition parts located before and after the primary swirl device caused; (i) The entering transition increased the overall swirl intensity. In contrast, the exit transition decreased the swirl decay. (ii) reduced pressure drops as a result of gradually changing from circular to lobe cross-sections and vice versa. In addition, the controllability of intermediate area development and twisted angle changing by modifying the exponential variables (*n*) and (*t*) at different values are considered the most influential factors (see Figure 2). In order to sketch the transition parts, lobe swirl radius (r_{lobe}), lobe swirl core (R_{cs}) and smooth pipe radius (*R*), using the Eq. (4) and (5), are taken into consideration. Eq. (6) and (7) are used to predict, respectively, the beta transition under the desired multiplier values of (*n*) and twisting growth at different variable helix (*t*).

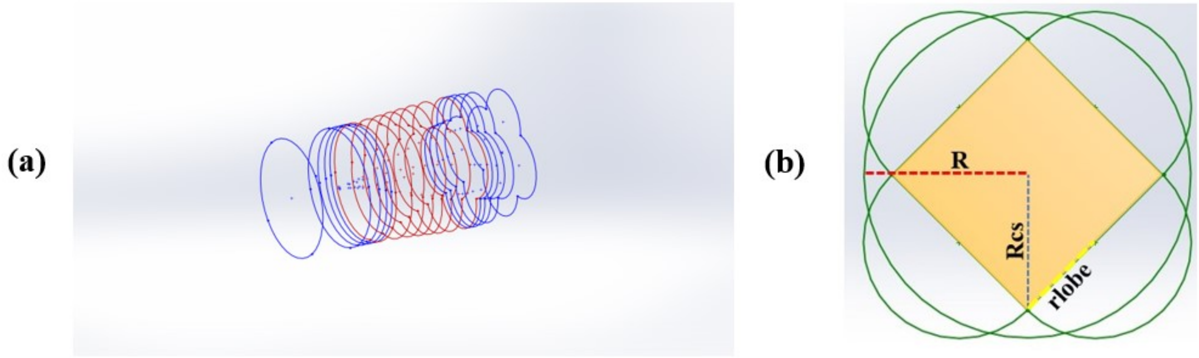

Fig. 2. (a) Transition part under development; (b) Main radii

$$rlobe = \sqrt{\frac{2\pi \times \tan\tan\left(\frac{360}{2n}\right) \times R^2}{2n + \pi n + \tan\left(\frac{360}{2n}\right)}} \tag{4}$$

$$R_{cs} = \frac{rlobe}{\sin\left(\frac{360}{2n}\right)} \tag{5}$$

$$\beta = \left[\frac{\frac{LA_i}{\pi R^2 - LA}}{\frac{LA_{Fd}}{\pi R^2 - LA^{Fd}}}\right]^n \tag{6}$$

$$Twist = \left(\frac{X}{L}\right)^t \times twisted\ \mathrm{angle} \tag{7}$$

Figure 3 describes the effect of the beta transition multiplier (*n*) under different values on the intermediate area development. It can be seen that the intermediate area pattern develops faster and close to the beginning of the transition part region when (*n < 1*) and development faster at the end of the transition suction region when it gets close to one. Regarding variable helix parameter impact, the entrance and the exit regions of the transition parts at (*t < 1*) and (*t > 1*) respectively growth faster, but in the case of (*t = 1*), the helix pattern growth constant (geodesic) concerning the length (see Figure 3b). Among all values of exponential variables influential studied, Beta transition parts at (*n = 0.5*) together with (*t =1*), presented the effective factors [7, 32].

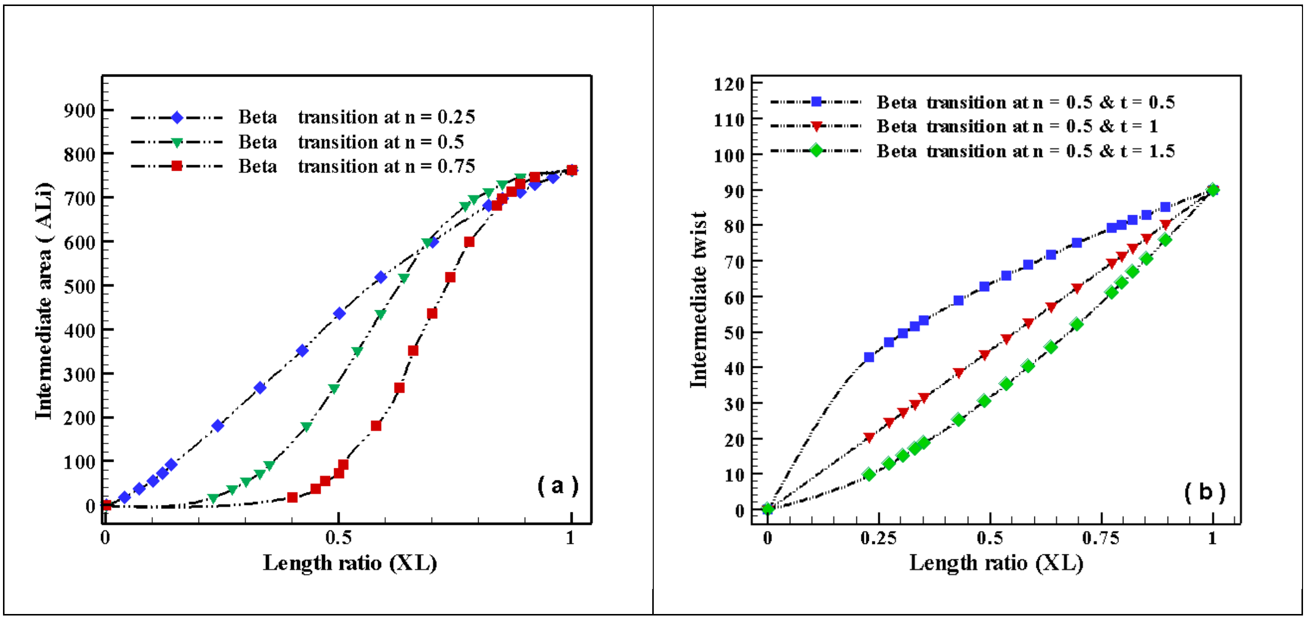

Fig. 3. The effect of (a) transition multiplier (*n*) on the intermediate area; and (b) variable helix (*t*) on the intermediate twisting development

2. Numerical approach

The geometrical cross-section of the lobe swirl adopted in the current study has numerous sharp angles along the pipe, making its structure extremely complex. Therefore, the cross-section was meshed by hexahedral cells using the Integrated Computer Engineering and Manufacturing software (ICEM CFD) Ansys, 2020 R2. The advantages of ICEM CFD can be attributed to its ability to deal with a complex model without subdividing the topology, according to the top-down blocking feature of ICEM CFD and the O-grid approach. The solution can run quicker and reduce numerical diffusion by combining structured mesh with hexahedral cells. The governing equation (Navier-Stokes Equation) is applied to estimate the swirl flow generated by a lobed swirl. The flow regime is turbulent, single-phase, and incompressible. The applicable shear-stress transport (*SST*) *k-ω* model was used to model the turbulence swirling flow.

2.1 Code Validation

Figure 4 clarifies the Nusselt number's comparison with Jafari *et al.*, [33] experimental work and the well-known Dittus-Boelter theoretical correlation Eq. (8) to verify the solver's ability to predict the current numerical result. It was found that the current numerical work to be reliable in predicting with a relative deviation, respectively 2.47% and 7.6% with Jafari *et al.*, [33] and Dittus-Boelter correlation.

$$\boldsymbol{Nu_{Dh} = 0.023Re_{Dh}^{4/5}P_r^{0.4} \quad where\ P_r^{0.4}\ is\ for\ heating} \qquad (8)$$

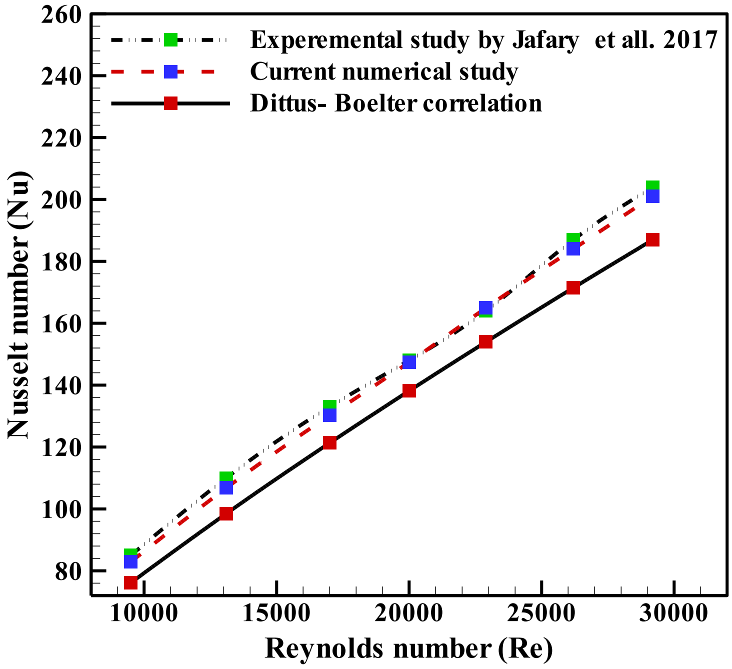

Fig. 4. Numerical study code validation

3. Thermophysical Properties of Nanofluids

Synthesis of nanofluid by the additive quantity of nanoparticles into a base fluid increases convective heat transfer coefficient, thermal diffusivity, viscosity and thermal conductivity. It is known that the volume concentration, temperature, types of the base fluid and nanoparticles highly affect the characteristics of nanofluids. The properties of oxide-nanoparticle adopted in the current study of SiO_2/water, Al_2O_3/water and CuO/water under 298 K and a volume fraction of 5% are depicted in Table 1.

Table 1
Nanofluid's thermophysical properties at 293 k and 5% vol

Thermophysical properties	SiO_2/water	Al_2O_3/water	CuO/water
Density, ρ (kg/m³)	1057.15	1127.15	1272.15
Dynamic viscosity, μ (kg/m.s)	0.00176	0.00176	0.00176
Thermal conductivity k (W/m.K)	0.62904	0.72935	0.72858
Specific heat, c_p (J/kg.K)	3819.998	3636.322	3250.443

4. Results Discussions

4.1 Effect of Different Nanoparticles on Nusselt Number and Friction Factor

The main objective of the current study is to examine the impact of lobe swirl device combined with several types of nanoparticle volume concentration on thermal performance enhancement. Therefore, the behaviour of lobed swirl with vireos type of SiO_2/water, Al_2O_3/water and CuO/water nanoparticles under different volume concentrations on Nusselt number (*Nu)* and friction factor (*f)* were investigated in detail. As shown in Figure 5, the maximum Nusselt number associated with an increase in friction factor is found for SiO_2/water nanofluid with a 5 % volume concentration and high Reynolds number compared to other nanofluids. Also, the same trends have been observed for Al_2O_3/water and CuO/water nanofluids. It can explain by the feature of silicon oxide, which is represented in low density and high velocity compared to all nanoparticles investigated. The Figure also signifies that the increase of the Reynolds number increased the heat transfer with a slight augmentation in friction factor. It can be attributed to the effect of additive nanoparticles volume concentration, the vigorous-intensity created between the core and the wall by the lobe swirl geometrical shape, and the turbulent flow regime in which the fluid undergoes irregular fluctuations.

4.2 The Effect on Thermal Performance

The Nusselt number ratio (heat transfer enhancement) is the heat transfer after enhancement (Nu) to the heat transfer obtained by plane tube (Nu_p). The evaluation of the Nusselt number ratio (Nu/Nu_p) and friction factor (f/f_p) with a variation of turbulent flow can be seen in Figures 6(a) and 6(b), respectively. The importance of these parameters is represented in their ability to demonstrate the system's capability in terms of thermal performance enhancement. According to Fig. 6 (a) and (b), lobe swirl generators improve the heat transfer rate factor in the range between 1.35–1.87 when the attained values of f/f_p are from 1.23 and 1.67. The outcome highlighted the impact of a high-volume concentration and a low Reynolds number on lobed swirl characteristics.

The impact of the lobed swirl generator under several nanoparticle volume concentrations and turbulent flow regime on performance evaluation criteria (PEC) is clarified in Fig. 6(c). It can attribute to the effect of nanoparticle additive, lobe swirl curvature and high turbulent intensity on pressure drop augmentation. It is confirmed that the low Reynolds number combined with a high-volume concentration caused a considerably promoting thermal performance at the value of 1.67 with SiO_2/water under a volume fraction of 5%. On the other hand, the result showed a slight increase in the Nusselt number ratio and thermal performance with a high Reynolds number when applying water as a working fluid.

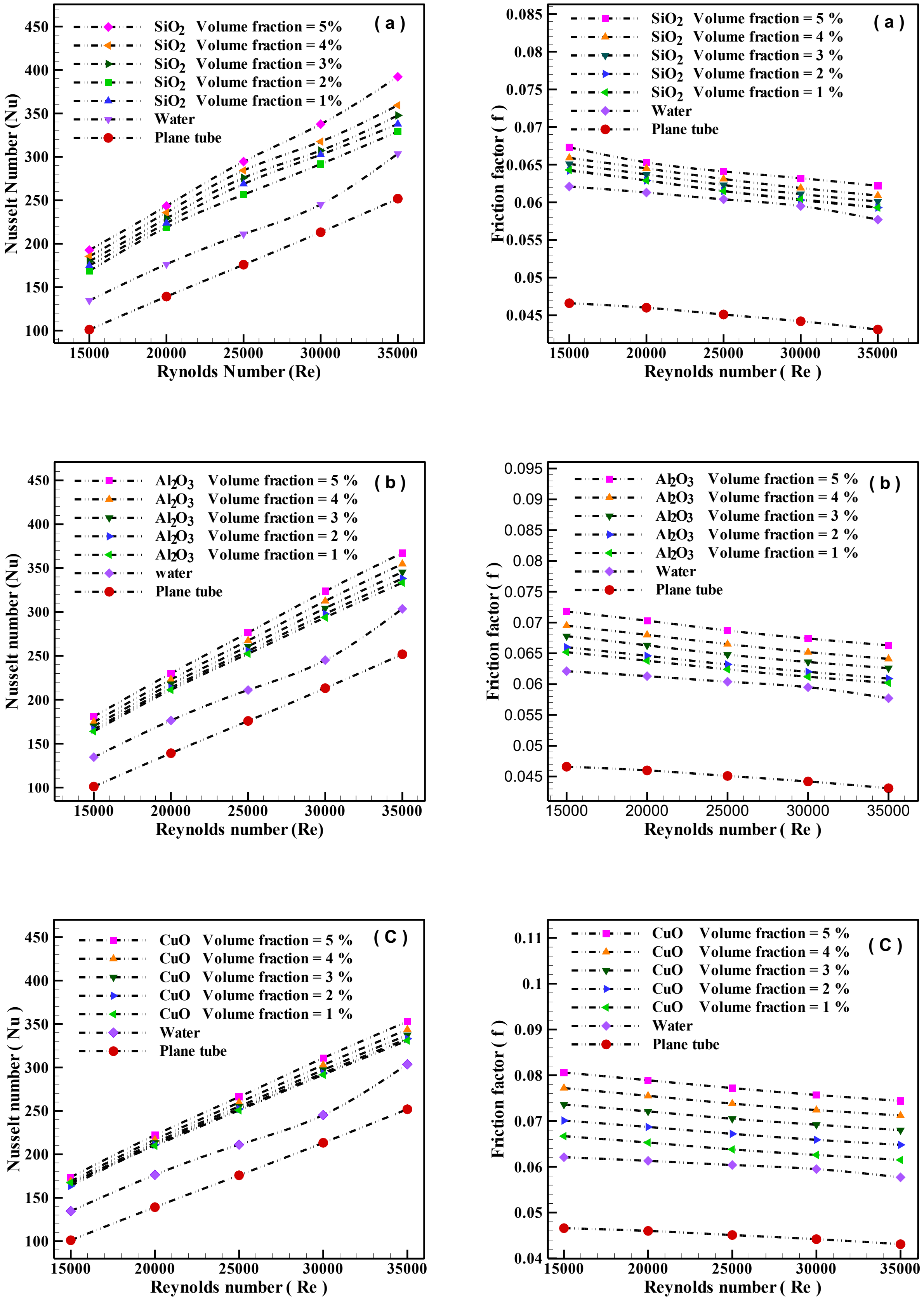

Fig. 5. Variation of Nusselt number and friction factor versus Reynolds number for different volume fractions and nanoparticles types of (a) SiO_2/water, (b) Al_2O_3/water, and (c) CuO/water

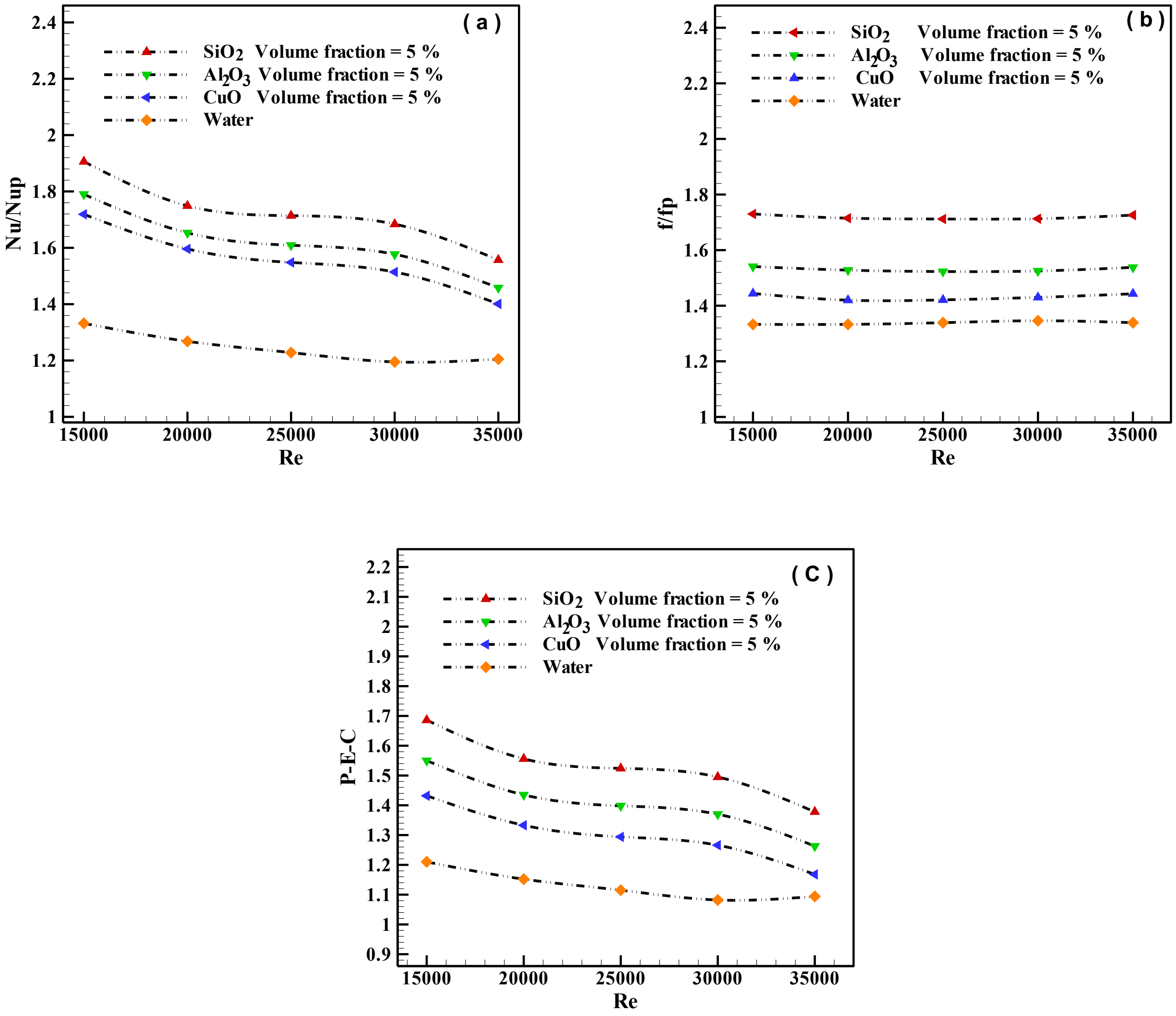

Fig. 6. the effect of various types of nanoparticles volume concentration and Reynolds number on (a) Nusselt number ratio, (b) Friction factor ratio, (c) Thermal performance

5. Conclusion

In the present work, the effect of a four-lobed swirl generated under several oxide nanoparticles of SiO_2/water, Al_2O_3/water and CuO/water at different volume concentrations (1% to 5%) on thermal performance was numerically investigated. The geometry adopted can be classified into two practical parts: A Lobed swirl device has a length of 200 mm, four lobes in structure, 360^0 in angle, and a 50 mm equivalent diameter. The second essential section is the transition parts, which were created at 100 mm in length, the exponential factor of beta transition set at transition multiplier (*n = 0.5 mm*), variable helix (*t = 1 mm*), and angle rotated at 90^0. All the modelling generated under the range of Reynolds numbers from 15,000 to 35,000. After conducting the simulation, the following results have been obtained:

i. Using SiO_2/water at 5% volume concentration together with *Re = 15,000* created the highest thermal performance, with a significant factor of 1.67 compared with all nanofluids investigated.
ii. The result demonstrated an enhancement in heat transfer value ranging from 1.35 to 1.87 and an increased pressure drop value from 1.23 to 1.67.
iii. The results proved the ability of lobed swirl under varied parameters to provide centrifugal force, which plays a vital role in heat transfer improvements.
iv. According to the outcome, substantial intensities generated between the core and the wall by a high turbulent flow regime and lobe swirl curvature increased pressure drop. Therefore, the use of nanofluids at high volume concentration with low Reynolds number is highly required.

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