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Nanofluids in Zigzag Elliptical Tube Heat Exchanger: A Design Perspective

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Abstract: Nanofluids contain nanometer-sized particles in suspension to enhance heat transfer by increasing the thermal conductivity. This paper provides an overview of particle size and volume fraction of nanofluids, and their roles in enhancing the heat transfer. Often, the transfer of heat is enhanced by dispersed particles with small diameter and high concentration despite some debate about the governing effects. The design of elliptical cross-section and zigzag tube also sheds insight into augmenting heat transfer for future research directions and applications.

Keywords: Elliptical cross-section, heat transfer coefficient, nanofluid, nanoparticle, zigzag tube.

1. Introduction

Heat is essentially migrated by temperature gradient, from hot to cold region. This principle has been applied in various chemical and industrial processes to exchange heat between two working fluids [1]. Heat transfer enhancement can be categorized as passive and active techniques. Active techniques depend on external source of power to induce the heat transfer process, whereas passive techniques rely on equipment design. Both techniques are aimed to reduce energy requirement to yield more efficient heat transfer process [2].

Water, gasoline, and ethylene glycol are some of the commonly used working fluids in heat exchangers, but their thermal conductivities are low. Consequently, the heat transfer is inefficient. To overcome this drawback, suspended nano-sized particles can be introduced in the base fluids to improve the thermal conductivity [3]. A suspension of CuO in ethylene glycol elevates the thermal conductivity by 20% [4]. Similarly, the conductivity is intensified when CuO nanoparticles are dispersed in water [5]. Recently, the addition of ZrO_2, TiO_2, and Al_2O_3 nanomaterials as compared to plain water gives rise to the outlet temperature of cold nanofluids by 7.7%, 11.3% and 17.4%, respectively due to the elevation of heat capacities [6]. Zinc oxide, silicon oxide, and other metal oxides are promising sources of nanoparticles to form nanofluids with varying results to improve the heat transfer in heat exchangers [7].

The fluid flow is generally categorized as laminar and turbulent. The flow regime is important in the design and operation of any fluid system. Several studies used the flow regimes to improve the heat transfer of nanofluids [8], [9]. A significant heat transfer performance at laminar regime is demonstrated by Al_2O_3 nanofluid in a copper tube [10]. Conversely, Kumar [11] reported the improvement of heat transfer by Al_2O_3 nanofluid at low volume fraction under turbulent flow inside a pipe of constant wall temperature. In a related work, Danook et al. [12] evaluated the heat transfer of nanofluid at Reynolds number between 1×10^4 and 1×10^5, as a specific transition from laminar to turbulent flow regime.

The volume fraction of particles (volumetric concentration) can also affect the thermal conductivity of a nanofluid. The manipulation of volumetric concentration is imperative to bring a positive response towards heat transfer performance at constant temperature for a fixed diameter of nanoparticles [13]. Fule et al. [14] used a 0.1 vol.% of CuO that brings a better heat transfer coefficient by 37.3% as compared to the base fluid, whereas the magnitude is even higher by 77.7% at 0.5 vol.%. The increase of flow rate of CuO nanofluid exhibits a significant increase in heat transfer coefficient, suggesting that the amount of CuO in the base fluid enhances the heat transfer coefficient. The influencing factors of particle diameter and volume fraction in heat transfer are noticeable. For instance, the decrease of particle size and the increase of volume fraction improve the heat transfer coefficient of the Al_2O_3 nanofluid in a helical coil at constant temperature [15].

The design of heat exchanger is generally composed of smooth circular tube. The thermal and hydrodynamic properties in circular tube have been investigated for many years, owing to its significance and relevance in industrial processes, in spite of low efficiency [16]. The poor heat exchanger efficiency can be partly resolved through design by means of internal fins [17], external fins [18], corrugated tube [19], square pipe [20] and hexagonal duct [21]. Theoretical studies about the elliptical ducts showed that flattening the duct by maintaining the constant cross-sectional area increases considerably the heat transfer coefficient [22], [23].

The old design of heat exchanger is normally confined to straight tube configuration. Now, it begins to evolve, aimed at improving the heat transfer coefficient. Parlak [24] studied heat transfer coefficient of water in three types of microchannels, i.e., straight, wavy, and zigzag, for which Ansys calculations have been used to optimize the geometry. The zigzag tube is the optimum geometry with high heat transfer coefficient compared to straight channel. Recently, Kishan et al. [2] also reported an improvement in heat transfer by zigzag tube, outweighs that of straight tube and U-shaped tube.

2. Nanofluid

A nanofluid is a mixture of nanoparticles (metal oxides) and base fluid (e.g., water and ethylene glycol). Often, the nanofluid is more viscous than base fluid. Nonetheless, the pumping power needs for the viscous fluid are compensated by the increase of thermal conductivity and heat transfer coefficient [25-27]. Generally, metal oxides increase the intensity of the heat transfer in nanofluids [28]. The thermal transfer of aluminum oxide nanofluids increases by 20% to 41% depending on base fluids [29]. Copper oxide, zinc oxide, silicon oxide and titanium oxide are examples of metal oxides that demonstrate similar influence on the thermal conductivity. For any volume fractions, zinc/water nanofluid displays an improved heat transfer compared to the base fluid. As compared to the base fluid, a 46% increase of heat transfer was recorded [30]. Similarly, a small fraction of SiO_2/water nanofluid elevates the heat transfer coefficient by 50% [31]. Table 1 summarizes the heat transfer improvement using zinc oxide and silicone oxide nanofluids.

Table 1: Heat transfer improvement using zinc oxide and silicone oxide nanofluids

Nanofluid	Finding	Reference
Al_2O_3/water, ZnO/water	Al_2O_3 performs better than ZnO as nanofluid for heat transfer.	Rasheed et al. [32]
ZnO@TiO_2/water	Maximum improvement at 0.1 wt.% concentration, 47% higher than water alone. ZnO and TiO_2 mixture elevates the overall heat transfer coefficient.	Ahmed et al. [33]
ZnO/water	The heat transfer coefficient is higher at 0.44 vol.%.	Safir et al. [34]
TiO_2@ZnO/water	Heat transfer rate increases at 2.0 vol.% of TiO_2 and 1.5 vol.% of TiO_2@ZnO hybrid.	Lahari et al. [35]
Al_2O_3/water, SiO_2/water, ZnO/water	Higher overall heat transfer coefficient by ZnO > Al_2O_3 > SiO_2.	Shahrul et al. [36]
ZnO/water	Heat transfer is enhanced by 46% compared to water alone at 0.2 vol.%.	Ali et al. [37]

Nanofluid	Finding	Reference
Al_2O_3/water, CuO/water, SiO_2/water	SiO_2/water exhibits only a slight increase of thermal performance by 2.5% at 4 vol.% compared to water.	Noorbakhsh et al. [38]
SiO_2/water	Low concentration of SiO_2 increases the heat transfer rate by 50% compared to water.	Hussein et al. [31]
TiO_2/water, SiO_2 /water	SiO_2 nanofluid increases the heat transfer rate by 18% compared to water.	Hussein et al. [31]
CuO, Al_2O_3, SiO_2 in water and ethylene glycol	Small particle diameter increases the viscosity. Nusselt number increased by 35% for 6 vol.% CuO.	Namburu et al. [39]

2.1 Particle Size of the Nanofluid

The size of nanoparticles can affect the thermal conductivity and viscosity of the nanofluid. There is a long debate about the relationship between nanoparticle size and viscosity. For instance, Namburu et al. [39] reported that nanoparticles with small diameter render high viscosity of nanofluid and high Nusselt number, and the heat transfer coefficients of Al_2O_3 and SiO_2 are better than that of CuO. Rudyak et al. [40] used Brookfield viscometer to quantify the effect of particle diameter (10 to 150 nm) in SiO_2/water, Al_2O_3/water, and TiO_2/water nanofluids at fixed volume fraction of 2%. It was found that the viscosity decreases with increasing particle diameter. Also, Nguyen et al. [41] showed that the viscosity of some nanofluids remain unchanged for concentrations less than 4 vol.%. However, as the volume concentration exceeds this limit, the particle size seems to have considerable effect on fluid viscosity. On the contrary, Lu and Fan [42] reported an increase in viscosity of the aluminum oxide/ethylene glycol nanofluid as the particle size decreases. Similarly, copper oxide, aluminum oxide and silicon oxide show the same pattern of increasing viscosity for smaller particle size in water as base fluid [43].

The particle diameter plays a considerable role in improving the conductivity of the nanofluid. Eastman et al. [44] showed that the thermal conductivity is more responsive to the particle size than to the volume fraction. Chon et al. [45] reported a decreasing trend of conductivity of Al_2O_3/water nanofluid with increasing particle diameter from 11 to 150 nm. This is due to Brownian motion that has a great influence on heat transfer; the smaller the particle, the faster the Brownian movement, thus the higher the conductivity that is responsible for the increase in heat transfer. Karthikeyan et al. [46] recognized the increase of thermal conductivity of copper oxide at 1 vol.% due to its smaller particle size of 8 nm. On the other hand, Beck et al. [47] showed the opposite perspective, whereby the conductivity decreases with decreasing particle size of less than 50 nm due to the increase in dispersion of smaller particle phonon (photon scattering at the solid-liquid interface). The thermal conductivity of aluminum oxide nanofluid was measured for different particle diameters of 8 to 282 nm using hot wire technique. The thermal conductivities of nanofluids made up of SiO_2/water, Al_2O_3/water, and TiO_2/water for particle size ranging from 10 to 150 nm reveal that as the size increased, the thermal conductivity also increased [40].

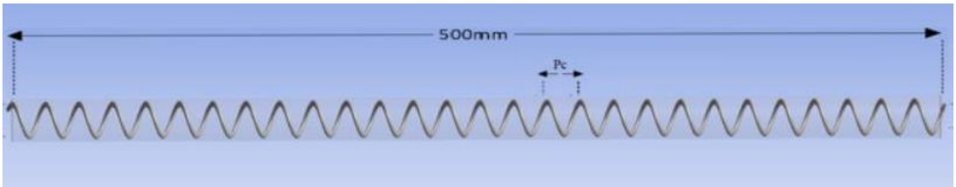
2.2 Volume Concentration of the Nanofluid

Volume concentration of the metal oxide in nanofluid can also affect the thermal conductivity and viscosity. Usually, the higher the volume concentration, the greater the conductivity. The conductivity of nanodiamond/water was studied as a function of concentration by KD_2-Pro equipment using transient line heat source method [48]. The thermal conductivity increased nonlinearly as the concentration increased from 0.8 to 3%. Similarly, Sundar et al. [49] reported the same pattern of increasing thermal conductivity with concentration of Fe_3O_4/water nanofluid that is ranging from 0.2 to 2%. As the concentration of metal oxide increases, the Brownian motion of the nanoparticles induces micro convection surrounding the liquid molecules, so elevating the conductivity. The thermal conductivities of Al_2O_3, CuO and TiO_2 nanofluids also improved as the volume fraction increased because of particle collision and Brownian motion [50], [51].

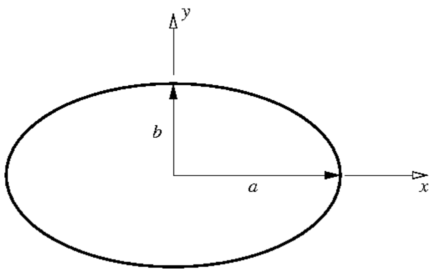
There is also a direct correlation between concentration and viscosity, whereby the higher the concentration of nanoparticles, the higher the viscosity. The increase in concentration of Al_2O_3/water and CuO/water nanofluids results in the increase of viscosity. For example, at particle diameter of 47 nm, the viscosity of Al_2O_3 nanofluid surges from 1.12 to 1.6 cP, and 3 to 5.2 cP at volume fractions of 1 to 4%, and 9 to 12%, respectively [41].

3. Elliptical Cross-Section Tube Heat Exchanger

The use of elliptical tubes has been an excellent approach to improve the hydraulic and thermal performance of the heat exchanger. Alias et al. [52] studied the thermal performance of Al_2O_3/water and ZnO/water nanofluids in a helical microtube coil with circular, oval, and elliptical tube cross-sections, wherein Al_2O_3 exhibits a better heat transfer than ZnO by circular cross-section. In a related work, the heat transfer was numerically explored for SiO_2 and ZnO nanofluids in elliptical cross-section of helical copper tube as shown in *Fig. 1*. For turbulent flow of Reynolds number 4×10^3 to 2×10^4, the Nusselt number rises as the volume fraction increases. At pitch diameter of 18 mm, ZnO at volume fraction of 2% exhibits a higher heat transfer coefficient.



a.)



b.)

Figure 1: Helical tube (a) with elliptical cross-section (b) [52]

Ahmadi et al. [53] numerically evaluated the heat transfer for CuO at volume fractions of 1 to 4% in circular pipe fitted with elliptical-cut and square-cut twisted tapes, in which the elliptical-cut with 4 vol.% CuO depicts an increase in thermal performance by 21% compared to the water alone, and 26% compared to square-cut with the same fraction of nanofluid. Qi et al. [54] studied the effect of TiO_2/water in elliptical tubes with a built-in turbulator that shows a 33.8% improvement in heat transfer using 0.5 wt.% nanofluid. An increase of 44.3% in heat transfer rate was recorded using 0.2 vol.% of Al_2O_3/water in elliptical cross-section tube [55]. Likewise, Al_2O_3/methanol nanofluid demonstrates a substantial increase of 50 to 70% in the overall heat transfer coefficient via numerical simulation of laminar flow in an elliptical duct [56]. Another form of the tube design is elliptical tube inside a circular tube. The elliptical annulus tube may improve the friction factor and heat transmission by 6 and 19%, respectively when compared to circular annulus [12], [57]. The Nusselt number and friction factor often increased with decreasing particle diameter but increased with volume concentration. Table 2 summarizes the findings of elliptical cross-section tube heat exchangers.

Table 2: Elliptical cross-section tube heat exchangers

Cross-section	Finding	Reference
Helical microtube coil (circle, oval, elliptical)	Al_2O_3 is better than ZnO. Best performance at volume concentration of 2%.	Rasheed et al. [32]
Copper elliptical tube, helical micro pipe	ZnO at 2 vol.% endows a high Nusselt number at pitch diameter of 18 mm.	Alias et al. [52]
Circular pipe fitted with elliptical-cut twisted tape	A 6.6% improvement compared to square-cut twisted tape.	Ahmadi et al. [53]
Elliptical tubes with a built-in turbulator	Thermal performance increased by 33.8% compared to water.	Qi et al. [54]
Elliptical-shaped cross-section	Heat transfer rate increased by 44.3% compared to water.	Chaurasia et al. [55]
Elliptical duct	Heat transfer coefficient improved by 25%. Overall heat transfer coefficient increased by 50 to 70%.	Ragueb et al. [56]
Elliptical tube inside a circular tube	Elliptical tube enhances the heat transfer and friction factor by 19% and 6% compared to circular tube.	Danook et al. [12]
Elliptical tube	The elliptical tube enhances the heat transfer and friction factor by 9% and 6% compared to a circular tube.	Hussein et al. [57]

4. Zigzag Tube Design of the Heat Exchanger

Zigzag tube design of the heat exchanger, as illustrated in *Fig. 2* has become a subject of considerable interest in improving the heat transfer efficiency. Zheng et al. [58] reported an increase in heat transfer using zigzag channel with square cross-section. The zigzag geometry renders chaotic advection that brings about an increase in heat transfer rate with increasing Reynolds number [59]. The use of the zigzag channel is not limited only to normal-sized tubes. Ma et al. [60] studied the heat transfer using zigzag microchannel. It successfully reduces the growth of surface temperature and flow resistance along the direction of flow. Parlak et al. [24] numerically assessed straight, wavy, and zigzag microchannels (*Fig. 3*), wherein the Nusselt number of the wavy microchannel is 10% higher than that of the zigzag microchannel, and 40% higher than that of the straight one. Similarly, Shi et al. [61] reported an increase in the heat transfer coefficient using a square cross-section of a 2 mm wide zigzag millimetric channel with 90° bends, with a curvature radius of 1.5 mm as opposed to a straight channel. The zigzag channel model can decrease the temperature gradient on the surface of the pipe for a better heat transfer compared to a straight channel [62]. In addition, finned zigzag tube demonstrates an increase of thermal performance by 59% in laminar flow regime compared to a finned straight tube [63]. Also, Nuntadusit et al. [64] showed the optimum performance of rectangular zigzag-cut baffle against the rectangular cross-section with no cut and triangle zigzag-cut baffles at Reynolds number of 2×10^4. The upstream and downstream sides of the baffle promote the efficient transfer of heat because of flow acceleration and low friction factor. *Fig. 4* illustrates the geometry of baffles.

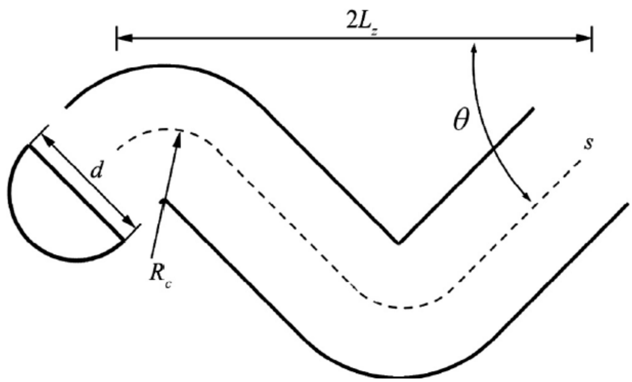


Figure 2: Schematic representation of zigzag unit with semi-circular cross-section; the dashed line represents the axial path of the passage [59]

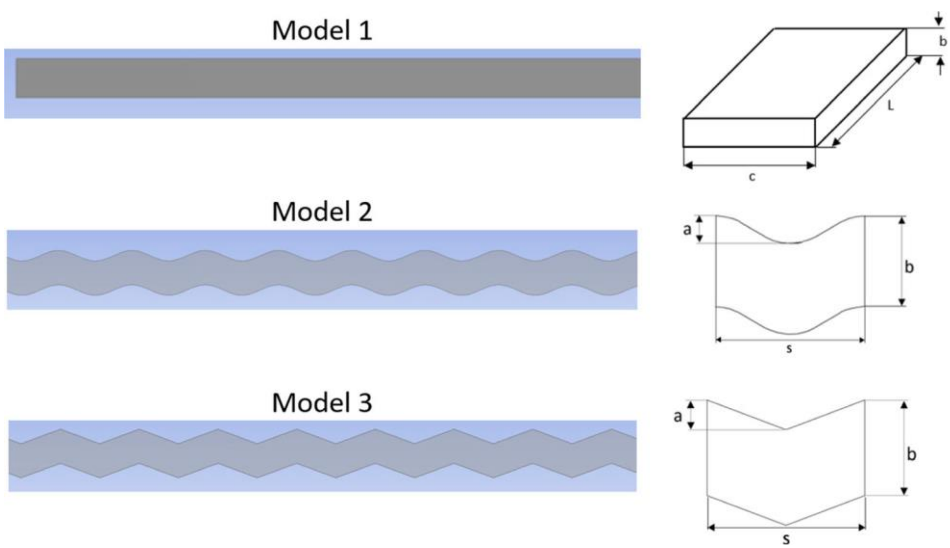


Figure 3: Straight (model 1), wavy (model 2) and zigzag (model 3) microchannels [24]

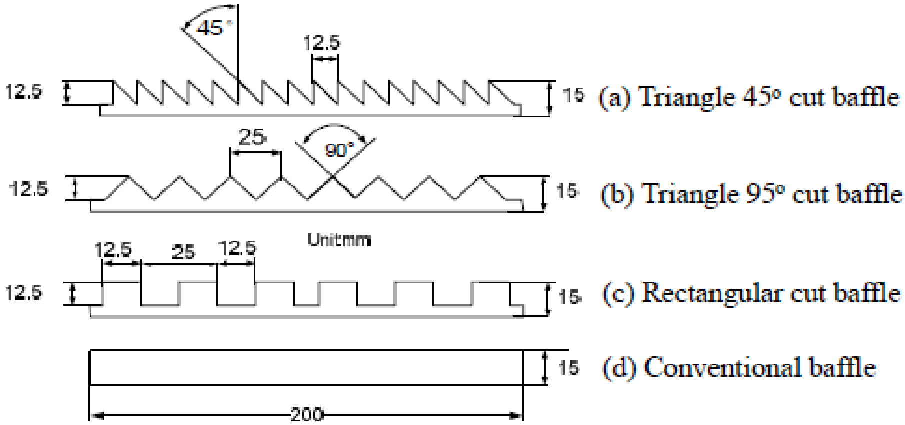


Figure 4: Geometry of baffles [64]

The use of nanofluids in zigzag channel has been reported in literature. Toghraie et al. [65] reported the heat transfer of CuO/water nanofluid in sinusoidal and zigzag-shaped microchannels, in which the Nusselt number increased by decreasing the microchannel wavelengths. Ajeel et al. [66], numerically investigated the effect of ZnO, Al_2O_3, CuO, and SiO_2 nanofluids on the heat transfer in trapezoidal-corrugated and zigzag channels. At Reynolds number of 1×10^4 to 3×10^4, the trapezoidal-corrugated channel exhibits a significant positive impact on the thermal performance and SiO_2/water shows a greater improvement in heat transfer. Table 3 summarizes the potential of zigzag tube design of heat exchangers.

Table 3: Zigzag tube design of heat exchangers

Pipe design	Finding	Reference
Zigzag channel with square cross-section	Heat transfer increases with Reynolds number, $50 < Re < 400$.	Zheng et al. [58]
Zigzag channel with semi-circular cross-section	Chaotic flow advection at Re > 200 for zigzag unit geometrical parameters of R_c/d = 0.51, L_z/d = 1.75 and h = 45 mm. Heat transfer rate increases with increasing Reynolds number.	Zheng et al. [59]
Finned zigzag tube	Heat transfer increased by 59% compared to finned straight tube.	Karmo et al. [63]
Periodic zigzag channel with semi-circular cross-section	Significant increase in heat transfer with increasing Reynolds number in transient regime.	Zheng et al. [67]
Zigzag microchannel	Zigzag channel (a = 0.04 and c = 0.1) prevents the rise of heat surface	Ma et al. [60]

Pipe design	Finding	Reference
	temperature along the flow direction and reduces the flow resistance compared to rectangle channel.	
Zigzag-cut baffle, rectangular cross-section with no cut, rectangular zigzag-cut baffle, and triangle zigzag-cut baffle	The baffle with rectangular zigzag-cut gives the best thermal performance due to heat transfer augmentation in the upstream and downstream sides of the baffle.	Nuntadusit et al. [64]
Zigzag channel	The zigzag channel reduces maximum surface temperature, surface temperature difference and temperature uniformity index by 5%, 23% and 8%, respectively compared to straight channel.	Afshari et al. [62]
Sinusoidal microchannel, zigzag microchannel	Zigzag is better than sinusoidal. Nusselt number increased with increasing volume fraction of CuO and decreasing microchannel wavelengths.	Toghraie et al. [65]
Straight, wavy, and zigzag microchannels	Wavy geometry exhibits greater Nusselt number; 10% higher than zigzag, and 40% higher than straight channel.	Parlak [24]
Trapezoidal, zigzag	The symmetry of trapezoidal-corrugated channel has a great effect on heat transfer compared to zigzag and straight channels. SiO_2/water is better than other nanofluids.	Ajeel et al. [66]
Zigzag millimetric channel with square cross-section	The ratio of Nusselt number in zigzag channel to that in straight channel is always higher, increases up to 6.4 with Reynolds number.	Shi et al. [61]

5. Conclusion

This paper presents an overview of heat transfer improvement by nanofluids and zigzag tube design. The addition of nanoparticles to the basic fluids improves the heat transfer due to increase in thermal conductivity. Generally, the heat transfer can be elevated via smaller particle size and higher volumetric concentration of the nanofluid. The elliptical cross-section often exhibits a better heat transfer compared to the circular cross-section. Also, the zigzag tube design of heat exchangers leads to a better heat transfer compared to the straight tube.

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