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Applications of Nanofluids and Various Minichannel Configurations for Heat Transfer Improvement: A Review of Numerical Study

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ABSTRACT

Nanofluid technology is regarded as one of the key emerging technologies that is presently attracting great effort with the aim to provide improved thermal fluid for efficient dissipation of high heat flux generating devices. In this paper, some recent advances in using nanofluid as heat transfer enhancement fluid with consideration of effects of variation of minichannel configuration as flow passage and effective parameters used to obtain optimum thermal parameters as well as correlations used to solve those parameters were systematically reviewed based on relevant numerical studies. Most of researchers concluded that adding nanoparticles usually in size of 1 – 100 nm in a base fluid can considerably improve heat transfer rate and consequently enhanced convective heat transfer coefficient (HTC), however, with a penalty on pressure drop, which consequently demands more pumping power of working fluid.

1. Introduction

Heat transfer and flow of fluid are processes that are prevalent in thermal engineering. They occur in many aspect of energy utilisation and management. Rapid technological advances in electronic devices which require miniaturization, and wide-ranging heat transfer hardware in process industries are continuously pushing the boundaries of heat transfer enhancement. Numerical analyses of thermal and hydraulic processes are regarded as vital methods for fundamental and feasible researches, and modifications to fluid and solid domains leads to an effective passive method of heat transfer technique.

Nanofluid is a colloidal suspension of base fluid usually (water, ethylene glycol, oil, polymer solutions, etc) in nano sized particles usually 1-100 nm to form a stable compound. It has been regarded as superior thermal fluid in terms of efficient heat transfer improvement in heat sinks, due to higher thermal conductivity of solid particles compared to the conventional base fluid. Nanofluids

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are usually produced using two methods, namely single step and two step methods. Usually two-step method is applied by many researchers.

In heat transfer enhancement, usually researchers are more concern with factors that affect thermophysical and hydraulic properties of the system. There are recent researches that focused on methods to enhance convective heat transfer coefficient (HTC) thereby reducing heat flux and providing sufficient cooling to thermal devices such as heat exchangers [1-7], electronic semiconductor devices [8, 9], automobile engine [10], Solar energy harvest [11, 12], Fuel cell [13], nuclear reactor [14], etc.

Micro and minichannels were first proposed by Tuckerman and Pearse [15] and differ from the conventional channels in terms of channel hydraulic diameters. They postulated that reduction in channel hydraulic diameter can increase heat transfer coefficient. The minichannel is usually within 200 µm to 3 mm hydraulic diameter based on Kandlikar and Grande classification scheme whom distinguished the channels according to manufacturing limitations and the Knudson number, while the other is Mehendale *et al.,* [16] classification who are more arbitrary in their classification, thus, less followed.

The mechanism that influence thermal and hydrodynamic properties of nanofluids were highlighted by some researchers [17-22] and the common mechanisms observed include: Brownian diffusion/motion that induce migration of nanoparticles, temperature gradient induced particles migration (thermophoresis), solid-like nanolayer formation at the nanoparticles surface, clustering mechanism, and interaction of nanoparticles' surface with base fluid compounds.

Some researchers compiled extensive review of literatures in relation to heat transfer enhancement of nanofluid, such as: investigations done with regards to development of thermal performance of heat sinks, their limitations and unsolved proposed solutions [23], numerical and experimental works on application of Nano-Microencapsulated phase change slurry for heat transfer enhancement [24], scaling effects of Micro/Minichannels, nanofluid physical properties and convective heat transfer, as well as the major current applications of nanofluids in Micro/Minichannels and challenges been faced [25].

In 2016, Vanaki *et al.,* [26] carried out a review with specific concern on several parameters that affect thermal and hydrodynamic characteristics on convective heat transfer of nanofluids involving numerical studies only, yet with no consideration of fluid transport media, i.e micro/minichannel. Since then, a lot of progresses were made in the area especially evolution of new designs of channels with variety of configurations, and it's the view of the authors that recent review of numerical studies of convective heat transfer of nanofluids in minichannel should be conducted to explore the advances made in utilisation of nanofluid using minichannel and recurring drawbacks towards solving high heat flux that hinder efficient performance of thermal systems.

2. Principle Parameters

Since the initial work of Choi [27] on new thermal fluid coined nanofluid, many researches were conducted to exploit the benefits of using nanofluid as thermal fluid for heat transfer enhancement of thermal system with much consideration given to factors that affect its thermal conductivity, such as: nanoparticles material , size and shape, concentration, properties of the base fluid and sometimes additional substances like surfactant and Ph value [28, 29].

2.1 Characterization of Nanofluid

Use of hybrid nanofluid is receiving attention recently. Sinz *et al.,* [30] studied turbulent force convective heat transfer of hybrid nanofluid Ag and Graphene dispersed in water via a circular channel with constant heat flux, the results indicated increase in Nusselt number as the Reynolds number increases. Bahiraei *et al.,* [3] investigated thermal and hydraulic characteristics of Tetra Methyl Ammonium Hydroxide (TMAH) coated Fe3O4 nanoparticles and Gum Arabic (GA) coated Carbon Nanotubes (CNTs) as non-Newtonian hybrid nanofluids in a double pipe heat exchanger. They confirmed adding nanoparticles leads to extra increment in heat transfer rate at lower Reynolds number relative to water, the nanofluid indicated heat transfer enhancement of 53.8% against 28.6% for water at Reynold numbers 500 and 2000 respectively. In another work, Bahiraei and Mazaheri [31] conducted a research on novel hybrid nanofluid compose of graphene nanoplatelets coated with platinum nanoparticles. The study was conducted with a chaotic twisted minichannel and compared with a simple channel. Bends along the channel strengthened the fluid flow and maximum rate was reached at the exit, which lead to minimum wall temperature in the region. They concluded that when the Dean number increases, the nanofluid temperature distribution levels in the chaotic channel. It was found that chaotic channel has better heat transfer and pressure drop performance than the simple channel. Dean no is a dimensionless number; Dean number (Dn) which occurs in the study of flow in curved tubes and channels, its expressed in equation 1.

$$\mathrm{Dn} = \left(\frac{\rho \mathrm{va}}{\mu}\right)\left(\frac{a}{R_c}\right)^{1/2} \tag{1}$$

where: v is the mean velocity, a and Rc are the duct width and the radius of curvature, respectively.

2.2 Thermophysical Properties of Nanofluid

Recently, considerable numerical studies were conducted to predict heat transfer performance of nanofluids with focus on thermal conductivity as vital factor of influence amongst the thermophysical properties. The thermal conductivity of nanofluids containing Ag, Si, Al_2O_3, CuO, TiO_2, and Carbon Nano Tube (CNT), with diverse carrier fluids, such as: water, oil, and ethylene glycol were numerically studied.

Ahmadi *et al.,* [1] studied heat transfer and pressure drop of water based nanofluid inside square channel with three variations using Euler-Lagrange approach and reported having 199.6% enhancement of heat transfer at 5% volume concentration of Al_2O_3-H_2O nanofluid having 25 nm as particle size. Ismail *et al.,* [10] investigated transient heat transfer and flow analysis in multi-pass crossflow minichannel heat exchanger using Al_2O_3-H_2O-Ethylene glycol which was considered as homogenous single-phase fluid. They observed that nanofluid has better convective heat transfer in contrast to the base fluid. Their results further indicated that the nanofluid at 3vol.% reaches quasi-steady condition earlier than that of base fluid. In addition, Zhou [32] used similar nanofluid but with particle size of 28 nm in three different rectangular minichannels and mass fractions of 0.2 %, 0.5 % and 1.0 wt.%, found average enhancement of 26.2% in heat transfer coefficient at 1wt.% for channel having dimension of 0.6 mm x 2 mm.

Silver (Ag) nanoparticle is also one of the promising materials used in nanofluid production with encouraging heat transfer performance. Using Ag-water nanofluid, heat transfer coefficient enhancement of 15.2% was reported by Bahiraei & Heshmatian [33] with volume fraction of 1% at Re of 500, while Bose *et al.,* [34] obtained 45.6% at 0.5% volume fraction of the same nanofluid, though at low Reynolds number. Sohel *et al.,* [35] conducted a comparative study of performances of nanofluid in a circular shaped copper minichannel heat sink having hydraulic diameter of 500 µm. The nanofluid used include Al_2O_3-H_2O, Cu-H_2O and Ag-H_2O, they found significant increase in heat transfer rate by the increase of volume fraction of nanoparticle, and Ag-Water nanofluid exhibited the highest performance amongst the nanofluids studied. This could be attributed to high thermal conductivity of silver solid particle.

Mahian *et al.,* [36] used four different types of nanofluids which include: Cu/water, Al_2O_3/water, TiO_2/water, and SiO_2/water having 25 nm size and at 4% volume concentrations to evaluate the turbulent flow effect on the performance of minichannel-based solar collector. They observed that effective thermal conductivity of Al_2O_3/water nanofluids is higher than that of TiO_2/water nanofluids, but TiO_2/water has a lower entropy generation than Al_2O_3/water. Ghasemi *et al.,* [37] studied the effect of using TiO_2 nanoparticle having mean diameter of 25 nm to form water-based nanofluid with 0.25%, 0.5% and 0.75% volume as a coolant on heat dissipation from electronic components using CFD analysis and experimental work. They found a good accord between the experimental and numerical results and concluded that heat transfer enhancement increases with an increase in Re. and the optimum performance evaluation criterion occurred in Re 490 and 0.75 vol% was around 1.23. thus, TiO_2 could be regarded also as important nanoparticle for nanofluid production.

There are some nanofluids that are applied by few researchers such as in Nikkam *et al.,* [21] investigated the relevance of MoS_2 nanoparticle having 90 nm mean diameter and its concentration on thermophysical properties of MoS_2-ETG nanofluid. They observed thermal conductivity enhancement of 16.4 % at 1 wt%. Bahiraei and Mazaheri [31] uses Graphene-nanoplatelets-platinum (GNP-Pt) with 0, 0.02, 0.06 and 1vol% concentration and Re up to 1658.3.

These results, confirmed that adding nanoparticles to base fluid especially at high volume fractions can significantly improves heat transfer performance of the nanofluid. Other research works that involved application of various nanofluid in minichannel were summarized in Table 1.

3. Numerical Analysis Approaches

3.1 Single-Phase

Few researchers employ single-phase modelling studies for the heat transfer performance factors of the nanofluids containing particles with various shapes. Ismail *et al.,* [10] conducted an analysis of the transient response for the variation of nanofluids volume concentrations by considering Al_2O_3-EG/W nanofluid as a homogenous single-phase fluid. The results show that heat transfer increases with the increase of particle volume concentration, also the nanofluid having higher volume fraction approaches quasi-steady state faster than that of base fluid. Bahiraie *et al.,* [38] studied mixed convection of the CuO–water nanofluid flow in an inclined annulus based on the first two laws of thermodynamics. They used concentration of 0.02% and 0.04% volume fractions, and Reynolds number between 1000 to 1600. They concluded that, increasing the inclination angle from 0° to 75° causes increase in convective heat transfer and decrease of overall entropy generation, and as concentration increases, thermal entropy generation also increases, while frictional entropy generation decreases. In addition, they employed single-phase Boussinesq approximation, and all properties excluding the density were considered as constant. The governing equations used include that of mass, momentum and energy for steady state laminar incompressible fluid. Different relationships were used to evaluate the thermophysical properties of nanofluid as expressed in equations (2) to (5).

Equations (2) is used to evaluate thermal conductivity (k_{nf}) based on the proposed Hamilton-Crosser model, while viscosity of nanofluid (μ_{nf}) was determined using equation (3) that was presented by Brinkman [39].

$$k_{nf} = \frac{k_p + 2k_f - 2(k_f - k_p)\varphi}{k_p + 2k_f + (k_f - k_p)\varphi} k_f \quad (2)$$

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \quad (3)$$

Moreover, they evaluated the density (ρ_{nf}) and specific heat capacity (C_{Pnf}) of base fluid and the nanofluid using equations (4) and (5), respectively.

$$\rho_{nf} = (1-\phi)\rho_f + (1-\phi)\rho_p \quad (4)$$

$$C_{Pnf} = \frac{(1-\phi)\rho_f C_{Pf} + \phi\rho_p C_{Pp}}{\rho_{nf}} \quad (5)$$

where φ is the volume concentration, and subscripts f and p refer to the base fluid and particles, respectively.

3.2 Two-phase Approach

Mostly, researchers solved flow parameters of nanofluid numerically by two-phase models with available models such as: Eulerian, Lagrangian, finite volume, mixture and volume of fluid (VOF), with accurate prediction of the models indicated by some researchers [44-46]. According to Liu *et al.,* [47], deviations of the numerical predictions resulted from the single-phase approach when compared with the experimental data could be due to the disregards of slip mechanisms between nanoparticle and base fluid, hence two-phase model can offer improved views in the nanofluid flow field, since the liquid and solid phases are regarded discretely. Ghasemi *et al.,* [48] studied the effect of CuO-water nanofluid on cooling performance of two dissimilar cross-sectional heat sinks using two-phase and single-phase models for the CFD analysis of the nanofluid flow. It was observed that comparing the numerical results with corresponding experimental data indicated better accuracy of the two-phase model than the single-phase model.

Most of researchers [8, 34, 46, 49-51] used Finite volume method (FVM) to solve governing transport equations with appropriate boundary conditions in two-phase numerical analysis. Ahmadi *et al.,* [1] studied heat transfer and pressure drop of Al_2O_3-water nanofluid inside square channel with three variations using two-phase Euler-Lagrange approach. They used control volume method for discretization, whereas SIMPLE algorithm is used for coupling the velocity and pressure fields, while the upwind scheme of second order is used for estimation of the diffusion and convection terms. They confirmed that heat transfer coefficient is considerably enhanced by the increase in Reynolds number and nanoparticle volume concentration, though they reported that the heat transfer coefficient decreases with increase in nanoparticles diameter. Moreover, addition of nanoparticles to the base fluid results in rise in pressure drop and its more noticeable for higher concentrations.

Hosseinirad *et al.,* [52] used Multiwalled Carbon Nanotube (MWCNT)-water and Al2O3-water nanofluids to observed the effect of thermal and hydraulic performance of these nanofluid on “area modification factor” (AMF) as new parameter for cross-section shape of pin fins. Using two-phase mixture model for the range of Re 300 – 1200 and volume fractions of 0 – 3%, they found that there is significant improvement in thermal performance for the nanofluid in comparison to the base fluid, though with minimal increase in pressure drop. They also used equations (2) – (5) to determine thermophysical properties of the nanofluid mixture, however, with a slight modification to equation (2) as expressed in equation (6) which cater for shape factor index (n). They further proposed new correlations based on analysis of multiple non-linear regression as a function of Re and Pr number, AMF and nanoparticles volume fraction to determine the Nusselt number and friction factor, and reported that 98% of the numerical data are predicted within ±10%, thus, these correlations can be applied for different pin fin minichannels for determination of their thermal and hydraulic performance.

$$K_{nf} = \frac{K_p+(n-1)K_f-(n-1)(K_f-K_p)\phi}{K_p+(n-1)K_f+(K_f-K_p)\phi} K_f \tag{6}$$

where n is the shape factor of nanoparticle which is equal to 3 for the spherical-shaped particles.

Mahian *et al.,* [36] conducted performance evaluation of minichannel solar collector performance using four different nanofluids, comprising Cu-water, Al_2O_3-water, TiO_2-water, and SiO_2-water with a concentration up to 4% and nanoparticle size of 25 nm. They found that Al_2O_3-water and SiO_2/water nanofluids exhibited the highest and lowest heat transfer coefficient, respectively. whereas Cu-H_2O has the lowest entropy generation. nanoparticles addition decreases the entropy generation and its more pronounced at high mass flow rates. They further proposed a model different from equation (6) to compute thermal conductivity based on consideration of aggregation and Brownian motion effect in the nano-particles, it is expressed in equation (7):

$$\frac{K_{nf}}{K_f} = \frac{K_p+2K_f-2\phi(K_f-K_p)}{K_p+2K_f+\phi(K_f-K_p)} + \frac{\phi\rho C_{Pf}}{2K_f}\sqrt{\frac{2K_bT_{ave}}{3\pi d_p\mu_f}} \tag{7}$$

Kumar and Sarkar [9] analysed the performance of minichannel heat sink of different geometries using hybrid nanofluid for heat transfer and pressure drop behaviours. They employed two-phase mixture model and compute viscosity using Batchelor model as expressed in equation (8) which was proposed for nanofluids having large volumetric fraction where hydrodynamic relations and nanoparticle accumulation are vital.

$$\rho_{eff} = (1-\phi)\rho_{bf} + \sum_{np}\phi_{np}\rho_{np} \tag{8}$$

where, bf and np refer to base fluid and nanofluid, respectively. for nanofluid and hybrid nanofluid, np is 1 and 2, respectively. For computation of thermal conductivity, they used equation (9) which differ from equations (2), (6) and (7), thus:

$$\frac{K_{eff}}{K_{bf}} = \frac{\left(\frac{1}{\phi}\right)\sum_{np}\phi_{np}k_{np}+2k_{bf}+2\sum_{np}\phi_{np}k_{np}-2\phi k_{bf}}{\left(\frac{1}{\phi}\right)\sum_{np}\phi_{np}k_{np}+2k_{bf}-\sum_{np}\phi_{np}k_{np}+2\phi k_{bf}} \tag{9}$$

4. Variations of Minichannel Configurations

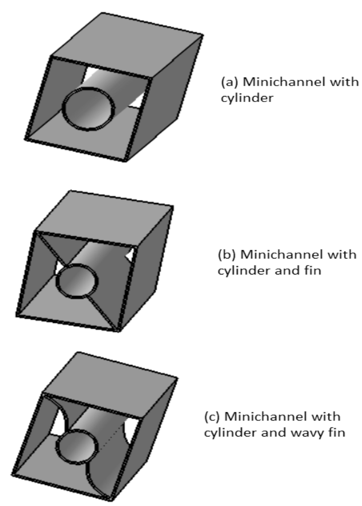
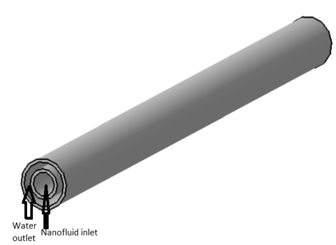
Researchers observed that reduction of hydraulic diameter and higher heat transfer surface area per unit fluid volume of nanoparticles can effectively remove excess heat and improves heat transfer coefficient (HTC), thus, a lot of methods were introduced by changing minichannel geometrical parameters, such as: channel number, aspect ratio, cross-sections and path configurations [25].

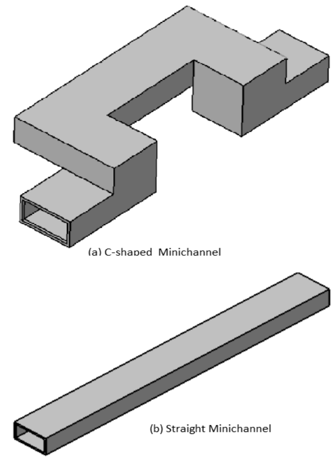
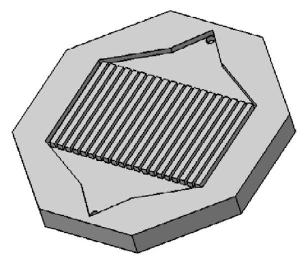
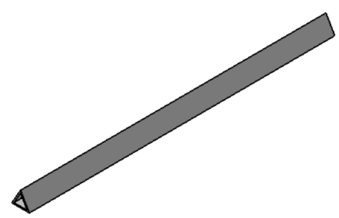
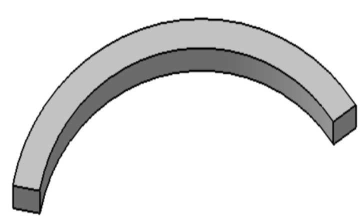
Khoshvagt *et al.,* [53] studied the use of Al_2O_3–H_2O nanofluid in the twisted minichannel (TMC) having various structural parameters for laminar flow and heat transfer characteristics using a 3D numerical scheme for Re within 300 to 1500. Their aim is to investigate the effect of the various cross-section configuration (elliptic, half circular, square, rectangular, and triangular), twist pitch to channel length ratio (P/L) of 0.25, 0.50, and 1.0, nanoparticle concentration and Reynolds number. The results indicated that all the TMCs tested, possessed improved heat transfer than the smooth circular minichannel. Heat transfer coefficient and pressure drop is higher for nanofluid compared to base fluid for all the cases, similarly, at 1vol.% concentration of nanofluid, thermal-hydraulic performance is higher than the base fluid. Finally, they developed correlations for the TMCs by dissimilar cross-section geometries in the range of the studied Reynolds number, as expressed in equation (10).

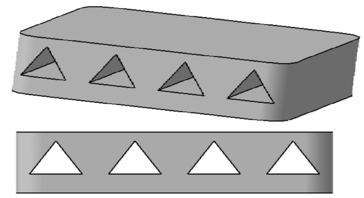
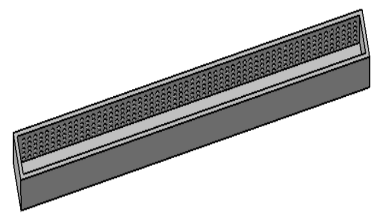
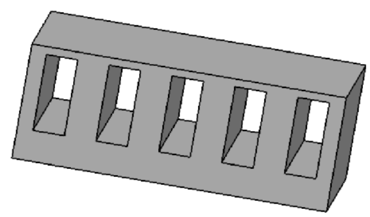
$$Nu \; or \; f = aRe^{b}Pr^{c}(1-\phi)^{d}(\frac{P}{L})^{e} \quad (10)$$

The constants of correlations (i.e. a, b, c, d, and e) were tabulated for different TMCs. They concluded that, using the above correlation, there is good agreement between the numerical results and predicted data, thus, around 98% of the data are correlated within ±5%. Table 2 presented summary and geometrical shapes used by different researchers.

Table 1
Different configurations of minichannel used by researchers with their findings

Researchers	Nanofluid	Model	Findings	Geometrical shape
Ahmadi *et al.,* [1]	Al_2O_3-H_2O	Finite Volume Method	• The passive way employed in the study, leads to higher pressure drops. • Nanoparticles addition increase the thickness of boundary layer and reduction of temperature gradient adjacent to the wall. Thus, thermal conductivity raises with concentration of nanoparticles and these aggregated effects enhances convective HTC at Re 1000 and 5vol.% by 26.47% compared to water. Heat transfer enhancement of 84.4% and 199.6% for 1vol% and 5vol.% respectively, observed for nanofluid at Re=100.	
Bahiraei *et al.,* [3]	Tetra Methyl Ammonium Hydroxide (TMAH) coated Fe_3O_4 and Gum Arabic (GA) coated Carbon Nanotubes (CNTs)	Multilayer Perceptron Neural Network	• The nanofluid indicated heat transfer enhancement of 53.8% against 28.6% for water at Reynold numbers 500 and 2000 respectively.	

Bahiraei *et al.,* [8]	Water-CMC/TiO_2	Finite Volume Method	• When concentration and Reynolds number increased by 4% and 200 respectively, frictional entropy generation also increases, while thermal entropy generation decreases.	
Bahiraei and Heshmatia [33]	Ag-H_2O	Control volume	• temperature reduction of 2.21°C for the nanofluid with concentration of 1% against water at Reynolds number of 500 with a least entropy of 56.2%. • Nanofluid's thermal conductivity improves with increase in concentration and consequently, convective HTC enhances by 15.2% with increasing concentration from 0 to 1% at Re = 1500.	
Bahiraei and Majd [44]	Al_2O_3-H_2O	FCV & ANN	• HTC enhances by 56% in average with increase in Re from 100 to 500 at 5%. In addition, at the same Re and concentration; increasing the Reynolds number from 100 to 300 and from 300 to 500 decreases the thermal entropy generation rate by 29.7% and 18.9%, respectively.	
Liu *et al.,* [47]	Al_2O_3-H_2O		• Forced convective heat transfer in laminar region within curved ducts can be improved by addition of Al2O3 nanoparticles. • Amongst the shapes, nanofluid with nanoplatelets particles shows the largest convective heat transfer improvement and its followed by cylindrical, blade, spherical, and brick shaped nanoparticles. Similar trend observed for pressure drop and convective HTC.	

Ghasemi *et al.,* [49]	Al_2O_3-H_2O	Finite Volume Method	• The thermal resistance value decreases as the volume fraction of nanoparticle increases. • Thermal performance factor of 1.24 was obtained at Re 490 for 1.5 vol%, and at same Re, 1.12 and 1.07 were obtained at 1 vol% and 0.5 vol% respectively	
Kumar *et al.,* [50]	Al_2O_3-H_2O		• Heat transfer and pressure drop were enhanced respectively by 3.73 times and 4.25 times as a function of (Xs/dp) and (Ys/dp) of 1.8.	
Bergman [54]	Al_2O_3 -H_2O	ε-NTU	• minimal enhancement, indicating the restricted usefulness of nanofluids in this application.	

4. Conclusions and Recommendations

This study reviewed and concisely summarized recent numerical researches conducted on application of nanofluids in minichannel for heat transfer enhancement, with the following inferences made from the review:

- Nanofluid due to its higher surface to volume ratio can significantly improves heat transfer than the base fluid, and hybrid nanofluid formed from combination of more than one nanofluids has better enhancement than the individual nanofluids. Thermal conductivity is dependents on size, material and concentration of nanoparticles. Similarly, viscosity also depends on nanoparticles concentration.
- Addition of surfactant can reduce agglomeration of nanoparticles, but it can increase the viscosity of the nanofluid, hence it might affect the heat transfer enhancement.
- Thermophysical properties such as thermal conductivity, viscosity, material density and specific heat capacity can be solved using classical theories, like Einstein, Maxwell, etc., however, these theories failed to describe thermal conductivity and viscosity of nanofluids, because those models considered only macro-sized particles.
- Two-phase models predict better results for convective heat transfer due to consideration of slip mechanism between nanoparticles and base fluid, which is mostly neglected in single-phase approach, though contradictory results reduced the certainty of the results obtained using these approaches.
- Reduction of hydraulic diameter can effectively remove excess heat and improves heat transfer coefficient (HTC), thus, a lot of methods were introduced by changing minichannel geometrical parameters, such as: channel number, aspect ratio, cross-sections and path

configurations; creating secondary flow, cavity, constriction along the passage and roughness of the surface.

Thus, its recommended that, appropriate concentration of the surfactants to be added into nanofluid should be determined to reduce the effect of increase in viscosity. Also, modification of classical theories or new correlations needed to incorporate micro and nano-sized particles for determination of thermophysical properties. Further research needs to be conducted using two-phase models for better and wider prediction of convective heat transfer coefficients.

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Table 1
Summary of principle findings from the numerical works

References	Nano particle properties	Particles size	Concentration	Maximum enhancement	Principle findings
Sidik and Adamu [2]	Ag-Graphene and Cuo-Graphene	No information	0.4-1 vol%	43.96% for CuO-HEG	• Using Reynold numbers of 60e3 and 40e3 and volume fraction of 1%, enhancement of 34.34% and 38.72%, respectively were obtained for Ag/HEG. Similarly, 35.95% and 43.96% were obtained for CuO/HEG at the same Reynolds number and volume fraction respectively.
Bahiraei *et al.,* [40]	Tetra Methyl Ammonium Hydroxide (TMAH) coated Fe_3O_4 nanoparticles and Gum Arabic (GA) coated Carbon Nanotubes (CNTs)	50 nm	0.1 and 0.9 vol% for Fe_3O_4 (magnetite) and CNT 0 and 1.35 vol%.	2800 W/m^{3}K	• Total entropy generation rates for CNT at concentration of 1.35% and Re 1000 and 2000 gives 0.00119W/K, while for Magnetite at 0.9vol.% and Re 1000, it was found to be 0.00124W/K
Ghasemi *et al.,* [41]	TiO_2–water	Not mentioned	0.25vol%, 0.5 vol% and 0.75 vol%	Not mentioned	• Heat transfer enhancement increases with an increase in Re. • the optimum performance evaluation criterion occurred in Re 490 and 0.75vol% was around 1.23.
Bahiraei and Abdi. [42]	TiO_2–H_2O	20, 40, 60 & 80 nm	1,2, 3 & 4%	66%	• Observed non- uniform distribution of concentration of nanofluid due to particle migration, thus, for mean concentration of 4% and particle size of 80nm, the amount of concentration increased from the wall to the pipe centre by about 32% and 66% for Reynolds numbers of1000 and 2000, respectively.
Sohel *et al.,* [43]	Cu, Al_2O_3- H_2O – EG	Not mentioned	2, 4 & 6 vol%	Not mentioned	• Cu-H_2O has 36% highest decreasing entropy generation ratio, which occurred at 6vol%. Cu-H_2O and Cu-EG nanofluid gave the maximum decreasing rates of the fluid friction entropy generation rate are 38% and 35% respectively at 6% volume fraction