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A review on enhancement of heat transfer in microchannel heat exchanger

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Abstract

This review paper is comprehensive study of heat transfer in micro-channel heat exchanger. In this study we have demonstrated research based result and outcomes without any assumptions. In this paper we have discussed slip flow effect on micro-channel, role of Knudsen number in heat transfer, influence of channel geometry, effect of entropy generation, effect of frosting and nano-fluids. With increasing applications of microchannel, it is important to cover all above factors. By considering these points we can increase the performance of microchannel and design an efficient microchannel heat exchanger.

Keywords: Slip flow, Knudsen number, Nano-fluids, Entropy generation, Frosting.

1. Introduction

Tuckerman and Pease [1] first proposed the concept of microchannel heat sinks in 1981. In the comparison with conventional heat exchanger microchannel has a higher heat transfer performance low to moderate pressure drops, smaller geometric size and lower coolant requirement and lower operational cost. Researchers have explained microchannel with different criteria. Some of those are reviewed here. First we discuss microchannel based on the hydraulic diameter of channel. Mehendale et al. [2] described microchannel based on the hydraulic diameter as:

Micro heat exchanger : 1 μm ≤ D_h ≤ 100 μm
Macro heat exchanger : 100 μm ≤ D_h ≤ 1 mm
Compact heat exchanger : 1 mm ≤ D_h ≤ 6 mm
Conventional heat exchanger : D_h ≥ 6 mm

Serizawa et al. [3] explained one criterion for classification of microchannels as follows:

$L \geq D_h$, where L is Laplace constant and D_h channel diameter.

Kandlikar and Grande [4] used the hydraulic diameter for classification of single-phase and two-phase heat exchangers as,

Microchannels : 10 μm ≤ D_h ≤ 200 μm
Minichannels : 200 μm ≤ D_h ≤ 3 mm
Conventional channels: D_h ≥ 6 mm

Some other theories are following.

Palm [5] described the microchannels as heat exchanger, where the classical theories (continuum approach) cannot correctly predict the heat transfer and friction factor. Stefan [6] defined a microscale system but it is not suitable to differentiate micro and minichannel by a specific diameter every time.

The applications of micro system are increasing day by day. Micro fluidic systems have many applications such as micro-flow pumps, heat exchanger, valves, thin film coating, combustion, micro-flow sensors and biomedical and biochemical analysis instruments [7,8]. Microchannel mostly used in micro electro mechanical systems (MEMS). The MEMS is new area of research where non continuum is important. During last decade progress in Micro-Electro-Mechanical Systems (MEMS) technology has increased rapidly.

For microchannel the continuum flow theory in the Navier-Stokes equations is not valid beyond a limit. Experiments conducted by Pfahler et al. [9], Harley et al. [10] and Arkilic et al. [11, 12] on the transport of gases and liquids in silicon micro-machined channels confirm that conventional (continuum) analyses are unable to predict flow rates in micron-sized devices with any degree of accuracy. Under this flow system can no longer be in thermodynamics equilibrium and thus rarefaction effects will be there. Mass flow rates, velocity pattern, wall shear stresses, hydrodynamic region at the channel entrance get affected by non-continuum.

2. Slip flow

Slip phenomenon is related to wall of fluid flow. It is assumed that slip is depend on the shear stress at the wall but many experiment investigates that it also depends on the normal stress. Rao and Rajagopal [13] investigated, If the slip velocity depends on normal stress, the flow field is not fully developed and rectilinear flow is not possible. It also found that the pressure gradient is not linear along the channel in case of slip flow.

Errol B. Arkilc et al. [14] investigated the effect of the slip velocity on the mass flow prediction of Navier-Stokes equations and compared with the measured flow results. It was found that the no-slip solution of Navier-Stokes equations fails to adequately model the momentum transferred from the fluid to the channel wall and calculated the mass flow for given inlet and outlet pressures. However, by including a slip-flow boundary condition at the wall, which is derived from a momentum equation, we can accurately model the mass flow-pressure relationship.

Yu and Ameel [15] studied slip flow heat transfer in micro channel and found that heat transfer increases, decreases and remain unchanged compared to no slip flow condition depending upon two dimension variables that include effect of rarefaction and fluid/wall interaction. Gad-el-Hak [16] investigated that the conventional no slip boundary conditions impose at a solid-fluid interface will begin to break before the linear stress -strain relationship becomes invalid.

Hence it is necessary to investigate the slip and no slip boundary conditions in the micro channel heat exchanger.

3. Knudsen number

Knudsen number is defined as the ratio of mean free path to characteristic dimension i.e. $Kn=\lambda/L$, Where λ mean free path and L is is characteristic dimension. Mean free path is defined as the average distance that a molecule travels between successive collisions.

Flow around the micro-devices is also in the category of “Rarefied gas flows”, but it is difficult to understand because the devices work mainly in the atmospheric condition.

Small Knudsen number, $Kn \leq 0.001$ (Continuum approach valid)

Large values, $Kn \geq 10$ (Free molecular flow)

Slip flow region, $0.001 \leq Kn \leq 0.1$

Knudsen number is very small for continuum flows. However for micro-scale gas flows where the gas mean free path become comparable with the characteristic dimension of the duct, the Knudsen number may be greater than 10^{-3}. Thus Knudsen number is an important dimensionless number as per design concerned of microchannel.

4. Influence of channel geometry

We have reviewed the micro channel of different shape. Some of them are discussed hear with conclusion.

Peng and Peterson [17] performed experimental investigations in rectangular micro channel. They found that that cross-sectional aspect ratio had significant influence on the convective heat transfer and pressure drop in laminar and turbulent flows.

Rachkovskij et al. [18] studied heat transfer in micro-tubes of cross flow micro heat exchanger. They analysed that the changes in heat transfer due to decrease of tube size and relative length.

Brandner et al. [19] analyzed various micro structure cross flow heat exchangers and compared their thermal performances. They found that heat transfer can be enhanced by decreasing the hydraulic diameter of the micro channels.

Foli et al. [20] presented two approaches for determining the optimal design parameters of mirco channels for maximizing heat transfer rate. The first approach is the combination of CFD with analytical solution. It is used to optimize aspect ratio of channels. The second approach is genetic algorithm in combination with CFD. It has been demonstrated that performance of a micro channel depends on the operating conditions.

Ngo et al. [21] investigated the thermal hydraulic characteristics of micro channel heat exchanger with *s*-shaped and zigzag fins. They found that the micro channel with *s*-shaped provided 5-6 times lower pressure drop. They found correlations of Nusselt number and pressure drop factor for micro heat exchanger with s-shaped fins and for a zigzag fins as a function of Reynolds number and Prandtl number.

Mushtaq et al. [22] investigated the counter flow of micro channel heat exchanger with different channel cross-sections such as circular, rectangular, square, trapezoidal and iso-triangular. They found that for the same volume of a heat exchanger, increasing the number of channels lead to increase in both effectiveness and pressure drop. They also found that circular channels give the best performance (Thermal and hydraulic) among other channel shapes.

In the micro channel there is an impact of channel geometry. From above study we can conclude that the effect of size and shape is important for the design of the micro channel heat exchanger.

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5. Nanofluid : As a Coolant

In the heat exchanger a coolant fluid is required, which dissipate heat form the channel. Some common coolants are water, air, engine oil and ethylene glycol. The heat transfer performance of these coolants depends on their conductivity. Hence, to improve heat transfer, it is necessary increase the thermal conductivity of the coolants. This is possible by adding an appropriate amount of solid nanoparticles having high thermal conductivity to abase fluid. This coolant is known as nanofluid. Choi[23] was the first wh proposed nanofluids at the Argonne national Laboratory, USA. He investigated that nanoparticles raise the thermal conductivity of the coolant and improving the heat transfer performance. Several researches have investigated that nanofluids have a higher thermal conductivity than pure base fluids and have great potential for heat transfer enchancement [24--26]. Hence, it becomes desirable to design microchannel containing nanofluids in order to improve the heat transfer performance. Several researches have experimentally examined the use of a nanofluid as a coolant for microchannel.

Xuan and Li [27] explained a theoretical model describing the heat transfer performance of a nanofluid flowing in a tube with solid particle dispersion.

Heris et al.[28] investigated the laminar flow forced-convection heat transfer of nanofluid (Al_2O_3-water) inside a circular microchannel with constant surface temperature. They found that increasing the nanoparticle concentration in the nanofluid improved the heat transfer performance.

Chein and Huang [29] investigated that the heat transfer performance of silicon microchannels improved when nanofluids were used as coolants.

Lee and Mudawar[30] studied the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro sink. They found that the heat transfer enhancement due to the high thermal conductivity of the nanoparticles and required effect on thermal boundary layer.

Wen and Ding[31] demonstrated the laminar flow of nanofluids of Al_2O_3 and de-ionized water through a copper tube. They observed enhancement of connective heat transfer when the nanofluids were used and proposed that nanoparticle migration and the resulting boundary layer disturbance were the main reasons for the enhancement.

Koo and Kleinstreuer [32] proposed that microchannel performance could be improved by using fluids having high Prandtl numbers, high volume concentrations of nanoparticles and microchannels with high aspect ratios.

Chein and Huang [29] investigated the heat transfer performance of nanofluid –cooled microchannel. They found better heat transfer performance than a water-cooled microchannel.

Tsai and Chein [33] analyzed microchannel performance usimg carbon nanotube-H_2O and Cu-H_2O nanofluids and a porous media approach. They found that the nanofluid reduced the temperature difference between the bulk nanofluid and bottom-heated wall.

Jang and Choi[34] numerically investigated a nanofluid-cooled microchannel. They found that the use of a water – diamond nanofluid enhanced the performance by about 11% compared with pure water.

Li and Kleinstreuer [35] compared thr thermal performance in trapezoidal microchannel using pure water and a nanofluid. They found that the nanofluid measurably enhanced the thermal performance of microchannel flow with the expanse of more pumping power.

Fard et al.[36] numerically analyzed laminar convective heat transfer of nanofluids in a circular tube under constant surface temperature. They found that the heat transfer coefficient increased with the nanofluids particle concentration and Peclet number.

Mohammed et al.[38,39] investigated the heat transfer of a trapezoidal microchannel using various nanofluids and substrate materials. They found that the heat transfer performance of water-based nanofluids can be increased in a heat sink having a steel substrate.

From above study many interesting results indicating the potential of nanofluids to enhance the thermal performance of a microchannel. We can say that heat transfer increased using nanofluids for various channel geometry. The results show the effects of the type of nanoparticle, volume concentration and nanoparticle size on the heat transfer performance of a microchannel.

5. Frosting problem

Frosting is most common problem in the heat exchanger. It affects the performance of heat exchanger . a defrosting cycle is required to minimize this effect. Defrosting cycle require additional energy to melt the frost layer. For the better heat exchanger, growth of frosting should be minimized. Research area of frosting and defrosting is limited. Some of those are reviewed here.

Wu et al.[40] investigated the wall temperature distribution by attaching thermocouples to parallel-flow evaporator. Xu et al.[41] investigated that vertical flow showed better thermal performance than the horizontal flow. Moallern et al.[42] investigated the channel wall temperature and effect of water retention on frost growth. Moallem et al.[43] found that formation of frost mainly depends on channel wall temperature and air humidity. Zhang et al.[44] gave a empirical correlations of Colburn j-factor and Framing friction f-factor for frost growth in early stage. Moallem et al.[45] investigated the design parameter for microchannel

during frosting Kyoungmin et al.[46] investigated that the performance loss of microchannel during frosting and defrosting cycles. They also found uniform frost growth between the front and rear side of microchannel and give better thermal performance.
Here we discussed frosting problem. By using better design parameter we can remove the frosting problem in microchannel.

6. Entropy generation

Entropy is an important property of the thermal systems. From the thermodynamics, the decrease of entropy generation means the decrease of irreversibility and less loss of energy. So it is important to evaluate the entropy generation of energy destruction due to heat transfer. We have studied following papers, which are related to entropy generation.
Haddad et al.[47] investigated numerically the entropy generation in parallel plates microchannel, with steady laminar forced convection fluid flow. They found that the entropy generation decreases as Knudsen number increases, and it increases as Reynolds, Eckert, Prandtl numbers, and the non-dimensional temperature difference increase.
Chen et al.[48] investigated the entropy generation in microchannel flows and analyzed for different thermal boundary conditions. They found that Local entropy generation rate dependent on the temperature gradient in the direction of flow.
Abbassi et al.[49] analyzed the entropy generation in a uniformly heated microchannel heat sink. They used Darcy equation (a porous medium model)for fluid flow and two-equation model for heat transfer. They found an optimum value for porosity at which entropy generation reaches its minimum value.
Erbay et al.[50] investigated numerically the entropy generation in the entrance between two parallel plates with the transient laminar forced convection. They found that the entropy generation is maximum at high value of Reynolds and Prandtl number.
Ogedengbe et al.[51] investigated that reduction of entropy generation in gas flow can be achieved by changing design parameters.
Hooman[52] analyzed that dimensionless entropy generation number always decreases with Knudsen number for forced convection in microchannel in the slip flow regime.
Yazdi et al.[53] have analyzed the entropy generation in external liquid flow over a surface of parallel microchannles. They found that the rate of entropy generation always decreases with increasing slip length.
Ibanez et al.[54] investigated the effects of slip flow on heat transfer and entropy generation in microchannel and found an optimum slip flow where the entropy generation rate i minimum.
Guillermo et al.[55] optimized the values of both the slip length and wall to fluid thermal conductivity ratio, where the entropy generation is minimum. Entropy generation rate decrease with the wall heat flux.
From above research we can say that entropy generation has an impact on the design of microchannel heat exchanger. By using proper condition we can remove the entropy generation problem.

7. Conclusions

In this review paper we have covered the factor affecting heat transfer in microchannel. We have discussed slip flow concept, Knudsen number, effect of channel geometry, problem of frosting, nanofluids and entropy generation. With the help of above study we can conclude following.

1- No slip condition is usually applied but we cannot ignore the effects of velocity-slip and temperature jump at the walls.
2- Knudsen number is one of the important dimensionless numbers for design parameter of microchannel.
3- Above study examined the influence of channel geometry (shape and size) on heat transfer performance. In case of counter flow microchannel heat exchanger the circular shape give best overall performance.
4- We can enhance the heat transfer performance by using nanofluids, which has high thermal conductivity than pure coolants.
5- Frosting is a common problem in condenser and evaporator. By using better design parameter we can minimize or remove the frosting problem in microchannel.
6- Before developing a new microchannel heat exchanger it is required to investigate the entropy generation.

These results are important to design an efficient microchannel heat exchanger. Thus we can make a microchannel heat exchanger of best overall heat transfer performance.

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