

A Review of Experimental Investigations on Heat Transfer Characteristics of Single Phase Liquid Flow in Microchannels

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Abstract

With the advances in micro-machining technology, the size of Micro-Electro Mechanical Systems (MEMS) is reducing day by day and power density of microdevices is increasing, posing a problem for thermal control and heat dissipation from these devices. Microchannel passages providing high surface area to volume ratio gives high heat transfer rates from small areas has emerged as potential heat dissipating and thermal control devices for MEMS. In this review paper heat transfer characteristics of single phase liquid flow in microchannels has been reviewed. The existing discrepancies and possible causes between experimental observations and theoretical predictions based on classical conventional theory presented by various researchers are critically analyzed. It has been also observed that Nanofluids as coolants in microchannels have excellent potential to enhance the heat transfer performance and are quickly establishing as future coolant to be reckoned with.

Keywords: Microchannels; MEMS; Nanofluids.

1. Introduction

Miniaturization of electronic gadgets has become necessity of today's world. In the last two decades researchers have devoted countless efforts in developing miniaturized microdevices. The reduced size has increased the heat flux density which causes overheating of devices and makes the overall well being and proper functioning of these devices a big challenge for researchers. So there is a need to develop highly efficient cooling technology and heat dissipation methods to meet the safety and stable

operation of MEMS. The simplest arrangements commonly used to this effect are microchannels. In a microchannel a fluid is used to carry away heat from the small hot surface by forcing it through passages having hydraulic diameters ranging from 10 μm to 200 μm [4]. As a microchannel has higher heat transfer surface area to fluid volume ratio, so it provides high heat transfer coefficient for convective heat transfer. However this small channel experiences a very high pressure drop.

The pioneer work in the field of heat transfer using microchannel heat sink for electronic cooling was first time demonstrated by Tuckerman and Pease [9] by achieving high heat flux removal capacity of up to 800 W/cm^2 with microchannels in single-phase and two-phase flows. They noted that as the hydraulic diameter of the channel decreases, the heat transfer coefficient increases. This landmark work paved the door for further research in the area of microchannel heat transfer. Thereafter lot of efforts have been put in improving the heat transfer capabilities through microchannel heat sinks for removing heat generated by electronic chips. Water, air and refrigerants are most commonly used fluids in microchannels, but heat transfer capabilities of these fluids is having limitations due to varying transport properties. In microchannels, preferably air has been used to cool electronic components. However, when heat fluxes going beyond 100 W/cm^2 , air cooling methods have become inadequate for most applications then liquid cooling performs better. Liquids having much higher convection heat transfer coefficient, provide a better performance in cooling. Fluids with higher convection heat transfer coefficients and higher specific heats are more effective in reducing heat from the surface [3]. A comparative study done by Ahmed et al.[2] summarizes the advantages and disadvantages of the coolants currently used in the microchannel heat sink industry are given in table 1.

Table 1: Specifications of the previously used coolants.

Gaseous coolants				Liquid coolants			
Air		N ₂ , He, NH ₃ and others		Water		Nanofluids and others	
Advantage	Disadvantage	Advantage	Disadvantage	Advantage	Disadvantage	Advantage	Disadvantage
Availability, Stability	Poor heat transfer	Better heat transfer	Flammability, Toxicity, Corrosive, Reactivity, Cost	Better heat transfer, Availability	Leakage, High power demands	Better heat transfer	Particle sedimentation, Passage clogging, High power demands

Steinke and Kandlikar have measured heat transfer coefficient values of over $500,000\text{W/m}^2\text{-K}$ using the offset strip-fin microchannel geometry in their practical implementation of liquid cooling using enhanced microchannel[4]. In the present circumstances, the microchannels are used not only in the fields of microelectronics and MEMS, but also in mini heaters and mini heat exchangers, aerospace, materials processing, thin film deposition technologies, micropumps, microvalves, and chemical separation processes. The application of microfluidics in the fields of bioengineering and biotechnology, especially in lab-on-a-chip or bio-chip systems for drug delivery and biomedical diagnosis also deserve special mention [8].

2. Heat Transfer Characteristics

The experimental investigations existing in open literature related to heat transfer characteristics of single-phase liquid flow in microchannels is critically analysed. The Nusselt number (Nu) which represents the heat transfer characteristics for microchannel flow is investigated by various researchers and correlations obtained for Nu are compared with Macroscale Nusselt number obtained from conventional correlations based on theoretical paradigms and reasons for deviations are suggested. Rahman and Gui [7] investigated forced convection of water in etched silicon microchannels having rectangular shape ($176\mu\text{m}\leq Dh\leq 325\mu\text{m}$) for Reynolds number Re ranging from 300 to 3500. They reported for developing laminar flow Nu obtained was higher than theoretical prediction, but lower for turbulent flows. However they did not give any correlation to infer the results. Further, the experiments conducted by Wang and Peng [10] reported that for single phase convective heat transfer for fully turbulent flow in microchannels Nu can be predicted by Dittus–Boelter correlation for conventional flows by modifying the empirical constant coefficient from 0.023 to 0.00805, which indicates the fact that the measured Nu were lower than predicted by conventional theory. The effect of geometrical parameters on the heat transfer characteristics of microchannel were investigated by Peng and Peterson [6] by passing water through rectangular microchannel of size ($133\mu\text{m}\leq Dh\leq 367\mu\text{m}$). They observed for both laminar and turbulent flow strong dependence of Nu on the microchannel aspect ratio and Nu obtained were lower than Macroscale Nu for both regimes. Adams et al.[1] investigated experimentally the turbulent single phase forced convective heat transfer when water flows in circular microchannels of hydraulic diameter $760\mu\text{m}$ and $1090\mu\text{m}$. The measured value of Nu were significantly higher than predicted by conventional correlations. Further the deviation in the values of Nu from conventional prediction increased with increasing Re and with decreasing channel diameter. Wu and Cheng [11] investigated experimentally the heat transfer in trapezoidal microchannel and observed that Nu was enhanced for channels having comparable geometric parameters but with a larger degree of surface roughness. The channel geometry had a much more prominent effect on Nu than surface roughness. The effect of surface roughness on increasing the heat transfer was more significant at larger value of Re than at lower ones. Lee et al. [5] experimentally investigated single phase convective heat transfer in rectangular microchannel using deionized water as coolant. They

reported measured Nu higher than predicted by correlations based on conventional theory and heat transfer coefficient increased with decreasing channel size. The reason for discord between experimental and theoretical values was attributed to the fact that the model based on conventional theory did not consider the effect of experimental inlet and boundary conditions.

Guo and Li in their experimental study reported the surface roughness, axial conduction, and measurement errors as possible sources for discrepancy in microchannel data. Lelea et al. presented data confirming the continuum theory. Steinke and Kandlikar have done experimental study on fluid flow and heat transfer in single phase microchannel flow and presented data confirming the validity of continuum theory. Analysis of previous data available in literature suggested major reasons for discrepancy were entrance region effects, entrance and exit losses and experimental uncertainties [4]. Warrier et al. also observed good agreement between experimental and theoretical measurements of local Nu for laminar microflows, especially for the fully developed region. Such coherency between experimental and theoretical approaches was further substantiated by the studies of Qu and Mudawar, Owhaib and Palm, and very recently by Wang et al. In the last work it was shown that classical theories were even applicable for flows in microchannels as small as $155\ \mu\text{m}$ in diameter. In a similar study, Mokrani et al. observed that microscale thermal characteristics adhered to the macroscale theory and correlations for channels having $Dh > 100\ \mu\text{m}$ [8].

3. Nanofluids

A suspension of small nanosized particles in a base fluid is known as Nanofluid. Generally in a nanofluid the size of small particles is kept below $100\ \text{nm}$ and the base fluids used are as water, glycol, ethylene, engine oil or refrigerants. Recent research concluded that nanofluids have very high thermal conductivity which enhances heat transfer performance, because suspended nano-particles increase the thermal conductivity of the fluids and the chaotic movement of ultrafine particles increase the fluctuation and turbulence of the fluids which accelerates the energy exchange process. Nanofluids as coolants are ideally suitable for practical applications in microchannels, because the nanoparticles are ultrafine, therefore appearing to behave more likely as single-phase fluid than a solid-liquid mixture. Generally the metallic materials used for nanofluids are Nitride ceramics (AlN , SiN), Carbide ceramics (SiC , TiC), Oxide ceramics (Al_2O_3 , CuO), metals (Cu , Au , Ag), Semiconductors (SiC , TiC_2) and Carbon nanotubes. The most common materials used are the oxides of ceramics [3]. Koo and Kleinstreuer reported an important finding that lists the conditions under which nanofluids may provide enhancement for application in practical single-phase microchannel devices. They reported that (i) a nanofluid concentration of at least 4%, (ii) elevated thermal conductivity of nanofluids, and (iii) treated channel walls, which prevent nanoparticle adhesion, may contribute in increasing the heat transfer. Enhancement in thermal conductivity of nanofluids was reported by Lee et al. , followed by a study showing heat transfer increase with nanofluids by Xuan and Li and Koblinski et al. [4]. Though

use of nanoparticles to a base fluid can improve the heat transfer in microchannels, but it may lead to high pressure drop, erosion and sedimentation of particles and even clogging of channel on prolong use[3].

4. Conclusion

This paper has critically reviewed the literature pertaining to heat transfer characteristics represented by Nu in single phase liquid flow of microchannel and conclude that Nusselt number reported in experimental studies by various researchers are not coherent. In some studies there are deviations between experimental microscale Nusselt number and Macroscale Nu based on classical conventional theory. The reasons attributed for discrepancy in experimental Microscale Nu and Macroscale Nu cited are not addressing the entrance region effects, exit boundary conditions and roughness effects in the macroscale conventional theory. The surface roughness has significant effect on increasing heat transfer at large Reynolds numbers. Experimental uncertainties and measurement errors at microscale further adds to the discrepancies. However a number of recent studies have observed that experimental data confirms the continuum theory, this indicates that macroscale correlations can be used to predict microscale heat transfer when hydraulic diameter is kept within a specified limit. Further the review shows that the Nanofluids as coolant in microchannel have strong potential to enhance heat transfer rate still leaving the problem of higher pressure drop and clogging of channel remains a challenge for future.

5. Nomenclature

Re	Reynold Number
Nu	Nusselt Number
Dh	Microchannel hydraulic diameter
MEMS	Micro-Electro Mechanical Systems

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