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Heat Transfer at Microscales – Accomplishments and Oppurtunities

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Abstract— The need for high removal of heat transfer rates yet lowering the dimensions demands for development of micro cooling techniques. In this regard many papers have been published in the recent past covering understanding the boiling mechanism, the effects of dimensions on flow boiling and attempt to enhance heat transfer. This paper presents the roadmap to cooling, difference between the conventional and the microchannels and the considerations which can affect the results significantly. Suggestions for efforts in specific areas in this field are also provided

Index Terms— Heat transfer, Scaling effects, Boiling, Microchannel.

I. INTRODUCTION

The continued trend towards increase in the speed and performance and reduced size of electronic devices result in large heat removal requirements. In order to accommodate such high demands special and high performance cooling techniques are needed. With the steady increase in heat dissipation of microelectronic modules and systems, one of the main challenges of the power electronics is the removal of heat flux as high as 300 W/cm^2. Also for dissipating heat fluxes over 100W/cm^2 conventional air cooling would not be sufficient. Single-phase liquid flow in microchannel provides the advantage of high heat capacity and conductivity of the liquids and the large surface area to volume ratio of microchannels. On the other hand, the single-phase apparatus due to the reduced feature size of the microchannels and the increased influence of surface tension, high flow rates will cause a sharp increase in pressure loss. Practical constraints in providing complex headers and employing large pressure drop are two reasons for searching other options.

Due to the latent heat involved the two phase cooling system provides better cooling performance, more uniform device temperature, and can be driven by a miniature pump which is ready to be integrated in the system or even on the board but volumetric changes of the liquids during the phase transition may cause a flow reversal which in turn lowers the heat transfer and the pumping efficiency of the system at a given pressure drop. The first application of small diameter channel mainly involved aerospace systems, in form of compact heat exchangers for managing onboard power systems. Tuckerman and peace also revealed flow and heat transfer characteristics of water in microchannels for cooling of electronic components by forced convection. Thus over the last decade substantial attention has been provided to heat transfer and fluid flow phenomenon at microscales. This will also help in the optimal design of small scale heat transfer devices in areas such as biomedical devices and advanced fuel cells. This paper presents practical considerations along with effects that are ignored while building conventional devices but are important when development of compact devices is a concern.

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II. SCALING EFFECTS AT MICROSCALES

When working at microscales, several additional factors such as rarefaction (significant for gas flows), electro- viscous effects, viscous dissipation (important for flows with Re > 100 for diminished channels) and axial conduction become significant which were remained untreated for the development of conventional devices. The rate of the transport process depends on the surface area which varies with the diameter D for a circular tube, where as the flow rate depends on the cross sectional area, which varies with D^2. Thus the tube surface area to volume ratio, will be proportional to (1/D). Therefore as the diameter decreases, surface area to volume ratio increases. Due to large surface area to volume ratio for microdevices factors related to surface effects have more impact to microscale flow and heat transfer. The increased surface forces causes production of large pressure drops, compressibility effects and viscous dissipation. On other hand decreased inertial forces, allows diffusion and conduction processes to become relatively more significant; and increased heat transfer may lead to variable fluid properties and creep flow. Thus one can classify primarily 4 scaling effects

1) Axial heat conduction effect in fluid: Pe number effects
2) Heat conduction in solid and convective heat transfer in fluid must be accounted for simultaneously: wall thickness conjugate effects
3) Variable property effects for temperature dependent properties and
4) Property variation due to large pressure drops (for gases density strongly depends on pressure)

Flow in microchannels is laminar accordingly low values of Peclet number results in axial heat diffusion along the fluid stream, in particular to the regions close to the inlet. Then both the upstream and downstream section of the microchannel that are actually not the active member may take part in the heat transfer process, generating different predictions than those obtained in conventional channels moreover single and multichannel arrangements affect the performance extensively. From the energy view point, the characteristic time for convection becomes analogous to conduction and both phenomenons drive the heat transfer characteristics in lower dimensions. This is defined by low Pe, which gets amplified as Pe decreases. Besides the axial conduction in fluid, the thickness of channel wall and hydraulic diameter of the channel are of comparable magnitudes specifying the heat transfer through conduction in solid is considerable and the heat transfer mechanism becomes conjugate.

At micron scales the specific amount of heat is carried through relatively small amount of coolant, revealing a huge difference in the inlet and outlet temperatures and thus property variation in the fluid. The non dimensional parameters taking into account the scaling effects are shown in table 1.

Dimensionless group	Taking into account	Formula	No scaling when
Gretz number	Entrance effect	$RePrd_h/L$	Gz < 10
Peclet number	Axial conduction in fluid	$(\rho u_m D_h c_p)/k$	$Pe \rightarrow \infty$
Wall thickness	Axial conduction in solid	s/D_h	$\Lambda \rightarrow 0$
variable property effects	Temperature variation	$(T_i\text{-}T_o)[(\partial\alpha/\partial T)(T/\alpha)]/T$ $\alpha = \rho, k, c_p,$	$\rightarrow 0$
variable property effects	Pressure variation	$(p_i\text{-}p_o)[(\partial\rho/\partial p)(p/\rho)]/p$	$\rightarrow 0$

Table I: Relevance of non dimensional parameters

III. LITERATURE REVIEW

Kandlikar Satish [1] provided fundamental concept to improve flow boiling systems performance. The two phase flow stability and pattern transitions for water and FC77 were estimated based on the scaling analysis of different forces on flow boiling. Surface tension and evaporation momentum forces are found to be dominant in flow boiling at lower scales. Heat transfer in slug flow pattern was discovered analogous to that around nucleating bubble in pool boiling. Transient conduction at the heater surface (either liquid covering the dry patches on heater surface or advancing film replenishes the film with cooler liquid) and micro convection (superheated liquid layer releases its energy by evaporation at the interface) is identified as the major heat transfer mechanism which results mostly in slug flow pattern in microchannels. Convective boiling component of heat transfer may be present in flow boiling which is usually in a wrong manner interpreted as independent of mass flux during experimental observation due to laminar flow conditions.

Kosar [2] examined the effect of surface thickness and material on convective heat transfer characteristics at microchannel of 200µm*200µm, 5cm length under constant heat flux boundary condition. The thickness was ranged between 100µm to 1000µm and material tested were Polyamide, silica, glass, quartz, steel, silicon, copper. The major finding was changing the thermal conductivity alters the conductive thermal resistance and thus Nu gets considerably effected by conductivity and substrate thickness effect was marginal. They also recommended that corresponding to Nu a value of 1.651 for $(Bi^{0.04} * k^{0.24})$ satisfied 95% of their experimental values.

Naphon and khonseur [3] experimentally investigated the effect of Reynolds number (range 200 – 1000) and heat flux (range 1.80 KW/m^2 – 5.40 KW/m^2) on the heat transfer characteristics and pressure drop. Two different geometrical configuration tested were w= 0.2 mm and h= 1.5 mm and w= 0.3 mm and h= 1 mm. The channel with w= 0.2 mm and h= 1.5 mm provided better performance than those of w = 0.3 mm and h= 1mm, former configuration has increased surface area for heat transfer.

Guo and Li [4] discussed the size effect induced by the variation of dominant factors. The effect of rarefaction i.e. Navier stokes and energy equation is not applicable for devices of 5µm or lower. Due to larger surface area to volume ratio, factors related to surface effects has more impact to the flow and heat transfer phenomenon even if the above mentioned applicability is valid. These include surface roughness and friction accountable for higher heat removal and pressure drop. As a result of laminar conditions, axial conduction contributes significantly to the variation of results at micro and conventional scales. The difference between results and standard values of heat transfer and fluid flow might be due to measurement errors.

Poulikakos D et al [5] experimentally presented convective heat transfer study in serpentine microchannel with segmented flow of water with mineral oil in square microchannel of 100µm. In segmented flow, intensive fluid recirculation in the carrier water between the slugs is possible because of the movement of oil slugs which disrupts the formation of boundary layer and improves mixing. The heat transfer from the wall in segmented flow is driven by a temperature difference of about 2°C, instead of 9°C with only water. The temperature difference of 2°C results in higher Nu. They additionally varied the temperature of working fluid from 23°C to 65°C in order to observe the effect of temperature rise due to heating on pressure drop. In segmented flow the pressure drop got three times than in pure water flow which got reduced by two fold in both cases as the temperature increased. This effect could be ascribed to the strong change in viscosity of fluids with change in temperature.

Hetsroni [6] compared two phase flow boiling of Vertral XF (low boiling point solution) to single phase water flow in multichannel configuration containing 21 parallel triangular microchannels of 250 µm base. Flow boiling of Vertral XF resulted in driving down the undesired temperature variation along the flow length and in crosswise directions. Maximum temperature difference in the range of 4 to 5K at the plain of heat sink was observed while working with boiling of Vertral XF whereas this difference was upto 20K for single phase water flow. For achieving the same temperature difference as of Vertral XF at least 2.5 times higher mass velocity is required. Regarding flow instability, the growth and collapse of bubble causes pressure fluctuations and reduction in heat transfer coefficient. Also the temporal manner of temperature fluctuations communicated with fluctuations in pressure.

Herwig [7] provided systematic approach and commented that there are no special effects at microscales but if treated in a non dimensional form all special effects are just scaling effects which were negligible during development of devices in original scales but become important in other scales. The analysis at these scales calls for additional non dimensional parameters that should be incorporated to the original scales.

Bhide et al [9] discussed experimental investigation of pressure drop and heat transfer and two phase flow instability of deionized water in microchannels of hydraulic diameter of 45µm, 65µm and 70µm. boiling flow pressure drop was found to follow Lockhart – Martinelli (within 20%) model which confirmed that flow in microchannel was laminar.

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The dominant mechanism of heat transfer was found to be forced convection. The sinusoidal oscillations obtained in 65µm were absent in 45µm channel because of the difference in bubble formation mechanism, as well it is suppressed in smaller diameters channels. They also found that rougher channels generate less oscillation than smooth channels indicating quick switch from bubbly or slug flow to annular flow without daunting additional pressure drop.

Cetin and Cole [10] numerically analysed axial conduction and conjugate heat transfer phenomenon inside a parallel plate microchannel. At higher values of Pe=100, the behaviour is agreeing to macro scale convection dominated heat transfer. As Pe decreases to 10 and further to 0.1 large upstream region is warmed by upstream axial conduction. The presence of this effect will affect the specified entrance or leaving temperatures which in turn will distort the predicted Nusselt number. The addition of wall causes heat to move axially upstream to prewarm the flow. Thus at small Pe increase in Nu values is magnified for larger k_{wall}/k_{fluid} which during the study varied from 0 to 500. The study collectively concluded that the effect of axial conduction is important for small Pe, small length to height ratio, large relative wall thickness to channel height, for high conductivity of wall material than conductivity of working fluid.

Ameel et. al [13] numerically considered frictional (Po) and heat transfer (Nu_{H2}, Nu_T) phenomenon for rarefied flows in rectangular microchannel. The effects of creep flow, viscous dissipation, and axial conduction were also incorporated. The results imply that in slip flow region all effects have significance with their degree depends on the extent of rarefaction, gas wall interaction and the boundary condition applied. Creep flow improved Nu_{H2} for heating but reduced the same during cooling. The viscous dissipation effect was found to be conjugate to creep flow. Axial conduction was observed to be considerable for low Peclet numbers and may raise Nu by 15% compared to Nu_T without axial conduction.

Teo et. al [14] numerically studied liquid laminar water flow in 3D rectangular wavy microchannels with 10 or 12 wavy units with different wavy amplitudes. The heat transfer enhancement results because of the enhanced fluid mixing created by the generation of the secondary Dean vortices by stretching and folding of the fluid element. The heat transfer coefficient in constant wavy channels at Re 800 is found to increase by 153% by expensing friction factor increase by 54%. Local heat transfer coefficient can be increased by tailoring relative waviness for hot spot mitigation.

Rosa et. Al. [15] presented a comprehensive review about various scaling effects and their importance, they observed that single channel configuration with macro correlations can be used for the reliable predictions at lower dimensions only if additional effects are unimportant because of absence any other interaction. They also underlined and explained the sub continuum mathematical models which are likely to be constructive in moving from micro to nano scales.

Harirchian and Garimella [17] indicated that it is the cross sectional area that determines the boiling mechanism and heat transfer in smaller channels. For $A_c < 0.089$ mm^2 larger values of heat transfer coefficient are because of vapor confinement and thin film evaporation and forced convection in thin liquid film surrounding the vapor slug are the main heat transfer mechanisms. For $A_c \geq 0.089$ mm^2 nucleate boiling is dominant over very high heat fluxes causing independence of heat transfer coefficient on channel dimensions.

Steinke and kandlikar [18] investigated the heat transfer performance and two phase flow characteristics of degassed water heated in six parallel microchannels of hydraulic diameter 207µm. The range of considerations tested were, mass flux 157 – 1782 kg/m^{2}s, heat flux 5 – 930 kW/m^2, inlet temperature of 22^{o}C, quality from sub-cooled to 1, single phase Reynolds number 116 – 1318. Heat transfer coefficient has very high values in low quality regions which decrease with increasing quality indicating the onset of nucleate boiling for all heat fluxes. The flow image revealed that flow reversal and local dry out conditions in multichannel configuration is caused by the presence of the parallel channels which allow a path of lower flow resistance during explosive growth of the nucleating bubbles. Change in contact angle at the liquid vapour interface was observed indicating the dry out condition.

Attinger and Betz [21] experimentally demonstrated the enhancement of Nu in segmented flow with polycarbonate heat sink consisting of 7 parallel channels of square cross 500 µm wide. They generated the segmented flow pattern by cyclic insertion of air in path of water. More than two fold increments in Nusselt number was observed when mass velocity was varied between 330 – 2000 kg/m^{2}s. Segmented flow enhances heat transfer because of the enhanced convection by recirculating wakes in the liquid slugs. The necessary condition for generation of recirculating wakes requires surface tension to dominate gravity i.e. bond number Bo< 3.368. Segmented flow enhances heat transfer only if the film between the bubbles and the wall will remain thin because the thick film will weaken the recirculation wakes. Heat transfer enhancement can be upto 140% but when considering same pressure drop Nu enhancement is about 50% in segmented flow than pure liquid flow.

Choi et. al [22] examined convective boiling Heat transfer of R-22, R 134a and CO_2. Local heat transfer coefficients for heat fluxes (10–40 kW/m^2), mass flux (200–600 kg/m^{2}s), a saturation temperature of 10^{o}C and quality upto 1 were examined. Nucleate boiling is predominant in small channels at low quality region as opposed to convective boiling heat transfer in conventional channels. The mean heat transfer coefficient ratio was found to be in ratio of R-22:R-134a:CO_2 = 1:0.8:2. The higher heat transfer coefficient of CO_2 is due to its high boiling nucleation. CO_2 has much lower viscosity ratio and lower density ratio, causing lower suppression of nucleate boiling. R22 and R134a are having similar physical properties.

K.H. Chang and C. Pan [23] reported two phase flow instability in heat sink containing 15 parallel microchannels of hydraulic diameter 86.3µm. They observed that two neighbouring channels can easily interact through conduction of dividing wall in addition to common inlet and outlet. For stable conditions bubble nucleation, slug flow appears successively in the flow direction followed by annular flow with the length of bubble slug possibly growing (although not very smoothly) exponentially. In contrast, forward or reversed flow of two phase mixture was evident in unstable situations for which length of bubble slug oscillates. They also revealed that reversed flow to inlet with two phase flow instability appears if the deviation of maximum pressure drop to minimum pressure drop is greater than 6kPa.

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Jacqueline Barber et al. [25] revealed periodic oscillations of temperature and pressure to explore bubble wavering of n-Pentane in single 771µm hydraulic diameter microchannel. The bubble confinement initially starts with internal diameter (d_i), then the internal width (w_i) and finally expands longitudinally. During the free stage the bubble grows linearly and once the bubble gets confined (partial and fully) the bubble undergoes rapid exponential expansion as it elongates. With the increase in pressure fluctuations indicating bubble confinement the heat transfer coefficient decreases and thus the wall temperature increases. The rate of wavering are driven by boiling phenomenon and the thermal possession of wall material. During flow boiling 216% of increase in heat transfer coefficient was observed simultaneously accompanied by 410% increase in pressure drop.

Li and Wu [28] provided general criteria of classify micro and macro channel based on 4228 data points gathered from various experiments of saturated flow boiling ranging variety of fluids and materials from different sources. Microchannels were found to have laminar flow and low bond number. A combined non dimensional number $Bo_* Re_l^{0.5} = 200$ was set as a criteria of transition with micro flow dominating when $Bo_* Re_l^{0.5} \leq 200$ and macro flow dominating otherwise. This correlation was found to predict 86.3% and 89.6% of the database points for micro and macrochannel phenomenon within ±50% band.

IV. CRITICAL CONSIDERATION

In addition to scaling effects, general recommendations based on the observations from the literature review which are vital and can have significant effect on outcome are presented below:

A. Integrate testing and modelling approaches:

All the three testing, modelling and interpretation are equally important in development of problem free system. Testing offers sufficient reality checks and analysis, while modelling can display in advance the problem behaviour and its consequences. To take scaling effects into account with the degree of precision, for better amount of correctness, concluding experimental results for the design and analysis at microscales must be validated with the help of numerical simulations to take care of 3D heat transfer pattern effect and the maldistribution effects.

Fig 1. [8] Illustrates the difference between assuming linear variation of bulk temperature ($T_{B,int}$) i.e the arithmetic mean throughout the flow length (dotted line) and the actual values obtained by the CFD simulations (dark lines) for flow through circular pipes subjected to constant heat flux condition. Nu varies about 4.36 (fully developed value for the case considered) when actual difference between TW and TB is considered. On the other hand linear interpolation approach provided lower estimation (about 1.6) of the dimensionless heat transfer coefficient.

Hence it is indicated that the bulk temperature is not linearly distributed between the inlet and outlet and the concepts of the macro world devices are applicable for the development of appliances at lower scales only is applicable when this additional conjugate heat transfer and the axial heat conduction effects are taken into consideration.

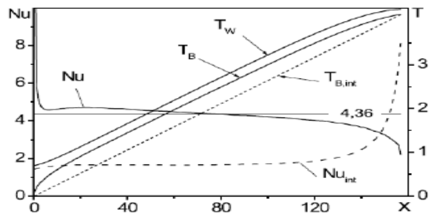

Fig 1: Temperature and Nusselt number variation: comparison of interpolated and actual values [8]

B. Accuracy in Measurements:

Flow and heat transfer analysis at microscales require some parameters like flow rate, dimensions of work piece to be accurately measured, which is difficult because of their size. This ambiguity in computations can produce deviations in the experimental and standard results.

Consider convective heat transfer in a flow past a circular cylinder is given by

$Nu = 0.246\, Re^{0.588}\, Pr^{1/3}$

$$\frac{U(Nu)}{(Nu)} = \left\{0.346\left(\frac{U(Re)}{(Re)}\right)^2 + 1/9\left(\frac{U(Pr)}{(Pr)}\right)^2\right\}^{1/2}$$ where

Re = (ρvD/µ) hence

$$\frac{U(Re)}{(Re)} = \left\{\left(\frac{U(\rho)}{(\rho)}\right)^2 + \left(\frac{U(v)}{(v)}\right)^2 + \left(\frac{U(D)}{(D)}\right)^2 - \left(\frac{U(\mu)}{(\mu)}\right)^2\right\}^{1/2} \quad (1)$$

Where ρ = density of fluid, v = velocity of flow, D = diameter of channel, µ = dynamic viscosity of fluid. Eq. (1) shows tube dimensions and flow rate are key player in establishing the uncertainty of heat transfer rate.

For calculating friction factors, Guo and Li [4] conducted experiments on a circular glass microtube, using 40 x microscope the diameter of channel was found to be 84.7µm whereas using 400 x microscope the diameter of the same channel was found to be 80µm accordingly the friction factors obtained using previous value were larger but were in good agreement with usual predictions when calculated with later diameter value.

C. Single channel and multi channel arrangements

Experimentation on microchannel test section with many parallel passages suffers fluid maldistribution between the channels and 3D conjugate heat transfer patterns in the solid and the fluid. Thus even if the scaling effects are properly considered the deviation in experimental results with single channels will be lesser and the results will be in good agreement with standard values, in contrast to multi channel arrangement.

This will be predominant in flow boiling cases owing to the flow reversal phenomenon caused by the presence of parallel channels, which provides a path of low flow resistance during explosive growth of nucleation bubbles [18]. The flow and pressure in the other channels balance and permit for the high pressure of vapor generation to dissipate through the other channels.

D. Prelims are equally vital as mains

Every section of the apparatus should be preliminarily checked individually for their applicability before performing its application as a component.

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This will provide a safeguard in thermal experiments about the uncertainty of the result. In flow through microchannels the pump should be verified for offering steady flow rate. The main source of uncertainty was found to be in measurement of temperature so inner channel wall temperature should be carefully obtained considering the thermal resistance from the location of thermocouple to the bottom wall of the channel.

V. RESEARCH ARREAS RECOMMENDED

- It was seemed that heat transfer enhancement occurred using segmented flow [5, 21] thus generating water – air segmented flow pattern requires air removal before pump and its reinjection after pump thus future research regarding the removal of air bubbles would be useful in development of commercial applications.
- The attempt to development of correlation for microscales have demonstrated considerable alteration in results as only few researchers are found to be progressing in establishing a comprehensive correlation with wide span of uncertainty. Consequently efforts in this way are highly appreciable.
- The unsteady behavior of heat transfer and flow instabilities at microscales due to bubble formation needs a confirmation. Thus attention in this course will drive the development of two phase systems.

VI. CONCLUSION

The heat transfer and pressure drop phenomenon at micro scales can be categorized in two parts i.e. the continuum assumption (characteristic length above 5μm) is valid but due to substantial surface phenomenon variation of surface forces are having more involvement in the final results. Continuum assumption fails (rarefaction effect in gases) when the mean free path of molecules and the characteristic flow length are of similar order of magnitude. Due to higher impact of surface forces many additional factors like axial conduction and variable properties effects collectively known as scaling effects are getting significant.

Experimental outcome depends on instrumentation used, complicated behaviour in measurements at smaller scales often induces measurement errors which develops divergence among real and standard results. Therefore for correctness of measurement uncertainty analysis should be integrated with the modelling approach for the confirmation of results.

Boiling flow heat transfer is preferable over single phase heat transfer for achieving better rate and uniformity in cooling. More studies in this area to better understand the physics of two phase flow are required to refine bubble formation and flow reversal aspects for product development.

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