A Review on Two Phase Flow in Micro channel Heat Exchangers

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Abstract—Partly because of the technological challenge, partly because of stark necessity, there has been an increasing movement towards a miniaturization of appliances in the last decade. In all technical fields solutions are sought that encumber as little as possible without compromising on performance: in medical diagnostics, environmental sample analysis, military defence, consumer electronics, biomedical appliances, chemical reactors and heat management a constant research for quicker response times and portable devices has driven the field of microtechnology to impressive levels. In many applications it has been found that many small active components are more productive than few large ones, which is also in keeping with the growing trend towards modular design. Microchannel heat exchangers were introduced in early 1980s and since then many studies have been conducted in field of micro channel heat exchanger. Research in early times was focused on single phase flow in micro channel heat exchanger, but the recent trend in research is focused on two phase flow in micro channel heat exchanger. The purpose of this article is to provide a state of art literature review of progress of research in field of two phase flow in micro channel heat sinks.

Keywords- Micro channel heat exchanger, two phase flow, flow pattern map, void fraction, pressure drop.

I. INTRODUCTION

In recent years the research in the field of single- and two-phase flow heat transfer at a microscale level has been constantly increasing due to the rapid growth of the technology applications that require the transfer of high heat rates in a relatively small space and volume. Such applications span from compact heat exchangers to cooling systems for computer CPU to microfluidic devices. Single- and two-phase flow heat transfer has been the subject of numerous researches for the last decades. A relevant knowledge has been constructed, which allows with more (single-phase flow) or less (two-phase flow) accuracy to cope with most heat transfer applications. Going down to microscale the first question which immediately pops up is: “Is the macroscale knowledge for single- and two-phase flow heat transfer applicable to microscale?” Over the last 10-15 years a good deal of publications has dealt with this matter producing a considerable amount of experimental data. Especially in the first years of publications, a large diversion of results to be discerned in the various experimental and numerical reports can be found. The diversion occurs in different contexts: fluid drag of laminar, transient and turbulent single-phase flows, heat transfer of liquid and gas flows, and two-phase flow in adiabatic and heated micropipes. On the one hand, it can be interpreted as displaying some new effects of heat transfer in flow in micro-channels. On the other hand, the phenomenon may be related to the discrepancy between the actual conditions of a given experiment and theoretical or numerical solution obtained in the frame of conventional theory.

A heat exchanger is a device that is used to transfer thermal energy between two or more fluids, between a solid surface and a fluid, or between solid particles and a fluid, at different temperatures and in thermal contact. Typical applications include heating or cooling of a fluid stream of concern and evaporation or condensation of single or multi component fluid stream. Heat exchangers can be classified in many different ways; for example, according to transfer processes, number of fluids and heat transfer mechanism, construction type and flow arrangements. Another arbitrary classification can be made, based on the heat transfer surface area/volume ratio into compact and non compact heat exchangers.

Tuckerman and Pease first made use of miniaturization for the purposes of heat removal, within the scope of a Ph.D. study in 1981. Their publication titled “High Performance
Heat Sinking for VLSI” is credited as the first study on microchannel heat transfer. Their pioneering work has motivated many researchers to focus on the topic and microchannel flow has been recognized as a high performance heat removal tool ever since. Presently, modelling and experimental investigation of microchannel flow and heat transfer are rapidly maturing, although conflicts among researchers as to how microscale flows should be modelled and discrepancies between experimental results remain. In last few decades, advances in our ability to produce microscale heat exchangers have opened up endless and new frontiers in the world of heat exchangers. Over the last decade, micromachining technology has been increasingly used for the development of highly efficient cooling devices called heat sink because of its undeniable advantages such as less coolant demands and small dimensions.

One of the most important micromachining technologies is micro channels. Hence, the study of fluid flow and heat transfer in micro channels which are two essential parts of such devices, have attracted more attentions with broad applications in both engineering and medical problems.

Heat sinks are classified into single-phase or two-phase according to whether boiling of liquid occurs inside the micro channels. Primary parameters that determine the single phase and two-phase operating regimes are heat flux through the channel wall and coolant flow rate. For a fixed amount of heat flux (heat load), the coolant may maintain its liquid state throughout micro channels. With a lower flow rate, the flowing liquid coolant inside the channel may reach its boiling point and thus flow boiling occurs, which results in a two-phase heat sink.

II. MICROCHANNEL HEAT EXCHANGER

A. Concept

Heat exchanger with reliable and high performance has been the study focus of the refrigeration and air conditioning system. In recent years, with increasing demand for lightweight and rising copper prices, copper substitution is also a widespread concern. Under the premise of meeting the heat exchange demand, micro-channel heat exchanger can reduce equipment weigh, improve the device compact. The manufacturing costs can be reduced and the product competitiveness can be improved by using aluminium. Micro-channel heat exchanger has been extensive researched and applied in cooling of electronic equipment. Along with the improving of process technology, micro-channel technology is gradually used in household air conditioning and automotive air conditioning system. The concept of micro-channel heat exchanger was first proposed and used by Tuckerman and Pease in 1981. Micro-channel heat exchanger is defined by Mehendale.S.S as if the hydraulic diameter of heat exchanger is less than 1mm. Micro-channel heat exchangers for heat exchanging between two different fluids was first developed out by the Swift in 1985. To meet the rapid development of modern microelectronic mechanical requirements of heat transfer, micro-channel heat exchangers began to be used in cooling high-density electronic devices in the 1980s, and then appeared in the MEMS (microelectronic mechanics system) industry in the 1990s. With studies on properties of micro-channel in depth and application in the promotion of electronic cooling, advantages of micro-channel heat exchanger which a traditional heat exchanger cannot match gradually appear. And micro-channel heat exchanger began to enter the refrigeration and air conditioning industry. At present, the micro-channel heat exchanger has been applied in automotive air conditioning system. In household air conditioner field, technology of micro-channel heat exchanger applied in single-cold air-conditioner condenser has gradually matured, however, this technology face big challenges, such as complex gas liquid two-phase uniform streaming. Just like "conventional" or "macro scale" heat exchangers, micro heat exchangers have either one or two fluidic passages. In the case of one passage, heat is transferred to the fluid (each of the fluids can be a gas, a liquid, or a multiphase flow) from electrically powered heater cartridges, or removed from the fluid by electrically powered elements like Peltier chillers. In the case of two fluidic passages, micro heat exchangers are usually classified by the orientation of the fluid passages to another as "cross flow" or "counter flow" devices. If a chemical reaction is conducted inside a micro heat exchanger, the latter is also called a microreactor. . Heat transfer in the microscale is a very complex issue due to challenges in microchannel fabrication as well as in performance characterization. The determination of heat transfer parameters in microchannel flow is often very difficult. There are physical size considerations, surface to fluid interaction concerns, and experimental uncertainties that can have drastic effects upon the heat transfer parameters. A clear picture of these issues is required in order to develop suitable correlations to predict the performance of a microchannel heat exchanger

B. Two Phase Flow

At the first glance, two-phase or, in general, multi-phase flow seems an exotic topic used only in scientific experiments. In reality however, we may encounter two-phase flow in everyday activities. Flow of carbonated water pouring out of a bottle, ocean waves carrying oxygen, or even the action of the windshield wiper to remove rain involves two-phase flow. Although continuous efforts are being made to formulate two-phase flow aspects by analytical means, most two-phase flow formulations are based on experimental data and hence are in the form of correlations. Two-phase flow generally refers to the flow of a liquid and a gas or vapour such as the flow of water and steam, water and air, etc. Void fraction in a control volume made up of liquid and gas mixture is the volume fraction of the gas phase. Flow patterns of gas-liquid flow in an unheated pipe depend on such factors as pipe orientation, diameter, mass flux, flow quality, and phasic density. Flow pattern map reduces various flow regimes to identifiable patterns. Such maps associate the key flow parameters to a specific pattern. For a given set of such parameters, the flow pattern map determines the corresponding flow regime. Conversely, by knowing the flow regime, we can find a specific range for the key parameters.

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III. STATE OF THE ART REVIEW

Some experimental and theoretical work on micro channel heat exchanger has been done in the last decades. Both the industrial and academic people have taken interest in this area. The following is a review of the research that has been completed especially on micro channel heat exchangers. The literature survey is arranged according to similarity to the aim of this review. In this literature review emphasis is directed on:

1. Experimental study of fluid flow and heat transfer in micro channels
2. Numerical study of fluid flow and heat transfer in micro channels

A. Experimental Study Of Two Phase Flow In Microchannel Heat Sinks

Micro channels are one of the essential geometry for microfluidic systems; therefore, the importance of convective transport phenomena in micro channels and micro channel structures has increased dramatically. In recent years, a number of researchers have reported the heat transfer and pressure drop data for laminar and turbulent liquid or gas flow in micro channels. The concept of micro channel heat sink at first proposed by Tuckermann and Pease (1981), they demonstrated that the micro channel heat sinks, consisting of micro rectangular flow passages, have a higher heat transfer coefficient in laminar flow regime than that in turbulent flow through conventionally-sized devices. They said that the heat transfer can be enhanced by reducing the channel height down to micro scale. This pioneering work initiated other studies, some confirmed findings reported by others. Many researchers compared their numerical or analytical studies with Tuckerman and Pease.

Roger S. Stanley, Timothy A. Ameel and Randall F. Barron (1997) investigated fluid mechanic and heat transfer characteristics of two-phase two-component flow in rectangular micro channels. Experiments were conducted by them using rectangular aluminium channels with hydraulic diameters ranging between 56 μm and 286 μm and aspect ratios which varied from 0.5 to 1.5. Both single- and two-phase tests were conducted in their work using water and gaseous argon, helium, and nitrogen as the working fluids. The Reynolds number for both types of experiments ranged from 50 to nearly 10,000. The Nusselt number ranged between 0.0002 and 70. Experimental data were also used and correlated to analytical one. At the end both single- and two-phase tests yielded excellent correlations of the friction factor but for Nusselt number, the correlations were fair to poor. Reynolds number and the combination of Reynolds number and Prandtl number remained the dominant parameters in the prediction of pressure drop and heat transfer rate, respectively, in both single- and two-phase flows. It was concluded that the pressure drop predictions based on the semi-empirical relations by Martinelli for two-phase flows were shown to substantially over-predict the pressure drop measured in their experiments. K.A. Triplett, S.M. Ghiaasiaan and S.I. Abdel-

Khalik, D.L. Sadowski (1999) experimentally investigated two-phase flow patterns in micro channels. Experiments were conducted using air and water, experiments in circular micro channels with 1.1 and 1.45 mm inner diameters, and in micro channels with semi-triangular (triangular with one corner smoothed) cross-sections with hydraulic diameters 1.09 and 1.49 mm. The gas and liquid superficial velocity ranges were 0.02±80 and 0.02±8 m/s, respectively. It was seen that overall, flow patterns and flow pattern maps using gas and liquid superficial velocities as coordinates, were similar for all the test sections. The flow patterns observed were bubbly, churn, slug, and annular. They found that they obtained data when compared with existing experimental data and with relevant flow regime transition models and correlations, gave generally poor agreement. Qu and Mudawar (2002) have performed experimental and numerical investigations of pressure drop and heat transfer characteristics of single-phase laminar flow in 231 μm channels. Deionized water was employed as the cooling liquid and two heat flux levels, 100 W/cm2 and 200 W/cm2, defined relative to the planform area of the heat sink, were tested. Good agreement was found between the measurements and numerical predictions, validating the use of conventional Navier–Stokes equations for micro channels. For the channel bottom wall, much higher heat flux and Nusselt number values are encountered near the channel inlet. Qu and Mudawar (2004) conducted a three-dimensional fluid flow and heat transfer analysis for a rectangular micro channel heat sink using a numerical method similar to that proposed by Kawano and Fedorov and Viskanta. This model considered the hydrodynamic and thermal developing flow along the channel and found that the Reynolds number would influence the length of the developing flow region. It was also found that the highest temperature is typically encountered at the heated base surface of the heat sink immediately adjacent to the channel outlet and that the temperature rise along the flow direction in the solid and fluid regions can both be approximated as linear. Weilin Qu and Issam Mudawar (2002) realized the need for fundamental understanding of the complex transport phenomena associated with convective boiling in small, parallel coolant passages for design and operation of two-phase micro channel heat sinks. This understanding was goal of their work. They explored few aspects like hydrodynamic instability, two-phase flow patterns, and pressure drop, and convective boiling heat transfer. Flow pattern transition was seen as in fig.1. Predictions of three popular two-phase pressure drop models and correlations were compared by them with micro channel water data, and only a separated flow (Lockhart- Martinelli) correlation based on the assumption of laminar flow in both phases gave acceptable predictions.
Hetsroni, A. Mosyak, Z. Segal, E. Pogrebnjak (2002) performed experiments for air–water and steam–water flow in parallel triangular micro-channels. They compared flow regimes in air–water flow to flow regimes in steam–water flow. They used parallel triangular channels with the common inlet and outlet collectors. For air-water at different flow condition, different flow patterns were observed which were classified, depending on the interfacial configuration according to Lowe and Rezkallah (1999): as liquid alone (or single-phase flow), bubbly flow, slug flow, annular flow (gas core with a thin liquid film, gas core with a thick liquid film). The flow pattern indicated that as the air velocity became high enough, the liquid droplets entrained in the gas core disappeared such that the flow became annular flow. Although the gas core may occupy almost the entire cross-section of the channel, thereby making the side-walls partially dry, the liquid phase always remained continuous because of the fact that the liquid was drawn into the triangular corners by surface tension. As far as steam-water flow is considered, their investigation focuses on a study of incipient boiling and bubble behavior at lower values of inlet liquid velocity. The experiments showed explosive bubble behaviour. The location (along the test section) of the appearance of the first bubble at a given flow rate, depends on local surface temperature variation. A. Kawahara, P.M.-Y. Chung, M. Kawaji (2002) carried out experimental investigation on two-phase flow characteristics in a 100 lm diameter circular tube. They determined two-phase flow patterns by video recording the flow in the transparent capillary tube made of fused silica, in which de-ionized water and nitrogen gas were injected at superficial velocities of JG ¼ 0:1–0:6 m/s for gas, and JL ¼ 0:02–4 m/s for liquid. Time-averaged void fraction and two-phase friction pressure drop data were also obtained and analyzed in their work. The observed flow patterns were intermittent and semi-annular flows, but a closer study of the liquid film structure revealed gas core flows with a smooth or ring-shaped film and a serpentine-like gas core surrounded by a deformed liquid film. Bubbly and churn flow patterns were not observed during investigation as seen in fig.2. Void fraction remained low even at high gas flow rates, indicating large slip ratios and weak momentum coupling between the phases.

Akimi Serizawa, Ziping Feng, Zensaku Kawara (2002) carried out visualization of Gas–liquid two-phase flow patterns are with a microscope for air–water flow in circular tubes of 20, 25 and 100 lm i.d. and for steam–water flow in a 50 lm i.d. circular tube. The superficial velocities were varied over a broad range of JL ¼ 0:003–17:52 m/s and JG ¼ 0:0012–295:3 m/s for air–water flows. Several flow patterns, like dispersed bubbly flow, gas slug flow, liquid ring flow, liquid lump flow, annular flow, frothy or wispy annular flow, rivulet flow, liquid droplets flow and a special type of flow pattern were identified both in air–water and steam–water systems. It was confirmed that two phase flow patterns are sensitive to the surface conditions of the inner wall of the test tube. It was evident that a stable annular flow and gas slug formation with partially stable thin liquid film formed between the tube wall and gas slugs appeared at high velocities under treated clean surface conditions. Dry and wet areas exist between gas slug and the tube wall at lower velocities. The cross-sectional average void fraction was also calculated and it showed a good agreement with the Armand correlation for air–water flow in larger tubes. V. G. Niño, P. S. Hrnjak and T. A. Newell (2002) carried out experimental investigation of void fraction and frictional pressure drop in micro channels. Another important goal of their work was two-phase flow behaviour understanding and experimental analysis. Experiments were performed with a 6-port and a 14-port micro channel with hydraulic diameters of 1.54 mm and 1.02 mm, respectively. Mass fluxes from 50 to 300 kg/s.m2 were operated, with quality ranging from 0% to 100% for two-phase flow experiments. R410A, R134a, and air-water mixtures were used as primary fluids. The results from the flow visualization studies indicated that several flow configurations may exist in multi-port micro channel tubes at the same time while constant mass flux and quality flow conditions are maintained. Experimental analysis and flow observations suggested that pressure drop and void fraction in micro channel is dependent on the most probable flow regime at which the two-phase
mixture is flowing. In general, their work pointed to a fact that correlations for void fraction and pressure drop predictions are based in a separated flow model and do not predict the experimental results in the range of conditions investigated. \textbf{Weilin Qu, Issam Mudawar (2003)}\cite{10} explored hydrodynamic instability and pressure drop in a water-cooled two-phase micro-channel heat sink containing 21 parallel 231x713 lm micro-channels which were severe pressure drop oscillation and mild parallel which can trigger pre-mature critical heat flux, can be eliminated simply by throttling the flow upstream of the heat sink. Different methods were assessed for predicting two-phase pressure drop for suitability to micro-channel heat-sink design. Generalized two-phase pressure drop correlations were examined, which include 10 correlations developed for both macro- and mini/micro-channels. They proposed a new correlation incorporating the effects of both channel size and coolant mass velocity which shows better accuracy than prior correlations. They gave a theoretical annular two-phase flow model which, aside from excellent predictive capability, possesses the unique attributes of providing a detailed description of the various channel instability. Their work showed that the severe pressure drop oscillation, transport processes occurring in the micro-channel, as well as fundamental appeal and broader application range than correlation. \textbf{Weilin Qu, Issam Mudawar (2003)}\cite{11} developed an annular flow model to predict the saturated flow boiling heat transfer coefficient. Two-phase micro-channel flow unique features, such as laminar liquid and vapour flow, smooth interface, and strong droplet entrainment and deposition effects, were identified and incorporated into their model. Their model correctly captured the unique overall trend of decreasing heat transfer coefficient with increasing vapour quality in the low vapour quality region of micro-channels. Fairly good agreement was achieved between the model predictions and heat transfer coefficient data over broad ranges of flow rate and heat flux. \textbf{Hassan, P. Phutthavong, and M. Abdelgawad(2004)}\cite{12} provided an overview of the research performed thus far in the field of micro channel heat sinks. There are many other research fields concerning micro channel heat sinks that have yet to be explored. This section will summarize the possible future directions of research that may be followed in order to obtain greater understanding of these micro devices. Effect of coolant types should be investigated more thoroughly. Liquids seem to provide superior cooling properties when compared to gases, since they offer lower thermal resistance. Water has been the coolant of choice for most experiments because it is readily available and cheap and has a high specific heat capacity. Yet, still the effect of the type of the liquid used is not studied. CFD packages could be used to simulate various types of coolants and help predict which one provides better cooling capabilities at affordable costs. Experiments may be performed later to validate the simulations’ results. \textbf{E. W. Jassim, T. A. Newell, and J. C. Chato (2006)}\cite{13} investigated with a purpose to develop models for two-phase heat transfer, void fraction, and pressure drop, three key design parameters, in single, smooth, horizontal tubes using a common probabilistic two phase flow regime basis. Probabilistic two-phase flow maps were experimentally developed for R134a at 25 °C, 35°C, and 50 °C, R410A at 25 °C, mass fluxes from 100 to 600 kg/m2-s, qualities from 0 to 1 in 8.00 mm, 5.43 mm, 3.90 mm, and 1.74 mm I.D. horizontal, smooth, adiabatic tubes in order to extend probabilistic two-phase flow map modelling to single tubes. An automated flow visualization technique, utilizing image recognition software and a new optical method, was developed to classify the flow regimes present in approximately one million captured images. The probabilistic two-phase flow maps developed were represented as continuous functions and generalized based on physical parameters. Condensation heat transfer, void fraction, and pressure drop models were developed for single tubes utilizing the generalized flow regime map developed. The condensation heat transfer model was compared experimentally obtained condensation data of R134a at 25 °C in 8.915 mm diameter smooth copper tube with mass fluxes ranging from 100 to 300 kg/m2-s and a full quality range. \textbf{Renqiang Xiong (2007)}\cite{14} performed some experimental and numerical investigations. He evaluated the pressure drops of liquid flow in straight and serpentine micro-channels with hydraulic diameters of 0.209 mm, 0.412 mm, and 0.622 mm. Three types of micro-channels: straight short, straight long, and long serpentine, were fabricated. Adiabatic nitrogen-water flow patterns and void fractions in straight micro-channels were experimentally investigated. Gas and liquid superficial velocities were varied from 0.06-72.3 m/s and 0.02-7.13 m/s, respectively. The instability of flow patterns was observed. Four groups of flow patterns including bubbly-slug flow, slug-ring flow, dispersed-churn flow and annular flow were observed in micro-channels of 0.412 mm and, 0.622 mm while in the micro-channel of 0.209 mm, the bubbly-slug flow became the slug-flow and the dispersed-churn flow disappeared. The flow regime maps showed that the transition lines shifted to a higher gas superficial velocity due to a dominant surface tension effect as the channel size was reduced. The void fractions held a non-linear relationship with the homogeneous void fraction as opposed to the relatively linear trend for the mini-channels. He developed a new correlation to predict the non-linear relationship that fits most of the current experimental data within ±15%. \textbf{Renqiang Xiong and J. N. Chung (2007)}\cite{15} studied adiabatic gas-liquid flow patterns and void fractions in micro channels experimentally. Nitrogen and water were used in rectangular micro channels with hydraulic diameters of 0.209 mm, 0.412 mm and 0.622 mm, respectively. Superficial velocities of gas and liquid were varied from 0.06–72.3 m/s 0.02–7.13 m/s, respectively. Their work focused mainly on the effects of macroscale channel sizes on the flow regime map and void fraction. Flow pattern instability was observed. Flow patterns including four groups namely bubbly slug flow, slug-ring flow, dispersed-churn flow, and annular flow were observed in micro channels of 0.412 mm and, 0.622 mm. The micro channel of 0.209 mm, showed the change from the bubbly slug flow to the slug flow and the dispersed-churn flow disappeared. The obtained flow regime maps reflected that the transition lines shifted to higher gas superficial velocity due to
a dominant surface tension effect with the channel size reduction. The regime maps given by other authors for minichannels were found not to be applicable for micro channels. G.P. Celata (2008)\(^{[16]}\) presented a critical evaluation of existing works in the field of heat transfer of single (liquid) and two-phase flow (boiling) in micro channels. There is more and more the general agreement on the validity of macroscale knowledge going down to microscale as far as liquid single phase flow heat transfer is concerned. The scale reduction gives relevance to some effects such as viscous dissipation (or viscous heating, due to the general large pressure drop associated with micro channel flow), thermal entrance (due to the generally short geometry of micro channels) and axial length (associated with the general large thickness of the micro channels), which becomes very important in microscale. Their neglectfulness is bounded to give poor analysis of heat transfer data misleading the possible correct conclusion of the experimental outcome. Once these so-called scaling effects are properly accounted for, microscale heat transfer in liquid single-phase flow looks well predictable using current knowledge of macroscale, such as Gnielinski (1978) correlation for turbulent flow and \( Nu = 4.36 \) equation for laminar flow. Occurrence of scaling effects can also be used to identify the threshold between micro- and macroscale, which depends not only on the geometry but also on fluid physical properties. More accurate experiments are still needed, though the knowledge looks now more assessed. Boiling heat transfer in microscale is associated with bubble confinement in the reduced scale, which is definitely expected to alter the flow dynamics inside the small size channel. Because of that, divergence between macroscale knowledge (often based on empirical bases or experimental evidences) is clearly awaited and understandable. Also conclusions drawn from the experimental data in tubes, estimated from the findings of boiling heat transfer in macroscale (nucleate versus forced convective boiling), might have led to erroneous conclusions about the type of boiling regime in microscale. Recent theoretical works, supported by first visualization works, have supposed a different boiling mechanisms for micro channels, based on elongated bubble existence and evaporation of thin liquid layer between the elongated bubble and the channel wall. This paper points out to need for further work to possibly validate the existing theory or produce new insights for a better mechanistic modelling of boiling heat transfer. M. M. Awad and Y. S. Muzychka (2010)\(^{[17]}\) have presented three different methods for two-phase flow modelling in micro channels and minichannels. They are effective property models for homogeneous two-phase flows, an asymptotic modelling approach for separated two-phase flow, and bounds on two-phase frictional pressure gradient. In the first method, new definitions for two-phase viscosity were proposed using a one-dimensional transport analogy between thermal conductivity of porous media and viscosity in two phase flow. The new definitions given by them can be used to compute the two-phase frictional pressure gradient using the homogeneous modelling approach. In the second method, a simple semitheoretical method for calculating two-phase frictional pressure gradient using asymptotic analysis is presented. Two-phase frictional pressure gradient is expressed in terms of the asymptotic single-phase frictional pressure gradients for liquid and gas flowing alone. In the final method, simple rules are developed for obtaining rational bounds for two-phase frictional pressure gradient in minichannels and micro channels. In all cases, the proposed modelling approaches are validated using the published experimental data.

### B. Numerical Study Of Two Phase Flow In Microchannel Heat Sinks

Literature shows that the micro channels and micro channels heat sinks were studied extensively, but it was found that there is limited research related to the performance study of micro channel heat exchangers using CFD models. Fundamental understanding of the characteristics of the heat transfer and fluid flow in micro channel are necessary for effective design of micro channel heat exchanger. The designs and relations of macro scale fluid flow and heat transfer were employed in earlier times. Numerical simulations give the strength to investigate small details that are impossible to observe in experiments.

Bogdan Alexandru Nichita (2010)\(^{[18]}\) used FLUENT in the study to model adiabatic and diabatic, time dependent two-phase flows. This work involved using a fifth order WENO (Weighted Essentially Non Oscillatory) scheme to discretize the space derivatives (otherwise oscillations of the interface occurred), and first order Euler method for the time integration. In another part of their study, a 3D dynamic contact angle model based on volume fraction, interface reconstruction, and experimentally available advancing and receding static contact angles was also developed and implemented into FLUENT via UDFs. Several validations for the developed CLSVOF method and dynamic contact angle model were presented in this thesis, which included a static bubble, a bubble rising in a stagnant liquid for Morton numbers ranging from 102 to 10−11, droplet deformation due to a vortex flow field, droplets spreading over a wall under the gravity effect and droplets sliding over a wall due to gravity. The validations demonstrated the high accuracy and the stability of their methods for modelling these phenomena. A heat and mass transfer model was also implemented into the commercial CFD code FLUENT for simulation of boiling (and condesation) heat transfer. Several simulations were presented with water and R134a as working fluids. Several 2D and 3D test were performed for air/water on a coated silicon wafer surface with different gravity vectors, which proved the accuracy of our model when compared to both numerically and experimentally data available in the literature.

Aakash Kumar Pandey (2011)\(^{[19]}\) predicted the experimental work done by Lee and Mudawar (2007) by CFD results. The hydrodynamics and thermal behaviour of a rectangular micro channel were studied here. The variation in wall temperature, pressure drop in the channel and the friction factors were calculated using ANSYS Fluent. The effect of Re on the behaviour the channel was also studied. The relation between heat transfer coefficient and thermal conductivity of the fluid i.e. \( h \propto k \) was proved his study. It was found that the entrance length

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Phase change can greatly enhance the performance of a micro-channel heat sink by providing higher convective heat transfer coefficients, better axial temperature uniformity, and reduced coolant flow rate requirements. Unfortunately, the number of investigations into fluid flow and heat transfer characteristics of two phase microchannel heat sinks is very limited. Table 1 summarises current status of understanding of transport phenomenon in microchannel heat sinks. [5]

### IV. CONCLUSION AND FUTURE DIRECTIONS

The present manuscript presents a critical evaluation of existing works in the field of heat transfer of two-phase flow in microchannel heat sinks. The literature survey provides with many works in this field, the accuracy of which is increasing with date, recent works being the most accurate. The study of flow and heat transfer in micro channels is very important for the technology of today and the near future, as it is evident from the diversified application areas of micro channel heat exchangers. The trend of miniaturization in all fields is the demand of time and field of heat exchange is no different. Literature shows that the micro channels and micro channels heat sinks were studied extensively, but it was found that there is limited research related to the performance study of micro channel heat exchangers using CFD models. Fundamental understanding of the characteristics of the heat transfer and fluid flow in micro channel are necessary for effective design of micro channel heat exchanger. It was found from literature survey that results found so far are not in strong agreement with each other, many variations were observed.

Effect of coolant types should be investigated more thoroughly. Liquids seem to provide superior cooling properties when compared to gases, since they offer lower thermal resistance. Water has been the coolant of choice for most experiments because it is readily available and cheap and has a high specific heat capacity. Yet, still the effect of the type of the liquid used is not studied. CFD packages could be used to simulate various types of coolants and help predict which one provides better cooling capabilities at affordable costs. Experiments may be performed later to validate the simulations’ results.

The field of two phase flow is still in its youth and needs much more attention. It can be concluded that in all for two phase flow behaviour in micro channel heat exchanger use of more sophisticated computational packages should be used which are specifically tailored to its needs so that strong validations can be found for existing experimental results. Recent theoretical works, supported by first visualization works, have supposed a different flow patterns and void fraction and pressure drop relations. Much work is still required to possibly validate this theory or produce new insights for a better mechanistic modelling of two phase heat transfer.
Boiling instabilities in two-phase microchannel heat sinks should be studied thoroughly. Instabilities were observed and were attributed to large pressure drops. Lateral instabilities also exist in wide microchannels. The fluid was observed to revert back to liquid upon boiling, and to begin boiling once again in cycles that last up to a few minutes. Hestroni et al. [6] noticed erratic pressure and temperature variations in two-phase microchannel heat sinks. These instabilities will hinder the implementation of microchannel heat sinks in commercial applications as long as they exist unexplained.

Different microchannel geometries should be tested to see if one shape in particular yields a better cooling performance. Experimental data for different geometries should be tested for two-phase flow in order to generate accurate flow regime maps that may be able to predict the flow pattern. Transitional flow regimes should also be clearly and universally defined in experiments in order to avoid confusion when attempting to model the flow regime maps. This experimental data will also be useful in generating models that may predict the heat transfer coefficient associated with two-phase flow in microchannels.

Fluid properties are affected by variations in temperature; however, most of the studies cited did not consider this fact. Studies accounting for the temperature-dependent fluid properties will certainly give more accurate and realistic results than constant fluid properties studies, thus predicting the real performance of microchannel heat sinks.

Spatially varying heat fluxes should be investigated further in the future. There was but one study that assumed spatially varying heat fluxes, which concluded that the best two-phase microchannel heat sinks have 80% of the total heat flux applied to the latter half of the channel. Future work might provide other nonuniformity patterns that may enhance microchannel heat sink performance.

Area worthy of new investigations have been identified and recommended, such as identification of micro-to-macroscale transition, critical heat flux, visualization, flow pattern transition, flow instability, two-phase pressure drop.

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