INVITED PAPER

On-Chip Thermal Management With Microchannel Heat Sinks and Integrated Micropumps

Coolant liquid could be moved through tiny channels on chip surfaces if suitably small and powerful pumps were developed and incorporated into these channels.

By Suresh V. Garimella, Vishal Singhal, and Dong Liu

ABSTRACT | Liquid-cooled microchannel heat sinks are regarded as being amongst the most effective solutions for handling high levels of heat dissipation in space-constrained electronics. However, obstacles to their successful incorporation into products have included their high pumping requirements and the limits on available space which precludes the use of conventional pumps. Moreover, the transport characteristics of microchannels can be different from macroscale channels because of different scaling of various forces affecting flow and heat transfer. The inherent potential of microchannel heat sinks, coupled with the gaps in understanding of relevant transport phenomena and difficulties in implementation, have guided significant research efforts towards the investigation of flow and heat transfer in microchannels and the development of microscale pumping technologies and novel diagnostics. In this paper, the potential and capabilities of microchannel heat sinks and micropumps are discussed. Their working principle, the state of the art, and unresolved issues are reviewed. Novel approaches for flow field measurement and for integrated micropumping are presented. Future developments necessary for wider incorporation of microchannel heat sinks and integrated micropumps in practical cooling solutions are outlined.

KEYWORDS | Electronics cooling; heat transfer; integration; microchannel heat sinks; micropumps

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I. INTRODUCTION

Continued increases in the density and speed of transistors in microprocessors have led to a rapid rise in the rate of heat generation in chips, as well as in the heat fluxes that need to be dissipated for maintaining chip temperatures below allowable maximum levels. Conventional fan-cooled heat sinks are fast reaching their limits for handling the increased cooling needs for processors in desktop computers and small-to-medium servers. Many new competing technologies have been proposed (as reviewed in [1]), among which liquid-cooled microchannel heat sinks are recognized as being among the most effective solutions. Other technologies such as spray cooling, thermoelectrics, microjets, and thin-film evaporation are either yet to be developed for implementation or suffer from noise, efficiency, or cost issues. Microchannel heat sinks consist of closed parallel channels with rectangular, trapezoidal, or triangular cross sections with hydraulic diameters ranging from 100 to 1000 μm. Microchannel heat sinks can be used either with single-phase flow, where heat is transferred from the electronic chip via sensible heat gain by the coolant, or with two-phase flow which also utilizes the latent heat of the coolant during liquid/vapor phase change.

The pump used to move coolant through the microchannel heat sinks is required to provide high flow rates so that high heat fluxes may be handled while minimizing temperature gradients on the chip. The pump must also overcome the large pressure drops encountered in flow through the small channel cross sections of microchannels. In addition, the pump must be small, lightweight, quiet, energy-efficient, low-cost, and reliable. The use of conventional pumps would not only be size- and price-prohibitive, but would also suffer from noise issues. Micropumps are an attractive alternative, as they can be smaller by more than an order of magnitude while

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providing the same flow rate; cheaper, since they are generally based on nonmechanical phenomena; noiseless; and reliable. Development of micropumps has largely been focused on micro total analysis systems (μ-TAS) and drug-delivery applications, which require low but well-controlled flow rates. Micropumps for microchannel heat sinks, on the other hand, must provide high flow rates and high pressure heads. Hence, most micropump designs presented in the literature are not suitable for use with microchannel heat sinks. Integration of micropumps into microchannels can lead to further compactness and a reduction in system cost as the fabrication of microchannels and micropumps can be integrated into the same process stream. However, integration into microchannels would require further miniaturization of micropumps and also add additional constraints which would limit their performance in terms of the flow rate and pressure head generated.

The thermal capabilities, state of the art, and performance limits of microchannel heat sinks and micropumps are presented in this paper. The flow and heat transfer in microchannel heat sinks, including diagnostic techniques for flow field measurements and choice of the working fluid, are then discussed. This is followed by an analysis of micropumps and their integration into microchannel heat sinks.

II. CAPABILITY OVERVIEW

Significant research effort has been directed towards the development of microchannel heat sinks and micropumps over the last two decades. The capabilities of microchannel heat sinks and the performance of micropumps reported in the literature are reviewed in this section.

A. Microchannels

Heat transfer in single-phase flow through a heat sink can be calculated using

$$q = \mathrm{Nu} \cdot k \cdot \Delta T \cdot A / D_h \tag{1}$$

in which k is the coolant thermal conductivity, ΔT_f the mean temperature difference between the substrate and the coolant, A the wetted area of the heat sink, D_h the hydraulic diameter of an individual microchannel (equivalent diameter of channel with noncircular cross section), and Nu the Nusselt number. The Nusselt number represents the nondimensional temperature gradient at the wall and is a measure of convection heat transfer. For fully developed flow in a channel of given shape, the Nusselt number is a constant irrespective of channel size. For rectangular channels with a depth-to-width aspect ratio of four with uniform heat flux on all four walls of the channel, $\mathrm{Nu} = 5.33$ [2]. Assuming a driving temperature difference of 30 °C between the substrate and water, 433 W of heat can be removed from a 1 cm × 1 cm chip using a microchannel heat sink with 100-μm-wide by 400-μm-deep channels separated by 50-μm-thick walls. Decreasing the channel width to 50 μm and depth to 200 μm, the heat removal rate from the chip can be increased to 650 W.

Even larger heat transfer rates can be achieved when the coolant is allowed to boil in the channels. The specific heat of water is 4.18 kJ/kg · K, while its latent heat is 2400 kJ/kg. Therefore, for the same mass flow rate, ten times more heat can be removed via boiling than with single-phase convection (allowing a 50 °C streamwise temperature rise of liquid water). Conversely, if the heat load is unchanged, only one-tenth the flow rate of coolant would be required for a two-phase microchannel heat sink when compared to the single-phase counterpart. This may help to alleviate the large pumping power requirements of microchannel heat sinks. In addition, much better temperature uniformity (and lowered thermal stresses) can be maintained over the chip, since the heat sink temperature would be limited to a value set by the saturation point of the coolant once boiling commences. In single-phase convection, much larger coolant flow rates would be necessary to achieve similar levels of temperature uniformity over the substrate.

Microchannel heat sinks can also be implemented in a manner that alleviates the increasingly significant problem of contact and spreading resistances in the thermal path between the chip and the heat sink. Microchannels may be etched into the back end of a chip or, alternatively, a microchannel heat sink can be attached to it, thus entirely eliminating or greatly reducing these intermediate thermal resistances. Since the temperature drop across a given thermal resistance increases with increasing heat load, a reduction of contact and interface resistances is critical at the increasing heat loads being dissipated.

Several experimental studies on microchannel heat sinks under both single-phase and two-phase operation have demonstrated very high heat transfer rates, as shown in Fig. 1 [3]–[9]. Results for both single-phase [3], [8] and subcooled two-phase operation [4]–[7], [9] are included, obtained using microchannel heat sinks [3], [8], [9] or single microtubes. Some of the very high heat fluxes observed in single tubes may not be easily scaled to heat sink operation, especially for two-phase flow, due to the significant preheating and boiling that would occur in the inlet manifold feeding the multiple, parallel channels.

Since heat transfer in microchannel heat sinks relies on the transfer of energy from substrate to coolant via convection, the cooling capability is proportional to the coolant flow rate. As long as an adequate supply of coolant can be maintained, there is no theoretical limit to the heat transfer rate that can be obtained in the heat sink. The primary obstacle in the practical application of microchannel heat sinks is thus the pumping requirement,

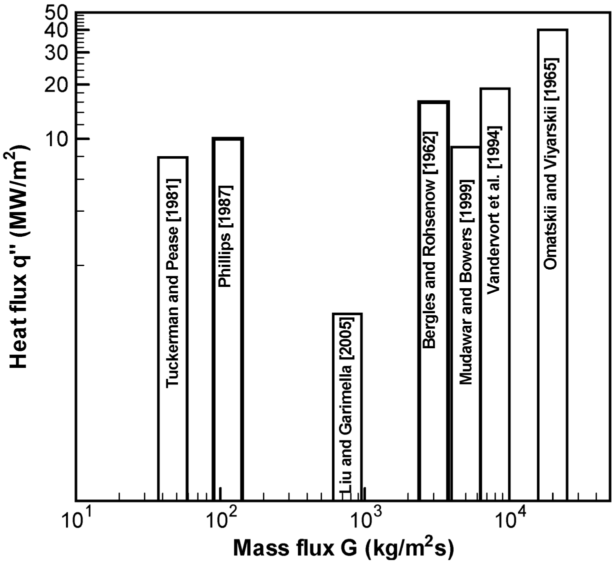

Fig. 1. ***Heat dissipation rates achieved with microchannels in the literature.***

which is especially pronounced in the case of single-phase flow. Two-phase operation requires lower coolant flow rates, although flow instabilities in the channels resulting from transitions between different boiling regimes in different parallel channels poses challenges for pump operation.

B. Micropumps

The primary metrics in measuring the performance of a micropump is the flow rate per unit volume and pressure head generated. Other important metrics in their selection are power consumption, input voltage, cost, and reliability. The performance of selected micropumps is summarized in Table 1 in terms of their flow rate (maximum flow rate at zero pressure head), pressure head (max head at zero flow rate), size (volume), and flow rate per unit volume. Information for a small conventional centrifugal pump [10] is also provided for reference.

The maximum flow rate among all the micropumps in Table 1 is 14 ml/min of ethanol obtained with an injection EHD pump [11]. This pumping capability compares favorably with a requirement of 29.2 ml/min of water to remove 100 W from a chip, assuming a temperature rise of 50 °C in the fluid. However, the performance of this pump degrades over time, and also, the pump does not function well with water due to electrolysis of water and formation of gases which in turn leads to performance degradation. The MHD pump included in the table with a liquid metal flow rate of 406 ml/min also appears to provide the required pumping rates [12]. However, it can only be used with fluids of high electrical conductivity, specifically liquid metals, the use of which may not be suited to many electronics cooling applications. An external (stand-alone) electroosmotic pump with an observed flow rate of 7 ml/min of buffered DI water is another attractive option [13], [14].

However, all of these pumps are for external use (as opposed to being integrated into microchannels), and would claim additional space in increasingly compact computers and consumer electronics. The true potential of micropumps may be realized by integrating them directly into the microchannel heat sinks. A significant advantage of integration, besides the obvious gains in terms of

Table 1 Quantitative Comparison of Selected Micropumps

Micropump Description	Q_{max} (μl/min)	$p_{back,max}$ (kPa)	Volume (mm^3)	Q_{max}/Volume (μl/min. mm^3)	Reference
Rotary micropump with a magnetic micromotor	350 (water)	14	6.03 (without motor)	58.05	Dewa et al. (1997) [15]
Vibrating diaphragm micropump with piezoelectric actuation	1500 (water)	17	42.14	35.60	Stehr et al. (1996) [16]
Valveless nozzle-diffuser micropump with piezoelectric actuation	1500 (ethanol)	1	122.4	12.25	Schabmueller et al. (2000) [17]
MHD micropump	4.06×10^5 ($Ga^{61}In^{25}Sn^{13}Zn^1$)	8	4400	92.31	Miner and Ghoshal [12]
External electroosmotic micropump	7000 (1 mM buffered DI water)	160	1413 (active volume)	4.95	Jiang et al. (2002) [13]
Electroosmotic micropump integrated into microchannels	15 (DI water)	151.99	3.42×10^{-3}	4385.96	Chen et al. (2000) [18]
Injection EHD micropump	14,000 (ethanol)	2.48	6.84	2046.78	Richter et al. (1991) [11]
Flexural plate wave micropump using piezoelectric actuation	1.6 (Fluorinert)		3.42×10^{-3}	666.67	Black and White (1999) [19]
Mini centrifugal magnetic drive pump	1.14×10^7	344.74	8.98×10^5	12.67	Cole-Parmer Product Manual [10]

reduced size and weight, is the potentially lower cost which could result from integrating the fabrication process of the micropumps with that of the microchannels. In the integration of micropumps into microchannels, the flow rate per unit volume achievable by the pump needs to be assessed. Different pump designs in the literature can be compared based on this parameter, as in Table 1, which shows a wide variation in this value ranging from 4.95 μl/min $\cdot$ mm^3 to 4385.96 μl/min $\cdot$ mm^3. The previously estimated flow rate of 29.2 ml/min required to remove 100 W using a microchannel heat sink from a 1 cm $\times$ 1 cm chip translates into a flow rate per unit volume requirement of 1095 μl/min $\cdot$ mm^3. It is clear from Table 1 that some of the pumps (rotary [15], vibrating diaphragm [16], valveless [17], MHD [12] and external electroosmotic [13]) would not achieve the required flow rate if integrated into microchannels. However, three pump designs—injection EHD, integrated electroosmotic [18], and flexural plate wave [19]—appear to satisfy this requirement. Integration of micropumps into microchannels is discussed further in Section IV.

Among the three candidate designs, the electroosmotic and flexural plate wave pumps use surface forces, which scale as L^2, while the injection EHD micropump uses volume forces which scale as L^3, L being the characteristic length. For pumps using surface forces, flow rate per unit surface area is a more suitable parameter to estimate their performance. To remove 100 W with the microchannel heat sink described above, this translates to a 438-μl/min $\cdot$ mm^2 requirement, while an integrated electroosmotic pump and flexural plate wave pump would provide 0.39 and 10.67 μl/min $\cdot$ mm^2, respectively [20]. These pumps thus may not be suitable for integration into parallel-channel microchannel heat sinks.

In conclusion, although several micropump designs have been presented in the literature which can achieve the flow rate required by microchannel heat sinks, there are few if any candidates suitable for integration operation within microchannels. A detailed literature review of micropump designs discussed in the literature is available in [20], where the performance of a wide variety of micropumps is quantitatively compared.

III. MICROCHANNELS

The current understanding of microchannel heat transport is reviewed in this section, with an emphasis on the information necessary for successful practical implementation of microchannel heat sinks in electronics cooling applications.

A. Single-Phase Heat Transfer

The fluid flow and heat transfer phenomena in microchannels can be different from the corresponding transport in macroscale channels, since the various forces affecting flow and heat transfer scale differently, and take on different levels of dominance as the dimensional scales are reduced. Single-phase transport characteristics are quantified in terms of the friction factor for pressure drop and Nusselt number for heat transfer, as a function of the Reynolds number

$$\mathrm{Re} = u_m D_h / \nu \tag{2}$$

which is a measure of the relative importance of inertial and viscous forces, in which u_m is the mean velocity of the bulk fluid, D_h the hydraulic diameter of the microchannel, and ν the kinematic viscosity of the fluid.

Quantitative comparison of the experimental results reported in the early literature shows large deviations between the different studies, not only in magnitudes but also in trends of variation of friction factor and Nusselt number with Reynolds number [21]. The product of friction factor and Reynolds number from these studies [22]–[25] is plotted against Reynolds number in Fig. 2(a) on a log-log scale; heat transfer results [23], [26]–[28] are compared to predictions from conventional correlations in Fig. 2(b). Only the laminar regime is considered in the figures, from which it is clear that the results from different studies varied widely and most deviated from the theoretical predictions. These results have been variously cited to support the existence of differences in the physics at macro and micro scales. Similar differences were observed in the literature for turbulent flow [29].

In view of the wide disparities in the early literature on pressure drop and heat transfer in microchannels, carefully designed experiments [30], [31] were recently performed to understand the reasons for these discrepancies. An experimental facility was designed to conduct fluid flow and heat transfer experiments in microchannels with hydraulic diameter ranging from 250 to 1000 μm. The experimentally determined friction factors are plotted against Reynolds number and compared to the predictions from conventional correlations in Fig. 3. A similar plot for heat transfer, in which experimentally determined Nusselt numbers are compared to predictions from correlations for conventional channels, is presented in Fig. 4. The good agreement between the experimental results and theoretical predictions indicates that the hydrodynamic and thermal behavior in microchannels is not different from that of conventional channels. Other recent investigations [32]–[35] have also confirmed this understanding. Discrepancies in earlier studies seem to have originated from mismatched entrance and boundary conditions, or difficulties with instrumentation. It has now been conclusively shown that a conventional Navier-Stokes approach, coupled with carefully matched entrance and boundary conditions, can be employed with confidence for

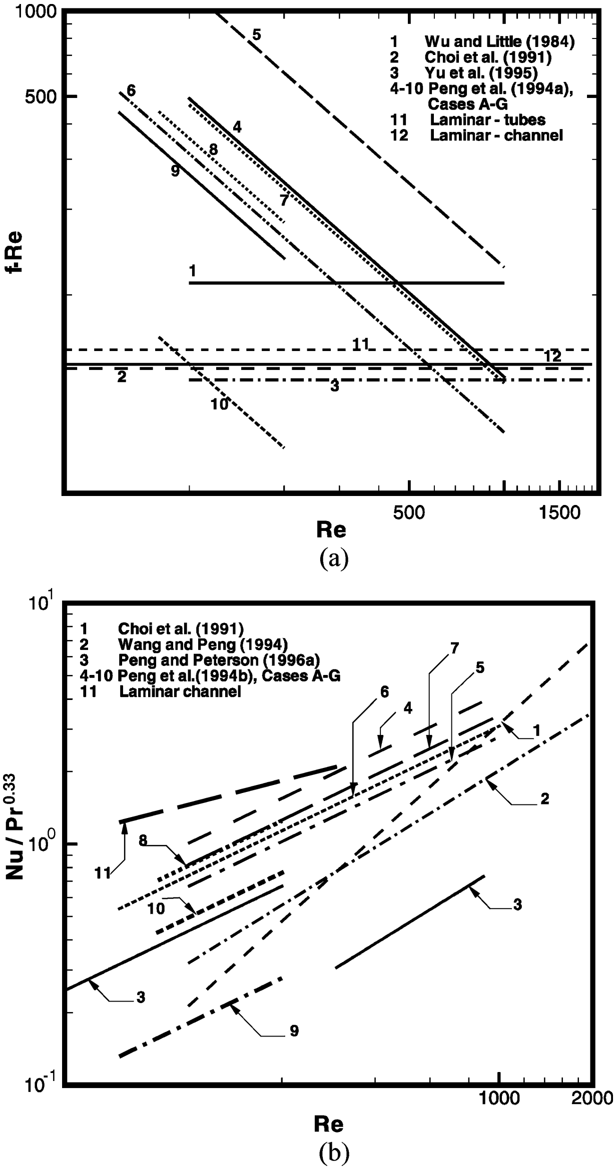

Fig. 2. ***Comparison of friction factor (pressure drop) and heat transfer from experiments and theoretical predictions for laminar flow in microchannels and microtubes [21]. In both graphs, trends 1–10 are from experiments and the rest are from theory.***

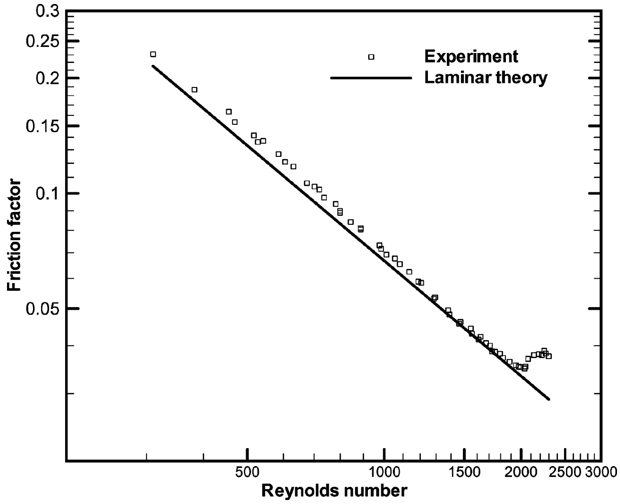

Fig. 3. ***Variation of friction factor with Reynolds number: D_h of 324 μm [30].***

predicting single-phase flow and heat transfer in microchannels in the size ranges relevant to electronics thermal management.

B. Two-Phase (Boiling) Heat Transfer in Microchannels

Convective boiling and two-phase flow in small-scale channels has also been widely studied. In spite of its appealing attributes—namely, a low flow rate requirement and uniform substrate temperature—the complex nature of convective flow boiling has hindered wide usage of two-phase flow in consumer products [7]. However, research efforts on this topic are being intensified [36], and should lead to improved predictive capabilities which facilitate implementation in practical applications. The discussion here focuses on topics of immediate importance to electronics cooling; more detailed reviews of two-phase flow and heat transfer research at the microscale are available in [29], [37]–[39].

Two-Phase Flow Patterns: Boiling is accompanied by the appearance of vapor in the liquid coolant as it absorbs heat and changes its state. Depending on the heat load and flow

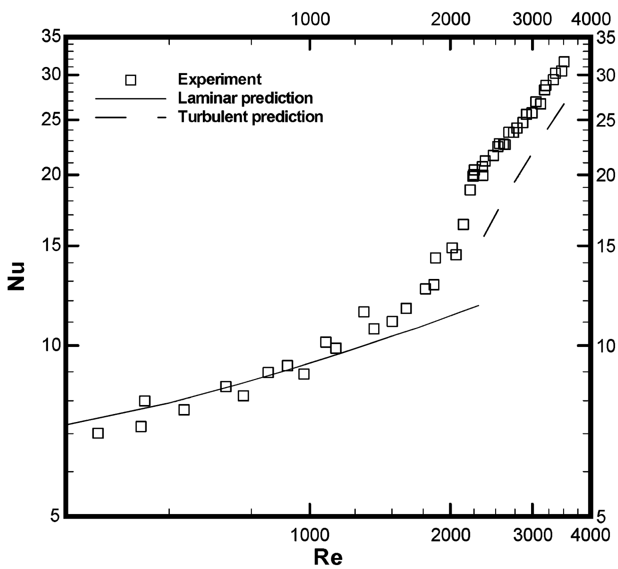

Fig. 4. ***Nusselt numbers for the 229-μm-wide microchannels [31].***

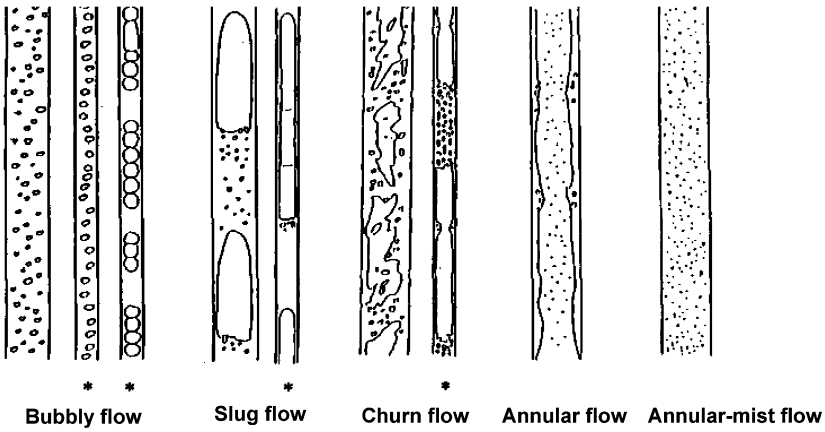

Fig. 5. *Observed flow patterns: bubbly, slug, churn, annular, and annular-mist flows in microchannels [41]; for bubbly, slug, and churn flows, the results for microchannels are denoted by asterisks. (Reproduced with permission.)*

rate, the liquid–vapor mixture assumes various morphological structures, or flow patterns. Due to the small dimensions of microchannels, the flow patterns can be dramatically different from those in larger channels [37], [39]. Identification of the flow patterns is necessary for the characterization of two-phase flow pressure drop, heat transfer, and boiling mechanisms. It also offers useful information in predicting premature dryout and designing the manifolds of two-phase heat sinks [37].

Several approaches are employed to study flow patterns. A popular approach is to introduce an air-water mixture into capillary tubes and study flow under adiabatic conditions [40]–[44]. Typical results from such studies are shown in Fig. 5 [41]. Five different flow patterns—bubbly, slug, churn, annular, and annular-mist flows—can be identified. For bubbly, slug, and churn flows, results on the left are for macroscale tubes while those on the right are for smaller tubes with inner diameters from 1 to 4 mm (denoted by the asterisks). For these three regimes, flows in the smaller tubes are seen to be significantly different from those in large tubes. Similar studies have been reported for tubes with much smaller inner diameters of 25 and 100 μm [42].

Another approach for studying flow patterns is to generate two-phase flow by supplying heat to the coolant (diabatic flow) in the microchannels. While this approach represents the heat transfer process in heat sinks more faithfully, systematic studies of diabatic two-phase flow patterns in microchannels are being attempted only recently [45]–[57]. Wu and Cheng studied the flow boiling of water in microchannels of trapezoidal cross section with hydraulic diameters of 158.8 and 82.8 μm [45], [46]. They observed that single-phase and two-phase flow alternate once boiling commences with large-amplitude and long-period fluctuations in the wall temperature, fluid temperature, fluid pressure, and fluid mass flux. As shown in Fig. 6, slug flow and churn flow were observed frequently for smaller microchannels, while bubbly flow was more common in larger microchannels. Several other studies [48]–[57] have also attempted to identify flow patterns in microchannels under specific flow and thermal conditions. Two important features of two-phase flow in microchannels are apparent from these studies. First, due to the dominance of surface tension over viscous and inertial forces at the microscale, the microchannel flow patterns exhibit significant differences from those in larger channels, such as the absence of stratified flow and the unique structures of bubbly and slug flows. Second, under diabatic conditions, two-phase flow in microchannels is highly transient and is characterized by the intermittent appearance of different flow patterns. Hence, information from macroscale two-phase flow pattern studies cannot be directly applied to microchannels.

Pressure Drop and Heat Transfer: A number of studies [40], [44], [58]–[69] have considered pressure drop and heat transfer under two-phase flow in microchannels, and a variety of correlations and models have been proposed. The majority of pressure drop correlations reported can be viewed as modified forms of one of the two classical one-dimensional two-phase flow models: the homogeneous flow model and the separated flow model. The homogeneous flow model assumes that two-phase flow behaves like single-phase flow with averaged fluid properties (weighted means of properties of the liquid and vapor phases). The separated flow model treats the two phases separately while assuming that the velocity of each phase is uniform but not necessarily equal to that of the other phase, and that the two phases are in local thermodynamic equilibrium [70]. The former model is particularly valid for bubbly flow while the latter is more accurate for slug flow.

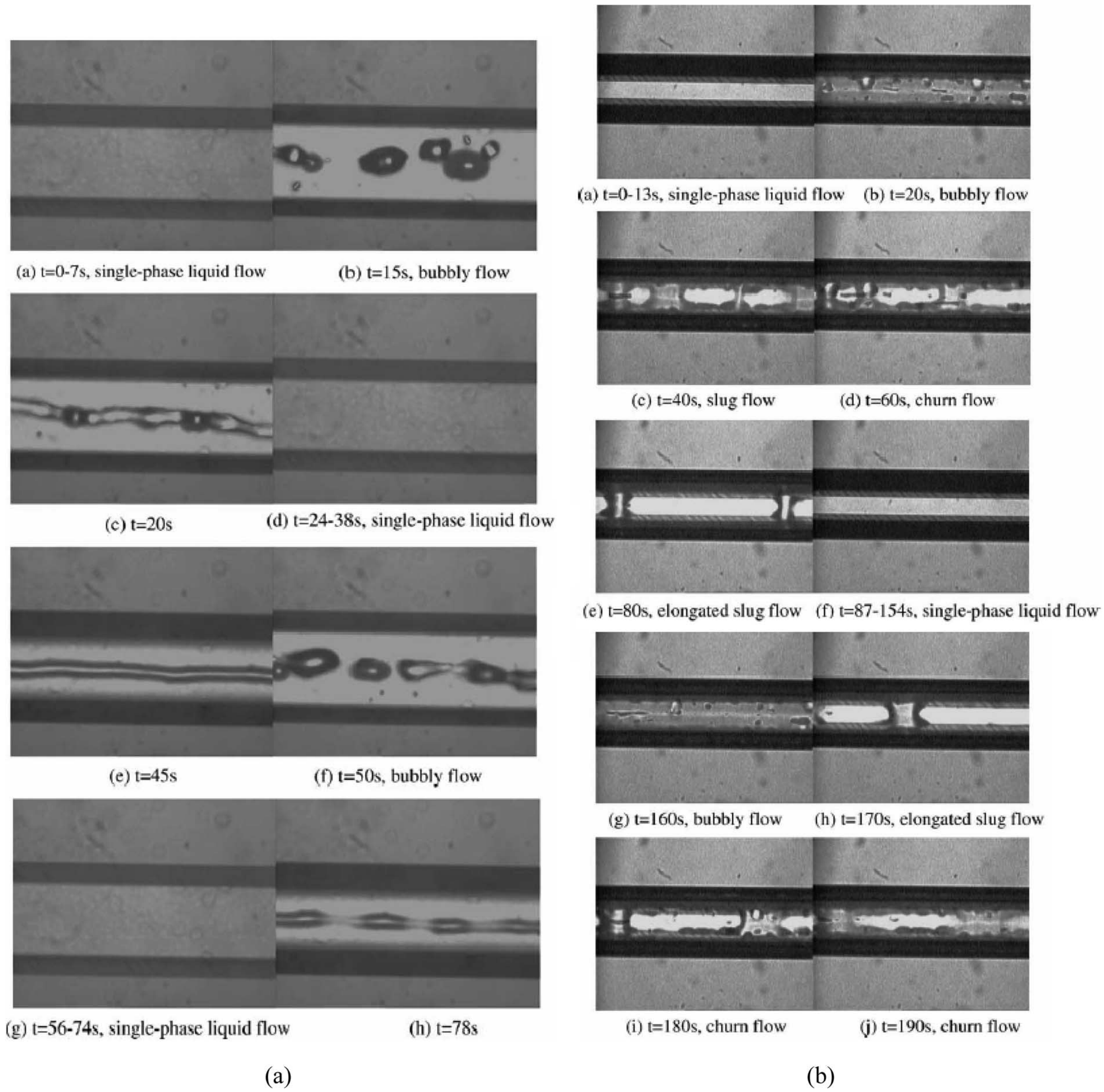

Fig. 6. ***Periodic boiling in microchannels of different hydraulic diameter: $D_h = 158.8\ \mu m$ and $82.8\ \mu m$ [45], [46]. (Reproduced with permission.)***

Triplett *et al.* [58] experimentally investigated the void fraction and pressure drop in the microchannels and employed the homogeneous model to calculate the frictional pressure drop in two-phase flow. Their model correctly predicted the ratio of volume taken up by the vapor phase to the total flow volume (void fraction) and pressure drop measurements for bubbly and slug flows in which the velocity difference between liquid and vapor phases is small; however, the model as well as all other empirical correlations tested overpredicted these parameters for annular flow. Bowers and Mudawar [59] developed a pressure drop model based on the homogeneous flow model which agreed to within $\pm 30\%$ with pressure drop measurements during boiling of R-113 in channels of diameter 2.54 mm (mini) and 510 μm (micro). The authors later demonstrated that the vapor fraction rises abruptly to above 0.9 over a very short distance downstream of the point of net vapor production, where the mean fluid temperature exceeds the saturation point [60]. Although this implies a departure from homogeneous flow to separated annular flow, the homogeneous model sufficiently predicted the pressure drop across this departure. Other advanced two-phase flow models only improved the description of the flow development but did not significantly improve prediction of the pressure drop. Other studies [44], [61] also reported success with using the homogeneous model. Modified separated flow models have also been used to model pressure drop and have yielded satisfactory agreement with experimental measurements [40], [62]–[69].

In spite of the relative success of the foregoing pressure drop models, caution should be exercised in choosing a model in designing two-phase microchannel heat sinks. Due to the intermittent nature of flow boiling, criteria need to be established to demarcate the ranges of applicability of the different models, since a universally applicable model is not available. Significant errors could result from the use of simplified one-dimensional models if the two-phase flow patterns are not properly matched.

The dominant boiling mechanism in microchannels has also not been unequivocally identified. Lazarek and Black [71] showed that the saturated boiling heat transfer coefficient for round tubes of diameter of 3.1 mm is strongly dependent on the applied heat flux, but is independent of the mass flux and quality (quality of a two-phase mixture is defined either in terms of mass quality, which is the mass ratio of vapor to liquid, or thermodynamic equilibrium quality, which denotes the enthalpy of the bulk liquid relative to that at saturation), which implies that the heat transfer is controlled by nucleate boiling. Similar observations have been made from other studies [49], [72]–[74]. On the other hand, a different group of studies [56], [58], [75], [76] points to a significant effect of mass flux and vapor quality on the heat transfer coefficient and the predominance of forced convection over nucleate boiling. Further careful investigations are needed before a clearer and more complete picture of boiling heat transfer in microchannels can be established.

Modeling: Flow boiling models are preferable to empirical correlations in the analysis and design of two-phase microchannel heat sinks. Such models should characterize boiling incipience, predict heat transfer and pressure drop in fully developed two-phase flow, and identify the critical heat flux [38]. However, a majority of the modeling efforts in the literature are dedicated to prediction of pressure drop in adiabatic/diabatic flows in microchannels. Only a few studies have emphasized bubble dynamics under microscale confinement [77]–[80]. The few boiling heat transfer models are mostly based on specific flow pattern observations, including the homogeneous model of Koo *et al.* [81], microlayer model of Jacobi and Thome [82], and annular model of Qu and Mudawar [83]. The underlying physics behind these models are dramatically different and their restricted applicability to specific flow conditions seriously limits their usage.

This brief survey reveals that although progress has been made towards characterizing pressure drop and heat transfer for two-phase flow in microchannels, an incomplete understanding of the basic boiling mechanisms persists. Other limitations include the inapplicability of the flow regime maps for macroscale flows to microscale flows and the unavailability of maps for these flows, disagreements in interpretation of experimental data, and lack of comprehensive models for flow boiling in microchannels. Also, results obtained from studies on single microchannels cannot be simply extrapolated to heat sinks featuring multiple microchannels because of flow maldistribution.

C. Flow Field Characterization

Several attempts have been made to visualize and characterize the flow field in microchannel flows. An excellent review of recent developments in microscale flow visualization techniques is available in [84]. Particle-based flow visualization methods, including laser Doppler velocimetry (LDV), particle streak velocimetry (PSV), and particle image velocimetry (PIV), and scalar-based flow visualization methods, including laser-induced fluorescence (LIF), flow-tagging velocimetry (FTV), molecular tagging velocimetry (MTV), laser-induced molecular tagging (LIMT), laser-induced photochemical anemometry (LIPA), photobleached fluorescence (PF), IR thermal velocimetry (ITV), and photoactivated nonintrusive tracking of molecular motion (PHANTOMM), were reviewed. In this section, a nonintrusive diagnostic technique (infrared microparticle image velocimetry, IR-μPIV) and a high-speed photographic technique are discussed for their particular suitability in characterizing microchannel flow and heat transfer.

A nonintrusive diagnostic technique, IR-μPIV, was developed by Liu *et al.* [85] for measurement of the flow field in silicon-based microelectromechanical systems (MEMS) devices with micrometer-scale resolution. The technique overcomes the limitation posed by the lack of optical access with visible light to subsurface flow in silicon-based microstructures by capitalizing on the transparency of silicon in the infrared region. Although studies exploiting similar concepts had been reported in the literature [86], [87], they were either limited by poor spatial resolution or were not validated against benchmark data or theoretical predictions. Liu *et al.* [85] address a variety of important issues in the implementation of IR-μPIV as a diagnostic tool for velocity-field measurements. The technique was validated by comparing experimental measurements of laminar flow of water in a circular microcapillary tube of hydraulic diameter 255 μm to theoretical predictions. The IR-μPIV technique effectively extends the application of regular micro-PIV techniques, and has great potential for flow measurements in silicon-based microdevices.

As noted earlier, boiling and two-phase flow in microchannels is characterized by spatial and temporal

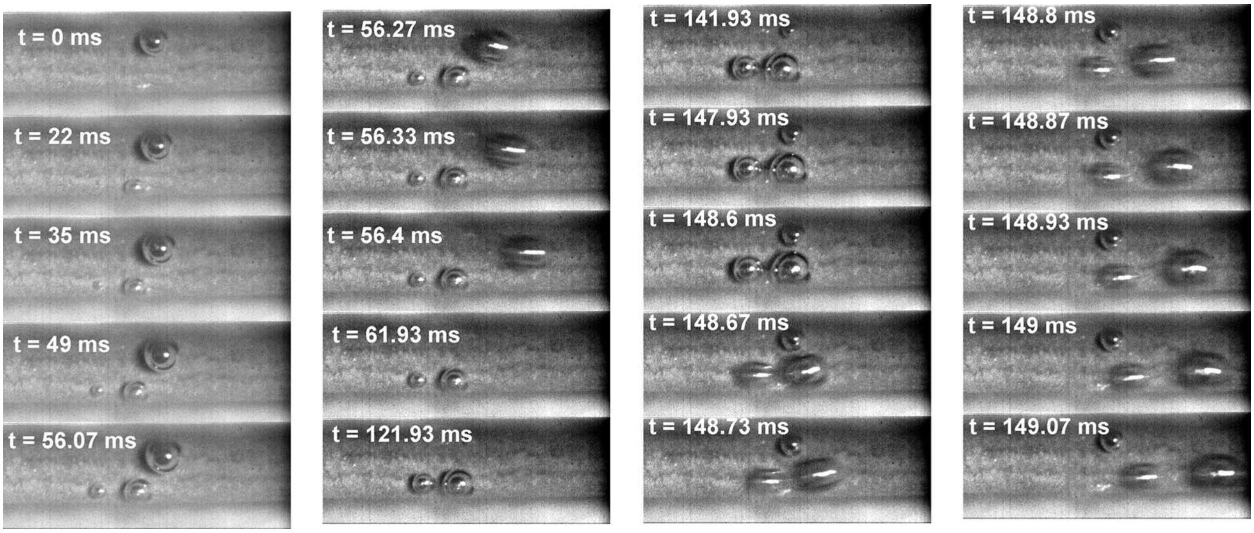

Fig. 7. ***High-speed imaging of nucleate boiling in microchannels (15 000 fps, only selected images in the time sequence shown) [88]. Test conditions: copper microchannels of hydraulic diameter 384 μm (275 μm wide and 636 μm high) and 25.4 mm in length; deionized water flow at a velocity of 0.68 m/s ($Re = 735$) and an inlet temperature of 86.5 $^\circ$C. A constant heat flux of 16 W/cm^2 is applied at the bottom of the microchannel heat sink.***

instabilities and transition between different flow patterns. A close examination of these dynamic processes can help in understanding and prediction of two-phase flow and heat transfer. However, the length scales in the microchannels as well as the time scales of the instabilities complicate the observation and analysis of bubble incipience, growth, and departure. Details of bubble evolution and motion during boiling need to be understood for the analysis of convective heat transfer. For this purpose, Liu *et al.* [88] employed a high-speed imaging system [capable of obtaining high-definition images at up to 120 000 frames per second (fps)] to study the complex bubble dynamics during nucleate boiling in a microchannel heat sinks. Experiments with deionized water in a copper microchannel heat sink with channel hydraulic diameter of 384 μm (275 μm wide and 636 μm deep) shed light on the transient processes of bubble nucleation and growth, as well as their subsequent departure and interaction (Fig. 7). Flow through one of the channels in a microchannel heat sink was captured at 4000, 8000, and 15 000 frames per second (fps); selected images are shown in Fig. 7. In the photographs in this figure, the fluid velocity was maintained at 0.68 m/s ($\mathrm{Re} = 735$) with an inlet temperature of 86.5 $^\circ$C, exit pressure of 1.05 bar, and a constant heat flux of 16 W/cm^2. The results can be used to determine the incipience of nucleate boiling and subsequent bubble growth in the microchannels [80].

Both IR-μPIV and high-speed imaging are valuable tools in further understanding two-phase flow in microchannels. The IR-μPIV technique facilitates the examination of unique flow field characteristics in silicon microchannels, while the high temporal and spatial resolutions possible with high-speed imaging enable the study of flow patterns in highly transient boiling and two-phase flow at the microscale.

IV. INTEGRATED MICROPUMPS

Integrated microchannel cooling systems, in which micropumps are integrated directly into microchannels, have only recently been proposed and investigated [89], [90]. In a typical microchannel cooling system, heat picked up by the coolant in the microchannel heat sink mounted on the electronic chip would be rejected through an external heat exchanger, with a pump connecting the two to complete the flow loop, as illustrated in Fig. 8. The high-pressure drops encountered in the microchannels necessitate the use of a rather large pump both in terms of space and power requirements, if a conventional rotary pump were used. For example, a conventional rotary or gear pump for removing 100 W using microchannels can be up to 100 cm^3 in size. Alternatively, one of the many micropump designs presented in the literature could be employed to replace this conventional rotary pump, as reviewed in [20]. However, since none of these external micropumps can, as a single unit, provide both the flow rate and the pressure head needed, a number of micropumps would need to be connected in series-parallel arrangements to achieve the required flow rate and pressure head, as described in [91]. Such a design would again increase the "pump" dimensions.

In the integrated microchannel cooling system design, the micropumps are integrated *within* the microchannels

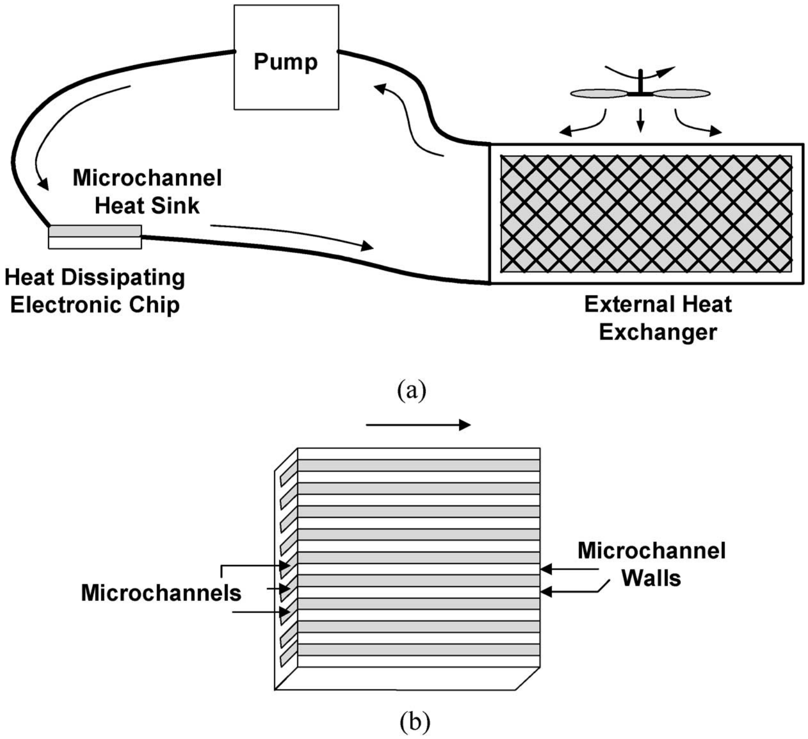

Fig. 8. *Schematic of: (a) a typical microchannel cooling system and (b) microchannel heat sink.*

in the heat sink so that they share the same footprint as the microchannels. This is schematically illustrated in Fig. 9. The main advantage of such a system is its greatly reduced size. Moreover, all of the microfabrication required (for microchannels and micropumps) can be accomplished in one process stream, potentially rendering the fabrication more economical as compared to designs employing external micropumps.

A micropump especially designed for integration into a microchannel cooling system is shown in Fig. 10(a) [92]. This micropump design is more amenable to direct integration into the microchannels as compared to the design presented in [89], [90]. It is assumed here that the micropump is integrated into microchannels of trapezoidal cross section (due to the ease of fabrication of this shape), although it can be integrated into rectangular or triangular channels as well. Narrow, closely spaced electrodes are deposited on the bottom side of the lid covering the microchannels as shown in Fig. 10(b). Small patches of piezoelectric material are deposited on top of the thin lid, so that there are alternating bands of parallel electrodes and piezoelectrically actuated diaphragms along the length of the channel.

Since the fluid in the microchannels is heated from below, a temperature gradient exists in the fluid with the fluid at the bottom being hottest and that close to the lid being coldest. This temperature gradient causes a gradient in electrical conductivity of the fluid. The presence of a traveling electric field, created using the series of parallel electrodes, then leads to the induction of charges in the fluid and creates bands of positive and negative ions, which lag behind the traveling potential wave [93]. Coulomb forces cause these ions to move in the same direction as the traveling potential wave. Momentum transfer due to repeated collision of the ions with neutral molecules leads to motion of the bulk fluid, which gives rise to a pumping action; this phenomenon is referred to as induction-type electrohydrodynamics (EHD).

Application of an alternating voltage across the piezoelectric diaphragms causes vibration of the diaphragms. The vibrating diaphragms cause increase in the bulk velocity of the fluid, which has been shown to result in an increase in the net flow rate [93] although the net flow due to the vibrating diaphragm itself, without EHD, is zero. This increase is due to an increase in the power output from EHD which is due to the combined effect of an increase in power drawn from the electrodes and an increase in the efficiency of the EHD, both of which stem from an increase in the bulk fluid velocity [94].

The performance of the micropump design was analyzed using a transient three-dimensional finite-element model [89], [90] which solves the coupled charge transport and Navier–Stokes equations [89], [90]. The model also accounts for the effect of the vibrating diaphragm

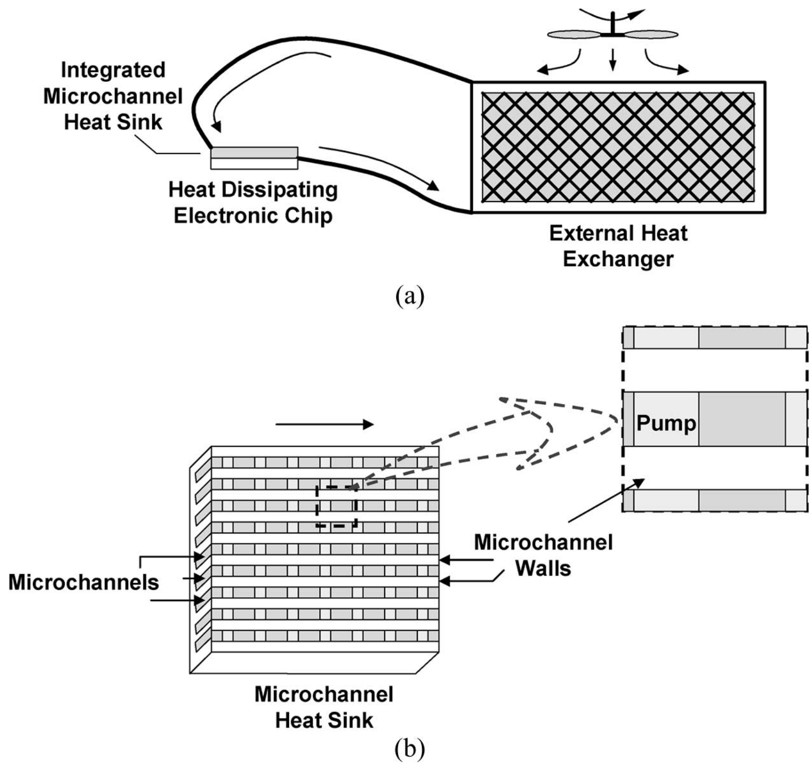

Fig. 9. *(a) Schematic of the proposed integrated microchannel cooling system (external pump removed). (b) Details of the integrated microchannel heat sink.*

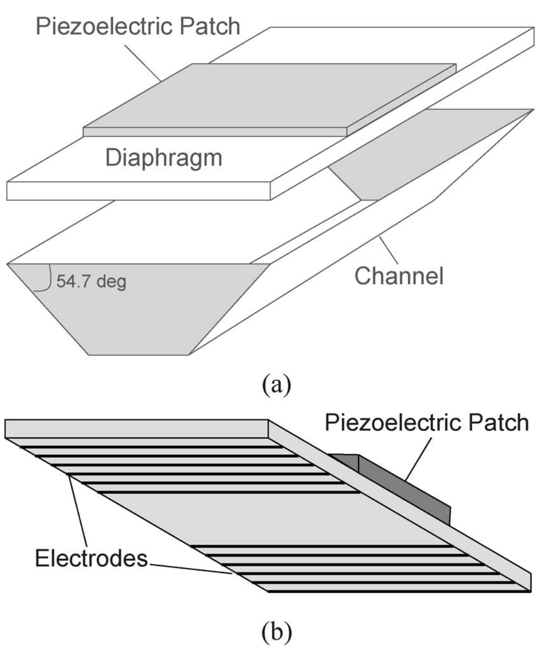

Fig. 10. *(a) Schematic of the micropump design. (b) Electrodes deposited on the bottom side of the diaphragm.*

on fluid flow. The flow rate from the pump with EHD only and with the simultaneous actuation of the vibrating diaphragm and EHD is presented in Fig. 11. Deionized water with a small amount of KCl added to increase electrical conductivity, is used as the working fluid (with properties as listed in Table 2). The pump dimensions and other parameters used for modeling are included in Table 3. The flow rate achieved from the combined action of the vibrating diaphragm and EHD is 1.75×10^{-10} m^3/s, which is 12% higher than that due to EHD alone (1.55×10^{-10} m^3/s) [92]. It may also be noted that in addition to this increase in flow rate caused by the vibrating diaphragm, an additional effect of the diaphragm is to cause enhanced heat transfer in the channels. Although the net flow due to the vibrating diaphragm itself is zero, the instantaneous flow due to its action adds significantly to the heat transfer rate from the channels. Integration of these micropumps into six parallel microchannels (channel width $= 200$ μm, fin width $= 50$ μm, channel length $=$ 1500 μm, area $= 2.25$ mm^2), would yield a flow rate of 63 μl/min. For a 20 K mean fluid temperature rise along the pump length, this implies a heat removal rate of 86.7 mW (heat flux of 3.85 W/cm^2) for a power input of merely 7.28 μW. Decreasing the width and spacing of the electrodes to 5 μm each will increase the flow rate due to

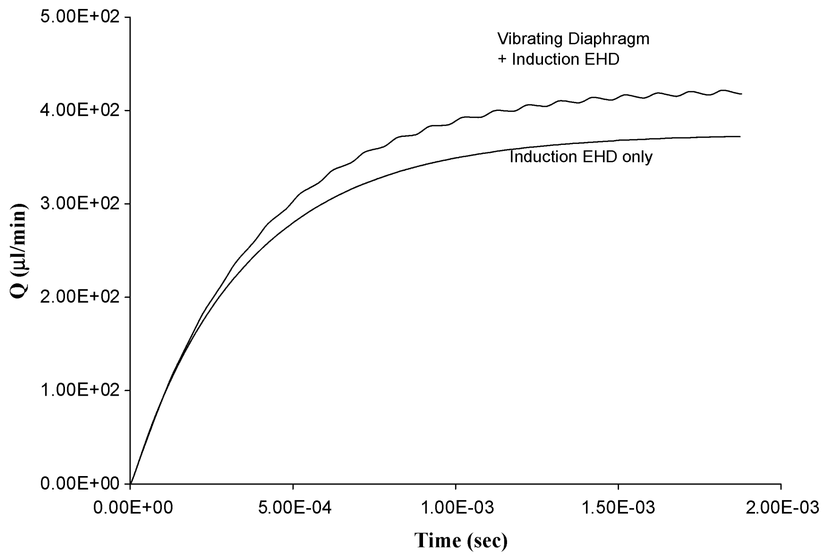

Fig. 11. ***Comparison of flow due to combined action of vibrating diaphragm and induction EHD action to that from action of induction EHD only.***

EHD alone by a factor of 16 [93]. Significant improvements in heat flux are also expected to result from the use of a larger diaphragm. A prototype chip-integrated micropump array is currently being developed.

The micropump design presented here is one of a number of candidates suitable for integration into microchannels. Pumps based on several other nonmechanical phenomena such as electroosmotic, injection EHD, conduction EHD [95], MHD, and others may also be suitable for integration. One recent example is an integrated air-cooled microchannel heat sink, called a microscale ion driven air flow (MIDAF) device [96]–[99]. In a MIDAF device, ions are generated in air using low-voltage (50–100 V) cold-cathode electron emitters that inject electrons into the air. Once in the air, the electrons generate ions by collision reactions. The ions are moved by a series of microfabricated electrodes that generate strong electric fields to pump ions through the air. The ions collide repeatedly with neutral molecules, thus generating bulk motion of the gas, similar to the EHD pump described earlier. First-order analyses demonstrate the feasibility of implementing this concept into a heat sink with air cooling rates as high as 40 W/cm^2 [100].

Table 2 Properties of the Working Fluid for the Micropump (Water Doped With KCL)

Property	Value
Density ρ	987.17 kg/m^3
Viscosity μ_{vis}	0.528×10^{-3} Ns/m^2
Dielectric constant ε	7.08×10^{-10} F/m
Electrical conductivity σ	0.20×10^{-3} S/m @ T = 0 °C
	0.70×10^{-3} S/m @ T = 72.8 °C

V. CLOSURE

Liquid-cooled microchannel heat sinks have been demonstrated to be capable of handling the ever increasing heat fluxes encountered in microprocessors. The understanding of single-phase flow and heat transfer in microchannels is at an advanced stage and is ready for implementation into practical designs. The applicability of conventional Navier–Stokes approaches for predicting the transport behavior in microchannels to be used for electronics cooling applications has been demonstrated conclusively. Single-phase microchannel heat sinks can be successfully

Table 3 Geometric and Operational Parameters of the Micropump

Parameter	Value
A_p (V)	200
f_p (kHz)	122
A_{vib} (µm)	0.1
f_{vib} (kHz)	10
n_{elec} (µm)	20
$spac_{elec}$ (µm)	20
w (µm)	200
l_e (µm)	500
l_d (µm)	500
h (µm)	50

designed for optimal performance based on the information available in the literature.

Microchannel heat sinks based on boiling and two-phase flow have even greater potential because of the higher heat transfer rates supported with lower flow rate requirements and better uniformity of substrate temperatures. However, the complex nature of flow boiling at small length scales introduces difficulties in experimental and theoretical analyses. Hence, even basic information for design of two-phase heat sinks such as reliable predictive tools for pressure drop and heat transfer performance is not available for all flow patterns. In addition, several complications such as flow maldistribution and excessive preheating in manifolds, transient flow patterns, and flow instability exist. These factors need to be better understood in order to render two-phase operation of microchannel heat sinks into a practical option for applications.

Several micropump designs have been presented in the literature which can meet the flow rate and pressure head requirements of microchannel heat sinks in smaller sizes compared to conventional rotary pumps. Some of these are more reliable and cost-effective because they utilize nonmechanical phenomena and hence are free of moving parts. However, the true potential of microscale pumps lies in their integration into microchannels, and very few suitable candidates exist for on-chip integration. The novel induction EHD pump discussed here is a good candidate for integration.

Present-day knowledge of liquid-cooled microchannel heat sinks and micropumps is sufficient to design a working microprocessor cooling system. Several commercial ventures are attempting to develop such systems [12], [14]. However, these systems are expected to be expensive and prone to reliability problems. Moreover, the total size and weight of these systems with a separate microchannel heat sink, micropump, and secondary heat exchanger is significant. Design and manufacture of a small, lightweight, low-cost, and reliable microchannel cooling system with performance superior to current solutions should be possible in the near future. However, a better understanding of two-phase flow and heat transfer characteristics and on-chip integration of micropumps is needed. Relative cost and reliability are the factors which will most influence widespread use of liquid-based microchannel heat sinks in consumer products. The complete cooling system—including the microchannel heat sink, the associated pumping solution, and the secondary heat exchanger—should be cost-competitive and provide superior reliability for the same performance as compared to current solutions for commercial applicability. ■

REFERENCES

[1] S. V. Garimella, "Advances in mesoscale thermal management technologies for microelectronics," *Microelectron. J.*, to be published.

[2] F. P. Incropera and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*. New York: Wiley, 2001.

[3] D. B. Tuckerman and R. F. W. Pease, "High-performance heat sinking for VLSI," *IEEE Electron Device Lett.*, vol. EDL-2, no. 5, pp. 126–129, May 1981.

[4] A. E. Bergles and W. M. Rohsenow, *Forced-convection surface boiling heat transfer and burnout in tubes of small diameter*, Massachusetts Inst. Technol., Cambridge, MA, NP-11831, U. S. Atomic Energy Commission, DSR Rep. 8767-21, 1962.

[5] A. P. Ornatskii and L. S. Viyarskii, "Heat transfer crisis in a forced flow of underheated water in small-bore tubes," Teplofizika Vysokikh Temperatur, vol. 3, pp. 444–451, 1965.

[6] C. L. Vandervort, A. E. Bergles, and M. K. Jensen, "An experimental study of critical heat flux in very high heat flux subcooled boiling," *Int. J. Heat Mass Trans.*, vol. 37, pp. 161–173, 1994.

[7] I. Mudawar and M. B. Bowers, "Ultra-high critical heat flux (CHF) for subcooled water flow boiling—I: CHF data and parametric effects for small diameter tubes," *Int. J. Heat Mass Trans.*, vol. 42, pp. 1405–1428, 1999.

[8] R. J. Phillips, "Forced-convection, liquid-cooled, microchannel heat sinks," Master's thesis, Massachusetts Inst. Technol., Cambridge, MA, 1987.

[9] D. Liu and S. V. Garimella, "Flow boiling in a microchannel heat sink," presented at the ASME Int. Mechanical Engineering Congr. and Exposition, Orlando, FL, 2005.

[10] Cole-Parmer Instrument Co., Cole-Parmer Product Manual 2001/02, Vernon Hills, IL, 2001.

[11] A. Richter, A. Plettner, K. A. Hofmann, and H. Sandmaier, "A micromachined electrohydrodynamic (EHD) pump," *Sens. Actuators A, Phys.*, vol. 29, pp. 159–168, 2001.

[12] A. Miner and U. Ghoshal, "Cooling of high-power-density microdevices using liquid metal coolants," *Appl. Phys. Lett.*, vol. 85, pp. 506–508, 2004.

[13] L. Jiang, J. Mikkelsen, J. M. Koo, D. Huber, S. Yao, L. Zhang, P. Zhou, J. G. Maveety, R. Prasher, J. G. Santiago, T. W. Kenny, and K. E. Goodson, "Closed-loop electroosmotic microchannel cooling system for VLSI circuits," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 25, no. 3, pp. 347–355, Sep. 2002.

[14] P. Zhou, J. Hom, G. Upadhya, K. Goodson, and M. Munch, "Electro-kinetic microchannel cooling system for desktop computers," in *Proc. 20th Annu. IEEE Semiconductor Thermal Measurement and Management Symp.*, 2004, pp. 26–29.

[15] A. S. Dewa, K. Deng, D. C. Ritter, C. Bonham, H. Guckel, and S. Massood-Ansari, "Development of LIGA-fabricated, self-priming, in-line gear pumps," in *Proc. Transducers'97*, pp. 757–760.

[16] M. Stehr, S. Messner, H. Sandmaier, and R. Zengerle, "The VAMP—a new device for handling liquids or gases," *Sens. Actuators A, Phys.*, vol. 57, pp. 153–157, 1996.

[17] C. G. J. Schabmueller, M. Koch, A. G. Evans, A. Brunnschweiler, and M. Kraft, "Design and fabrication of a self-aligning gas/liquid micropump," *Proc. SPIE*, vol. 4177, pp. 282–290, 2000.

[18] C. H. Chen, S. Zeng, J. C. Mikkelsen, and J. G. Santiago, "Development of a planar electrokinetic micropump," in *Proc. ASME Int. Mechanical Engineering Congr. and Exposition*, 2000, pp. 523–528.

[19] J. P. Black and R. M. White, "Microfluidic applications of ultrasonic flexural plate waves," in *Proc. Transducers' 99 Conf.*, pp. 1134–1136.

[20] V. Singhal, S. V. Garimella, and A. Raman, "Microscale pumping technologies for microchannel cooling systems," *Appl. Mech. Rev.*, vol. 57, pp. 191–221, 2004.

[21] S. V. Garimella and C. B. Sobhan, "Transport in microchannels—a critical review," *Annu. Rev. Heat Transf.*, vol. 13, pp. 1–50, 2003.

[22] P. Y. Wu and W. A. Little, "Measurement of friction factor for the flow of gases in very fine channels used for micro miniature Joule Thompson refrigerators," *Cryogenics*, vol. 23, pp. 273–277, 1983.

[23] S. B. Choi, R. F. Barron, and R. O. Warrington, "Fluid flow and heat transfer in microtubes," *Micromech. Sens., Actuators Syst.*, vol. 32, pp. 123–134, 1991.

[24] X. F. Peng, G. P. Peterson, and B. X. Wang, "Frictional flow characteristics of water flowing through microchannels," *Exp. Heat Transf.*, vol. 7, pp. 249–264, 1994.

[25] D. Yu, R. Warrington, R. Barron, and T. Ameel, "An experimental and theoretical investigation of fluid flow and heat transfer in microtubes," in *Proc. ASME/JSME Thermal Engineering Conf.*, 1995, pp. 523–530.

[26] B. X. Wang and X. F. Peng, "Experimental investigation on liquid forced convection heat transfer through microchannels," *Int. J. Heat Mass Transf.*, vol. 37, pp. 73–82, 1994, suppl. 1.

[27] X. F. Peng, G. P. Peterson, and B. X. Wang, "Heat transfer characteristics of water flowing

through microchannels," *Exp. Heat Transf.*, vol. 7, pp. 265–283, 1994.

[28] X. F. Peng and G. P. Peterson, "Convective heat transfer and flow friction for water flow in microchannel structures," *Int. J. Heat Mass Transf.*, vol. 39, pp. 2599–2608, 1996.

[29] C. B. Sobhan and S. V. Garimella, "A comparative analysis of studies on heat transfer and fluid flow in microchannels," *Microscale Thermophys. Eng.*, vol. 5, pp. 293–311, 2001.

[30] D. Liu and S. V. Garimella, "Experimental investigation of fluid flow in microchannels," *J. Thermophys. Heat Transf.*, vol. 18, pp. 65–72, 2004.

[31] P. S. Lee, S. V. Garimella, and D. Liu, "Experimental investigation of heat transfer in microchannels," *Int. J. Heat Mass Transf.*, vol. 48, pp. 1699–1704, 2005.

[32] J. Judy, D. Maynes, and B. W. Webb, "Characterization of frictional pressure drop for liquid flows through microchannels," *Int. J. Heat Mass Transf.*, vol. 45, pp. 3477–3489, 2002.

[33] A. Popescu, J. R. Welty, D. Pfund, and D. Rector, "Thermal measurements in rectangular microchannels," presented at the IMECE 2002, New Orleans, LA, 2002, IMECE2002-32442.

[34] T. M. Harms, M. J. Kazmierczak, and F. M. Gerner, "Developing convective heat transfer in deep rectangular microchannels," *Int. J. Heat Fluid Flow*, vol. 20, pp. 149–157, 1999.

[35] W. Qu and I. Mudawar, "Experimental and numerical study of pressure drop and heat transfer in a single-phase micro-channel heat sink," *Int. J. Heat Mass Transf.*, vol. 45, pp. 2549–2565, 2002.

[36] S. G. Kandlikar, "Microchannels—short history and bright future," *Heat Transf. Eng.*, vol. 24, no. 1, pp. 1–2, 2003.

[37] ——, "Fundamental issues related to flow boiling in minichannels and microchannels," *Exp. Thermal Fluid Sci.*, vol. 26, pp. 389–407, 2002.

[38] A. E. Bergles, V. J. H. Lienhard, G. E. Kendall, and P. Griffith, "Boiling and evaporation in small diameter channels," *Heat Transf. Eng.*, vol. 24, pp. 18–40, 2003.

[39] J. R. Thome, "Boiling in microchannels: A review of experiment and theory," *Int. J. Heat Fluid Flow*, vol. 25, pp. 128–139, 2004.

[40] K. Mishima and T. Hibiki, "Some characteristics of air-water two-phase flow in small diameter vertical tubes," *Int. J. Multiphase Flow*, vol. 22, pp. 703–712, 1996.

[41] K. Mishima and M. Ishii, "Flow regime transition criteria for upward two-phase flow in vertical tubes," *Int. J. Heat Mass Transf.*, vol. 27, pp. 723–737, 1998.

[42] A. Serizawa, Z. Feng, and Z. Kawara, "Two-phase flow in microchannels," *Exp. Thermal Fluid Sci.*, vol. 26, pp. 703–714, 2002.

[43] K. A. Triplett, S. M. Ghiaasiaan, S. I. Abdel-Khalik, and D. L. Sadowski, "Gas-liquid two-phase flow in microchannels, Part I: Two-phase flow patterns," *Int. J. Multiphase Flow*, vol. 25, pp. 377–394, 1999.

[44] B. Sumith, F. Kaminaga, and K. Matsumura, "Saturated flow boiling of water in a vertical small diameter tube," *Exp. Thermal Fluid Sci.*, vol. 27, pp. 789–801, 2003.

[45] H. Y. Wu and P. Cheng, "Visualization and measurements of periodic boiling in silicon microchannels," *Int. J. Heat Mass Transf.*, vol. 46, pp. 2603–2614, 2003.

[46] ——, "Liquid/two-phase/vapor alternating flow during boiling in microchannels at high heat flux," *Int. Commun. Heat Mass Transf.*, vol. 30, pp. 295–302, 2003.

[47] D. Brutin, L. Topin, and F. Tadrist, "Experimental study of unsteady convective boiling in heated minichannels," *Int. J. Heat Mass Transf.*, vol. 46, pp. 2957–2965, 2002.

[48] L. Zhang, J. M. Koo, L. Jiang, K. E. Goodson, J. G. Santiago, and T. W. Kenny, "Study of boiling regimes and transient signal measurements in microchannels," in *Proc. Transducers'01*, pp. 1514–1517.

[49] J. Pettersen, "Flow vaporization of CO2 in microchannel tubes," *Exp. Thermal Fluid Sci.*, vol. 28, pp. 111–121, 2003.

[50] L. Jiang, M. Wong, and Y. Zohar, "Forced convection boiling in a microchannel heat sink," *J. Microelectromech. Syst.*, vol. 10, pp. 80–87, 2001.

[51] ——, "Phase change in microchannel heat sinks with integrated temperature sensors," *J. Microelectromech. Syst.*, vol. 8, pp. 358–365, 1999.

[52] A. Tabatabai and A. Faghri, "A new two-phase flow map and transition boundary accounting for surface tension effects in horizontal miniature and micro tubes," *J. Heat Transf.*, vol. 123, pp. 958–968, 2001.

[53] J. W. Coleman and S. Garimella, "Characterization of two-phase flow patterns in small diameter round and rectangular tubes," *Int. J. Heat Mass Transf.*, vol. 42, pp. 2869–2881, 1999.

[54] C. Y. Yang and C. C. Shieh, "Flow pattern of air-water and two-phase R-134a in small circular tubes," *Int. J. Multiphase Flow*, vol. 27, pp. 1163–1177, 2001.

[55] T. S. Zhao and Q. C. Bi, "Co-current air-water two-phase flow patterns in vertical triangular microchannels," *Int. J. Multiphase Flow*, vol. 27, pp. 765–782, 2001.

[56] J. L. Xu, P. Cheng, and T. S. Zhao, "Gas-liquid two-phase flow regimes in rectangular channels with mini/micro gaps," *Int. J. Multiphase Flow*, vol. 25, pp. 411–432, 1999.

[57] A. Kawahara, P. M. Y. Chung, and M. Kawaji, "Investigation of two-phase flow pattern, void fraction and pressure drop in a microchannel," *Int. J. Multiphase Flow*, vol. 28, pp. 1411–1435, 2002.

[58] K. A. Triplett, S. M. Ghiaasiaan, S. I. Abdel-Khalik, and D. L. Sadowski, "Gas-liquid two-phase flow in microchannels Part II: Void fraction and pressure drop," *Int. J. Multiphase Flow*, vol. 25, pp. 395–410, 1999.

[59] V. P. Carey, *Liquid-Vapor Phase-Change Phenomena*. New York: Taylor & Francis, 1992.

[60] M. B. Bowers and I. Mudawar, "High flux boiling in low flow rate, low pressure drop mini-channel and micro-channel heat sinks," *Int. J. Heat Mass Transf.*, vol. 37, pp. 321–332, 1994.

[61] ——, "Two-phase electronic cooling using mini-channel and micro-channel heat sinks: Part 2—Flow rate and pressure drop constraints," *J. Electron. Packag.*, vol. 116, pp. 298–305, 1994.

[62] W. Qu and I. Mudawar, "Thermal design methodology for high-heat-flux single-phase and two-phase microchannel heat sinks," in *Proc. Intersoc. Conf. Thermal Phenomena in Electronics Systems*, 2002, pp. 347–359.

[63] M. Zhang and R. L. Webb, "Correlation of two-phase friction for refrigerants in small-diameter tubes," *Exp. Thermal Fluid Sci.*, vol. 25, pp. 131–139, 2001.

[64] H. J. Lee and S. Y. Lee, "Pressure drop correlations for two-phase flow within horizontal rectangular with small heights," *Int. J. Multiphase Flow*, vol. 27, pp. 783–796, 2001.

[65] ——, "Heat transfer correlation for boiling flows in small rectangular horizontal channels with low aspect ratios," *Int. J. Multiphase Flow*, vol. 27, pp. 2043–2062, 2001.

[66] W. Yu, D. M. France, M. W. Wambsganss, and J. R. Hull, "Two-phase pressure drop, boiling heat transfer, and critical heat flux to water in a small-diameter horizontal tube," *Int. J. Multiphase Flow*, vol. 28, pp. 927–941, 2002.

[67] G. R. Warrier, V. K. Dhir, and L. A. Momoda, "Heat transfer and pressure drop in narrow rectangular channels," *Exp. Thermal Fluid Sci.*, vol. 26, pp. 53–64, 2002.

[68] X. Tu and P. Hrnjak, "Pressure drop characteristics of R134A two-phase flow in a horizontal rectangular microchannel," presented at ASME Int. Mechanical Engineering Congr. and Exposition, New Orleans, LA, 2002, IMECE 2002-39195.

[69] Y. Y. Yan and T. F. Lin, "Evaporation heat transfer and pressure of refrigerant R-134a in a small pipe," *Int. J. Heat Mass Transf.*, vol. 41, pp. 4189–4194, 1998.

[70] Z. Y. Bao, D. F. Fletcher, and B. S. Haynes, "An experimental study of gas-liquid flow in a narrow conduit," *Int. J. Heat Mass Transf.*, vol. 43, pp. 2313–2324, 2000.

[71] G. M. Lazarek and S. H. Black, "Evaporative heat transfer, pressure drop and critical heat flux in a small vertical tube with R-113," *Int. J. Heat Mass Transf.*, vol. 25, pp. 945–960, 1982.

[72] M. W. Wambsganss, D. M. France, J. A. Jendrzejczyk, and T. N. Tran, "Boiling heat transfer in a horizontal small-diameter tube," *J. Heat Transf.*, vol. 115, pp. 963–972, 1993.

[73] Z. Y. Bao, D. F. Fletcher, and B. S. Haynes, "Flow boiling heat transfer on Freon R11 and HCFC 123 in narrow passages," *Int. J. Heat Mass Transf.*, vol. 43, pp. 3347–3358, 2000.

[74] B. S. Haynes and D. F. Fletcher, "Subcooled flow boiling heat transfer in narrow passages," *Int. J. Heat Mass Transf.*, vol. 46, pp. 3673–3682, 2003.

[75] S. Lin, P. A. Kew, and K. Cornwell, "Two-phase heat transfer to a refrigerant in a 1 mm diameter tube," *Int. J. Refrigerat.*, vol. 24, pp. 51–56, 2001.

[76] Y. W. Hwang, M. S. Kim, and S. T. Ro, "Experimental investigation of evaporative heat transfer characteristics in a small diameter tube using R134a," in *Proc. Symp. Energy Engineering in the 21 Century*, 2000, pp. 965–971.

[77] E. Ory, H. Yuan, A. Prosperetti, S. Popinet, and S. Zaleski, "Growth and collapse of a vapor bubble in a narrow tube," *Phys. Fluids*, vol. 12, pp. 1268–1277, 2000.

[78] S. V. Ajaev and G. M. Homsy, "Steady vapor bubbles in rectangular microchannels," *J. Colloid Interface Sci.*, vol. 240, pp. 259–271, 2001.

[79] ——, "Three-dimensional steady vapor bubbles in rectangular microchannels," *J. Colloid Interface Sci.*, vol. 244, pp. 180–189, 2001.

[80] D. Liu, P. S. Lee, and S. V. Garimella, "Prediction of onset of nucleate boiling in microchannels," *Int. J. Heat Mass Transf.*, vol. 48, pp. 5134–5149, 2005.

[81] J. Koo, L. Jiang, L. Zhang, P. Zhou, S. Banerjee, T. W. Kenny, J. G. Santiago, and K. E. Goodson, "Modeling of two-phase microchannel heat sink for VLSI chips," in *Proc. IEEE 14th Int. MEMS Conf.*, 2001, pp. 422–426.

[82] A. M. Jacobi and J. R. Thome, "Heat transfer model for evaporation of elongated bubble flows in microchannels," *J. Heat Transf.*, vol. 124, pp. 1131–1136, 2002.

[83] W. Qu and I. Mudawar, "Flow boiling heat transfer in two-phase micro-channel heat sinks—II. Annular two-phase flow model," *Int. J. Heat Mass Transf.*, vol. 46, pp. 2773–2784, 2002.

[84] D. Sinton, "Microscale flow visualization," *Microfluid Nanofluid*, vol. 1, pp. 2–21, 2004.

[85] D. Liu, S. V. Garimella, and S. T. Wereley, "Infrared micro-particle velocimetry of fluid flow in silicon-based microdevices," *Exp. Fluids*, vol. 38, pp. 385–392, 2005.

[86] J. Chung, C. P. Grigoropoulos, and R. Greif, "Infrared thermal velocimetry in MEMS-based fluidic devices," *J. Microelectromech. Syst.*, vol. 12, pp. 365–372, 2003.

[87] K. Breuer, J. C. Bird, G. Han, and K. J. Westin, "Infrared diagnostics for the measurement of fluid and solid motion in micromachined devices," presented at the ASME Int. Mechanical Engineering Congr. and Exposition, New York, 2001.

[88] D. Liu, P. S. Lee, and S. V. Garimella, "Nucleate boiling in microchannels," *J. Heat Transf.*, vol. 127, p. 803, 2005.

[89] V. Singhal and S. V. Garimella, "A novel micropump for electronics cooling," in *Proc. Int. Mechanical Engineering Congr. and Exposition*, 2004, pp. 1–12, IMECE2004-61147.

[90] ——, "A novel valveless micropump with electrohydrodynamic enhancement for high heat flux cooling," *IEEE Trans. Adv. Packag.*, vol. 28, no. 2, pp. 216–230, May 2005.

[91] V. Singhal, D. Liu, and S. V. Garimella, "Analysis of pumping requirements for microchannel cooling systems," in *Advances in Electronic Packaging: Proc. Int. Electronic Packaging Tech. Conf. and Exhibition (IPACK03)*, pp. 473–479.

[92] V. Singhal, "A novel micropump for integrated microchannel cooling systems," Ph.D. dissertation, Purdue Univ., West Lafayette, IN, 2005.

[93] J. R. Melcher and M. S. Firebaugh, "Traveling-wave bulk electroconvection induced across a temperature gradient," *Phys. Fluids*, vol. 10, pp. 1178–1185, 1967.

[94] V. Singhal and S. V. Garimella, "Influence of bulk fluid velocity on efficiency of electrohydrodynamic pumping," *J. Fluids Eng.*, vol. 127, pp. 484–494, 2005.

[95] S. I. Jeong and J. Seyed-Yagoobi, "Experimental study of electrohydrodynamic pumping through conduction phenomenon," *J. Electrostatics*, vol. 56, pp. 123–133, 2002.

[96] W. Zhang, T. S. Fisher, and S. V. Garimella, "Simulation of ion generation and breakdown in atmospheric air," *J. Appl. Phys.*, vol. 96, pp. 6066–6072, 2004.

[97] D. J. Schlitz, S. V. Garimella, and T. S. Fisher, "Microscale ion-driven air flow over a flat plate," presented at the 2004 ASME Heat Transfer/Fluids Engineering Summer Conf. (HT-FED04), Charlotte, NC, HT-FED04-56470.

[98] ——, "Numerical simulation of microscale ion driven air flow," presented at the ASME Int. Mechanical Engineering Congr. and Exposition, Washington, D.C., 2004, IMECE2003-41316.

[99] M. S. Peterson, T. S. Fisher, S. V. Garimella, and D. J. Schlitz, "Experimental characterization of low-voltage field emission from carbon-based cathodes in atmospheric air," presented at the ASME International Mechanical Engineering Congress and Exposition, Washington, D.C., 2003, IMECE2003-41775.

[100] D. J. Schlitz, "Microscale ion driven air flow," Ph.D. dissertation, Purdue Univ., West Lafayette, IN, 2004.

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