Journal of Heat Transfer

Guest Editorial

Microchannels: Rapid Growth of a Nascent Technology

It gives me great pleasure in presenting this special issue of the *ASME Journal of Heat Transfer* with focus on microchannels. Although not new in the biological field, the real impetus of their use in engineering systems was provided by the pioneering work of Tuckerman and Pease [1] in the early 1980s. Interest was renewed beginning in the late 1990s with the need to remove higher heat fluxes from electronic chips. Major efforts on microscale transport phenomena were undertaken worldwide by the advent of the twenty-first century. The birth of what is now an ASME International Conference on Nanochannels, Microchannels and Minichannels (ICNMM) in June 2003 provided a forum for interdisciplinary activities in this field. The promise of microchannels in future technologies, as highlighted in an editorial "Microchannels—Short History and Bright Future" by Kandlikar [2], is a result of the convergence of different application interests. Today, within a span of less than a decade, there are over four conferences held every year that focus on microchannels, and many sessions are devoted to this topic in any general heat transfer conference. This special issue is largely a collection of papers presented at a recent ICNMM09 conference held in Darmstadt, Germany.

From an engineering perspective, transport processes in microchannels are of importance in a number of practical applications. Single-phase flow of gases in microchannels has opened up a new dimension where rarefaction effects begin to become important at relatively high pressures. Coupling fluid flow in microchannels with heat transfer to obtain accurate solutions, while avoiding the rigor of molecular dynamic simulation poses a number of challenges. Microchannels present the first step in the journey from continuum mechanics to discrete molecular simulations.

Although liquid flows in microchannels are not affected from a continuum flow standpoint, many of the empirical correlations, such as entrance loss coefficients, need to be reevaluated. Further enhancement in heat transfer performance in single-phase liquid systems, while keeping pressure drop low, is still an active area of research [3]. As the earlier concerns on instabilities have been addressed by incorporating flow restrictors and artificial nucleation sites, flow boiling heat transfer in microchannels is facing new challenges with its lower than expected heat transfer coefficients and CHF as reported in the literature [4–8].

One of the issues still being discussed in this field relates to providing a broader definition for microchannels in engineering applications. Contrarily, defining microchannels explicitly based on the respective underlying phenomena, wherein the microscale effects start to become relevant for each process, will lead to separate classification schemes for gas flows, liquid flows and two-phase flows. Further, if we adopt such a scheme, the distinction among microchannels, minichannels and conventional channels will be dependent on the fluid, operating pressure, temperature, flow rate, etc. Two-phase flows provide additional challenges due to the presence of both gas and liquid phases, different mass fractions and void fractions, different heat fluxes and different flow patterns. One would expect a single nucleating bubble to be affected quite differently than, say, vapor under slip flow conditions in the core of a liquid annulus flowing in a channel. As an example, the confinement parameter was defined by Kew and Cornwell [9] to capture the effect of departing bubble size in relation to the channel diameter. Recently, Fogg and Goodson [10] extended this concept to include the dependence of bubble size on surface tension, buoyancy and drag forces, and the bubble growth rate expressed as a function of wall superheat. Although the confinement parameter is very valuable in understanding the bubble growth and in modeling its effect on the flow characteristics, it may not be suitable as a general channel classification scheme. A more generic classification scheme is therefore desirable to recognize a microscale system.

Among the proposed classifications, the earlier criteria in 2000 by Mehendale et al. [11] provided a simple dimension-based scheme. Mehendale et al. state in their paper that "we will arbitrarily adopt the following scheme for consistency and ease in understanding." According to their criteria, channels below 100 μm are called microchannels, channels in the 100 μm to 1 mm range are called meso-channels, in the 1–6 mm range are called compact passages, and above 6 mm are called conventional channels.

In a short span of six years, we saw an emergence of many research papers that focused on microscale effects on different transport processes. Heat exchangers with channel diameters greater than 3 mm are rarely classified as compact heat exchangers. At the same time, in addition to studying single phase and two phase flows in passages of a few hundred micrometers, manufacturing techniques and flow behavior in nanochannels were also being investigated [12]. A general classification scheme was thus warranted to address some of these emerging applications.

The classification by Kandlikar and Grande [13] is based on the microscale effects seen in several different applications. In the case of gas flow, the mean free path is used as a reference dimension, while in case of two-phase flow, the deviation from a straight-line relationship between mass fraction and void fraction for channels below 200–250 μm reported by Kawahara et al. [14] is used. The general classification scheme also provides a link to nanoscale phenomena by proposing transition boundaries between nanochannels and microchannels. In reality, the classification scheme provides mere guidelines, and is not intended to automatically define a set of analytical or empirical tools for a given problem. Under this scheme, conventional channels are greater than 3 mm diameter, minichannels cover the range 3 mm to 200 μm, microchannels cover a range from 10 μm to 200 μm, transitional microchannels cover 10 μm to 1 μm, transitional nanochannels cover 1 μm to 0.1 μm, and nanochannels cover the region below 0.1 μm. A recent evaluation of some of these criteria by Cheng et al. [15] shows that the 3 mm threshold for minichannel classification is in line with the microscale effects seen for water and some other refrigerants during flow boiling as well. The collection of papers presented in this volume mainly cover the microchannel range, from 10 μm to 200 μm, although some papers that deal with microscale effects in the minichannel range are also included.

The papers presented in this special isue provide a snapshot of the current state of microchannel research in various applications. A number of papers in this volume were presented at the Sixth International Conferences on Nanochannels, Microchannels and Minichannels held in Darmstadt, Germany in June 2008. The topics covered include single-phase gas flow, condensation, flow boiling studies in plain and enhanced microchannels, numerical and analytical modeling of single-phase gas flow and flow boiling processes, and application in high heat flux removal systems. It is also becoming clear that the interaction between microscale and nanoscale phenomena is of great importance as the local transport processes are governed by smaller scale processes. The interaction between nanoscale processes at the wall (nanostructures) as well as local modification of the transport processes (nanoparticles) are expected to yield valuable insights in developing new technologies in the future.

Special thanks to all the authors for their valuable contributions and to the reviewers who have provided in-depth reviews that helped the authors in elevating the quality of their papers. I am also very thankful to the Editor-in-Chief, Dr. Yogesh Jaluria for providing this forum to address the research issues in this emerging field. Out of the total of thirteen papers, three papers were submitted directly to the *Journal of Heat Transfer*. I am thankful to Roger Schmidt, W. Q. Tao and Jayanthi Murthi for handling the review of these three papers as Associate Editors. The assistance provided by Shefali Patel in organizing this special volume is sincerely appreciated. I would like to thank Peter Stephan at Technische Universität of Darmstadt, Darmstadt, Germany for co-chairing and hosting the ASME ICNMM08 conference.

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References

[1] Tuckerman, D. B., and Pease, R. F. W., 1981, "High Performance Heat Sink for VLSI," IEEE Electron Device Lett., EDL-2, **5**, pp. 126–129.
[2] Kandlikar, S. G., 2002, "Microchannels—Short History and Bright Future," Heat Transfer Eng., **24**, pp. 1–2.
[3] Steinke, M. E., and Kandlikar, S. G., 2004, "Review of Single-Phase Heat Transfer Enhancement Techniques for Application in Microchannels, Minichannels and Microdevices," International Journal of Heat and Technology, **22**(2), pp. 3–11.
[4] Kandlikar, S. G., 2002, "Fundamental Issues Related to Flow Boiling in Minichannels and Microchannels," Exp. Therm. Fluid Sci., **26**(2–4), pp. 389–407.
[5] Kandlikar, S. G., Kuan, W. K., Willistein, D. A., and Borrelli, J., 2006, "Stabilization of Flow Boiling in Microchannels Using Pressure Drop Elements and Fabricated Nucleation Sites," ASME J. Heat Transfer, **128**(4), pp. 389–396.
[6] Kuo, C. J., and Peels, Y., 2008, "Flow Boiling Instabilities in Microchannels and Means for Mitigation by Reentrant Cavities," ASME J. Heat Transfer, **130**, p. 072402.
[7] Kuo, C. J., and Peels, Y., 2008, "Critical Heat Flux of Water at Subatmosheric Pressures in Microchannels," ASME J. Heat Transfer, **130**, p. 072403.
[8] Wojtan, L., Revellin, R., and Thome, J. R., 2006, "Investigation of Saturated Critical Heat Flux in a Single, Uniformly Heated Microchannel," Exp. Therm. Fluid Sci., **30**(8), pp. 765–774.
[9] Kew, P., and Cornwell, K., 1997, "Correlations for Prediction of Boiling Heat Transfer in Small Diameter Channels," Appl. Therm. Eng., **17**, pp. 705–715.
[10] Fogg, D. W., and Goodson, K. E., 2009, "Bubble-Induced Water Hammer and Cavitation in Microchannel Flow Boiling," ASME J. Heat Transfer, **131**, p. 121006.
[11] Mehendale, S. S., Jacobi, A. M., and Shah, R. K., 2000, "Fluid Flow and Heat Transfer at Micro- and Meso-Scales with Application to Heat Exchanger Design," Appl. Mech. Rev., **53**, pp. 175–193.
[12] Perry, J. L., and Kandlikar, S. G., 2005, "Review of Fabrication of Nanochannels for Single Phase Liquid Flow," Microfluid. Nanofluid., **2**(3), pp. 185–193.
[13] Kandlikar, S. G., and Grande, W. J., 2003, "Evolution of Microchannel Flow Passages—Thermohydraulic Performance and Fabrication Technology," Heat Transfer Eng., **24**(1), pp. 3–17.
[14] Kawahara, A., Sadatomi, M., Kawaji, M., Okayama, K., and Chung, P.M.-Y., 2005, "Assessment of Void Fraction Correlations for Adiabatic Two-Phase Flows in Microchannels," ASME Paper No. ICMM2005-75031.
[15] Cheng, L., Ribatski, G., and Thome, J. R., 2008, "Two-Phase Flow Patterns and Flow Pattern Maps: Fundamentals and Applications," Appl. Mech. Rev., **61**(5), p. 050802.