ISBN 1-56700-208-0

Heat Transfer and Fluid Flow in Microchannels Gian Piero Celata

Series in Thermal & Fluid
Physics & Engineering

Editor: G.F. Hewitt

Heat Transfer and Fluid Flow in Microchannels

Gian Piero Celata

CHAPTER 1

INTRODUCTION

G. P. Celata and G. Zummo
ENEA Casaccia, Institute of Thermal Fluid Dynamics, Via Anguillarese 301
00060 Santa Maria di Galeria, Rome, Italy

Microsystems technology is gaining more and more interest in the scientific and industrial communities. Recently published articles concerning possible future applications of micro technologies predict a big commercial impact on nearly all branches of industry.

Generally, given the multliple fields of applications of microsystems, it is quite difficult to obtain a straightforward definition of such a system. Perhaps the simplest way is to define the field with respect to the dimensions of the system components as shown in Fig. 1, where the scale of objects is represented in meters. Thus, a microsystem can be defined as a device that is characterised by a microstructure where the geometry size of at least one functional component is below 100 μm and where this component produces physical/chemical effects that cannot be achieved, without loss of performance, if the critical dimensions are significantly higher than 100 μm without loss of performance.

The main users of microsystems are industries in the field of microelectronics, chemical, pharmaceutical, and medical technology, included the automotive and aerospace companies. Typical microdevices are cardiac pacemakers, pressure sensors, accelerometers, inkjet heads, components for telecommunications and components for microelectronics. Generally, these components are characterised by reduced dimensions and increasing power generation. Therefore, the need to transfer high heat fluxes in relatively small surfaces and volumes brings new challenges in heat removal and cooling techniques.

In the present context, a new generation of micro thermal devices are developed and are gaining importance. These micro thermal devices range from compact heat exchangers for air conditioning and refrigeration systems, to cooling elements for electronic components, portable telephones and computers, and aerospace avionics. Heat removal enhancement is obtained through the increase of heat transfer coefficient and of the heat exchange surface with decreasing channel hydraulic diameter. In particular, the hydraulic diameter in these micro thermal devices ranges from 1 μm up to 2 mm, significantly smaller than acroscale channels that are on the order of 5.0 to 50 mm.

Generally, the classical thermal and fluid dynamic theories developed for "macro systems" are not applicable to fluids in microscale structures. Thermo-fluid-dynamic phenomena that are generally not noticeable in macro systems, may play a dominant role in microsystems with the consequence that a lot of open questions exist and the few experimental results available in literature reveal that there are still important differences in the conclusions. Therefore, conventional macroscale methods are generally not satisfactory for thermal design of micro thermal devices in single-phase and two-phase flows.

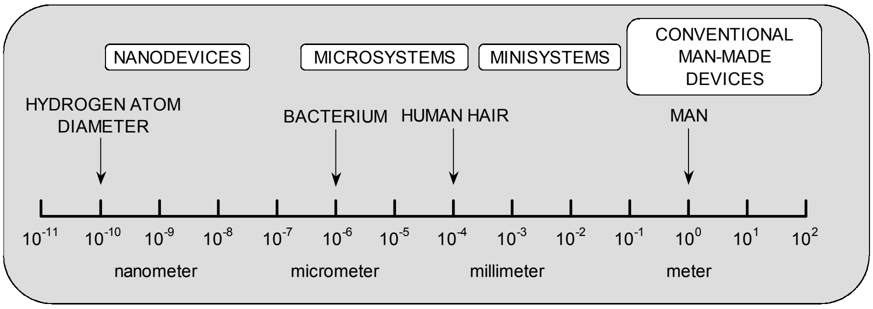

Figure 1.1 Given the multliple fields of applications of microsystems, it is quite difficult to obtain a straightforward definition. May be the simplest way is to define the field with respect to the dimensions of the components.

The purpose of Section 2.13 of HEDH is to provide a comprehensive overview of recent research results of fluid dynamics and heat transfer in single-phase and two-phase flow in microchannels and confined geometries. The presentation is divided into sections dedicated to different aspects of fluid flow and heat transfer in microgeometries. Thus, Section 2.13.2 reviews the results of single phase fluid flow of liquid and gases in microchannels. Disagreements reported in literature on deviations from classical theory are discussed and analysed. Section 2.13.3 is a summary of single phase convective heat transfer in laminar and turbulent flow.

Sections 2.13.4 to 2.13.6 and 2.13.8 deal with microchannel systems in which the flow is two-phase in nature. Section 2.13.4 introduces the research on boiling and evaporation in microgeometries. The topics covered include flow patterns observations, flow boiling heat transfer and the description of heat transfer model developed for microgeometries. Section 2.13.5 is dedicated to the researches on multiphase flow in microchannels. Multiphase flow regimes, flow pattern maps, and pattern transitions are presented and their deviations from those observed macro systems are discussed. Section 2.13.6 is a summary of research trends in condensation in microchannels. Flow pattern maps, heat transfer correlations are presented. Section 2.13.8 deals with micro heat pipes and their applications. The section contains a review of recent research results on micro heat pipes including pulsating heat pipes.

At the very small scale, channel dimensions approach molecular dimensions and the fluid can no longer be treated using the classical continuum mechanics approaches. In this situation modelling of the detailed molecular motions (“molecular dynamics”) becomes an important tool. Section 2.13.7 introduces molecular dynamics and its applications.

CHAPTER 2

SINGLE-PHASE FLUID FLOW

G. P. Celata, Z.-Y. Guo, Z.-X. Li and G. Zummo
ENEA Casaccia, Institute of Thermal Fluid Dynamics, Via Anguillarese 301
00060 Santa Maria di Galeria, Rome, Italy

A. INTRODUCTION

In recent years, research in the field of thermal-hydraulics at microscale level has been increasing constantly due to the rapid growth of applications which require the transfer of high heat rates and fluid flows in relatively small space and volume. Such applications range from compact heat exchangers to cooling systems for computer CPU's, to microfluidic devices. Additionally, flow in microgeometries is required in the application of microelectromechanical systems (MEMS), and micro-energy and chemical systems (MECS).

Generally, the classical thermal and fluid dynamic theories developed for "macro systems" are not always applicable to fluids in microscale structures with the consequence that standard design correlations are not appropriate at the microscale level.

The relatively few works available in literature in the field of microscale thermal-hydraulics reveal contradictory results and there are still important discrepancies between the results obtained by different researchers.

In what follows in Section 2.13.2B, we deal first with the problem of deviations from conventional equations for friction factor in the case of incompressible flow in microchannels. Various causes for such deviations are discussed. We then review (in Section 2.13.2C) the related matter of the laminar-to-turbulent transitions in microchannels. Finally, in Section 2.13.2D, we review work on compressible flows; compressibility effects are often very significant in microchannels because of the large pressure gradients occurring.

B. FRICTION FACTORS IN INCOMPRESSIBLE FLOWS IN MICROCHANNELS

(a) Background

Flow resistances are commonly expressed in terms of the friction factor[*] (*f*) which can be calculated from the Darcy equation:

---

[*] Note that the friction factor used in this Section is defined as $8\tau_o/\rho u^2$ where τ_o is the wall shear stress, ρ the fluid density and u the fluid velocity. This friction factor is 4 times the Fanning friction factor.

Subscripts

c	capillary
crit	critical
e	evaporator
eff	effective
h	hydraulic
ir	irreducible
l	liquid
max	maximum
min	minimum
v	vapor

REFERENCES

1. Akachi H., United States Patent, Patent Number 4921041, 1990.
2. Akachi H., United States Patent, Patent Number 5219020, 1993.
3. Akachi H., Polášek F. and Štulc P. Pulsating Heat Pipes, Proc. 5th Int. Heat Pipe Symp. Melbourne, pp. 208-217, 1996.
4. Akachi H. and Y. Miyazaki, Stereo –Type Heat Lane Heat Sink , Proc. 10th Int. Heat Pipe Conf., Stuttgart, 1997.
5. Babin B. R., Peterson G. P. and Wu D., Steady-State Modeling and Testing of a Micro Heat Pipe, J. of Heat Transfer, Vol. 112, pp. 595-601, 1990.
6. Bear J., Dynamics of Fluids in Porous Media, ISBN: 0-486-656-756, Dover Publications, 1988.
7. Benson D. A., et al., Micro-Machined Heat Pipes in Silicon MCM Substrates, Sandia Report No. SAND97-0100/UC-704, 1997.
8. Bretherton F., The Motion of Long Bubbles in Tubes, J. Fluid Mech., Vol. 10, pp. 166-188, 1961.
9. Brown G. G., Unit Operation, Wiley, pp. 210-228, 1950.
10. Cao Y., Faghri A. and Mahefkey E., Micro/Miniature Heat Pipes and Operating Limitations, Proc. ASME National Heat Transfer Conf.- HTD Vol. 236, pp. 55-62, 1993.
11. Carey V. P., Liquid-Vapor Phase Change Phenomenon, Hemisphere Publishing Corporation, 1992.
12. Chen H., Groll M. and Rösler S., Micro Heat Pipes: Experimental Investigation and Theoretical Modeling, Proc. 8th Int. Heat Pipe Conf., Beijing, pp. 396-400, 1992.
13. Chen H., Ma T. and Groll M., Performance Limitation of Micro Closed Two-Phase Thermosyphon, Proc. 10th Int. Heat Pipe Conf., Stuttgart, 1997.
14. Chi S. W. Heat Pipe Theory and Practice, Series in Thermal and Fluids Engineering, ISBN:0-07-010718-1, Hemisphere Publishing Corporation, 1976.
15. Chisholm D., Two Phase Flow in Pipelines and Heat Exchangers, George Goodwin, 1983.
16. Cotter T. P., Principles and Prospects for Micro Heat Pipes, Proc. 5th Int. Heat Pipe. Conf., Tsukuba, pp. 328-335, 1984.
17. Dunn P. and Reay D. A., Heat Pipes, 3rd edition, ISBN 0-080-022127-0, Pergamon Press, 1982.
18. Faghri A., Heat Pipe Science and Technology, ISBN 1-56032-383-3, Taylor & Francis, 1995.
19. Fukano T., and Kariyasaki A., Characteristics of Gas-Liquid Two Phase Flow in a Capillary Tube, Nuclear Engineering and Design, Vol. 141, pp. 59-68, 1993.
20. Gaugler R. S., United States Patent, Patent Number 2350348-1944, 1942.

21. Gerner F. M. et al., Flow and Heat Transfer Limitations in Micro Heat Pipes, Topics in Heat Transfer HTD-ASME 206-3, pp. 99-104, 1992.
22. Groll M. and Rösler S., Operation Principles and Performance of Heat Pipes and Closed Two-Phase Thermosyphons, J. Non-Equilib. Thermodynamics, Vol. 17, pp. 91-151, 1992.
23. Groll M., Schneider M., Sartre, V., Zaghdoudi, M. and Lallemand, M., Thermal Control of Electronic Equipment by Heat Pipes, Rev. Gén. Therm., Vol. 37, pp. 323-352, 1998.
24. Gromoll B., Advanced Micro Air-Cooling Systems for High Density Packaging, Proc. 10th IEEE Semi-Therm 94, pp. 53-58, 1994.
25. Grover G. M., United States Patent, Patent Number 3229759, 1963.
26. Grover G. M., Cotter T. P. and Erickson G. F., Structures of Very High Thermal Conductivity, J. Applied Physics, Vol. 35, pp. 1190-1192, 1964.
27. Ha J. M. and Peterson G. P., The Maximum Heat Transport Capacity of Micro Heat Pipes, ASME J. Heat Transfer, Vol. 120, pp. 1064-1071, 1998.
28. Harmathy T. Z., Velocity of Large Drops and Bubbles in Media of Infinite or Restricted Extent, A.I.Ch.E. Journal, Vol. 6, No. 2, pp. 281-288, 1960.
29. Hosoda M., Nishio S. and Shirakashi R., Study of Meandering Closed-Loop Heat –Transport Device, JSME Int. Journal, Vol. 42, Series B, No. 4, pp. 737-743, 1999.
30. Hu Y. and Tu C., Experimental Study of Heat Transfer in a Micro Thermosyphon, Proc. Int. Heat Pipe Symp., Shanghai, pp. 445-450, 1991.
31. Itoh A. and Polášek F., Development and Application of Micro Heat Pipes, Proc. 7th Int. Heat Pipe Conf., Minsk, Belarus, pp. 295-310, 1990.
32. Ivanovskii M. N., Sorokin V. P. and Yagadkin I. V., The Physical Principles of Heat Pipes, Clarendon Press, Oxford, 1982.
33. Kawara Z. and Takahashi, O., Visualization of Flow in Heat Pipe by Proton Radiography, Proc. 24th Visualization and Information Symp., Osaka, pp. 27-23, 1996.
34. Khandekar, S., Groll, M., Choroensawar, P. and Terdtoor, P., Pulsating Heat Pipes: Thermo-fluidic Characteristics and Comparative Study with Single Phase Thermosyphon, Proc. 12th Int. Heat Transfer Conf., Grenoble, 2002.
35. Khandekar S., Schneider M., and Groll M., Mathematical Modeling of Pulsating Heat Pipes: State of the Art and Future Challenges, Proc. 5th ASME/ISHMT Joint Int. Heat and Mass Transfer Conf., Kolkata, pp. 856-862, 2002.
36. Khandekar S., Cui X. and Groll M., Thermal Performance Modeling of Pulsating Heat Pipes by Artificial Neural Network, Proc. 12th Int. Heat Pipe Conf., Moscow, 2002.
37. Khandekar S. and Groll M., Pulsating Heat Pipes: A Challenge and still unsolved problem in Heat Pipe Science, Proc. 3rd Int. Conf. on Transport Phenomenon in Multiphase Systems (HEAT 2002), Kielce, 2002c.
38. Khrustalev D. and Faghri A., Thermal analysis of a micro heat pipe, J. Heat Transfer Vol. 116, pp. 189-198, 1994.
39. Kirshberg J., Yerkes K. and Liepmann D., Demonstration of a Micro-CPL Based on MEMS Fabrication Technologies, Vol. 2, Proc. 35th Intersoc. Energy Conv. Engg. Conf., Las Vegas, pp. 1198-1204, 2000.
40. Lee et al. Flow Visualization of Oscillatory Capillary Tube Heat Pipe, Proc. 11th Int. Heat Pipe Conf., Tokyo, pp. 131-136, 1999.
41. Longtin J. P., Badran B. and Gerner F. M., A One-Dimensional Model of a Micro Heat Pipe During Steady-State Operation, J. Heat Transfer, Vol. 116, pp. 709-715, 1994.
42. Maezawa S. et al., Thermal Performance of Capillary Tube Thermosyphon, Proc. 9th Int. Heat Pipe Conf. Albuquerque, 1995.
43. Maezawa S., et al., Experimental Study on Chaotic Behavior of Thermo-hydraulic Oscillation in Oscillating Thermosyphon, Proc. 5th Int. Heat Pipe Symp., Australia, 1996.
44. Maezawa S., Izumi T. and Gi K., Experimental Chaos In Oscillating Capillary Tube Heat Pipes, Proc. 10th Int. Heat Pipe Conf., Stuttgart, 1997.

45. Maezawa, S., et al., Chaotic Dynamics of Looped Oscillating Heat Pipes (Theoretical Analysis on Single Loop), Proc. 6th Int. Heat Pipe Symp., Chiang Mai, 2000.
46. Mallik A. K., Peterson G. P. and Weichold M. H., On the Use of Micro Heat Pipes as an Integral Part of Semiconductor Devices, J. Electronic Packaging, Vol. 114, pp. 436-442, 1992.
47. Mallik A. K., Peterson G. P. and Weichold M. H., Fabrication of Vapor-Deposited Micro Heat Pipe Arrays as an Integral Part of Semiconductor Devices, J. Micro-electromechanical Systems, Vol. 4, No. 3, pp. 119-131, 1995.
48. Mallik A. K. and Peterson G. P., Steady-State Investigation of Vapor Deposited Micro Heat Pipe Arrays, J. Electronic Packaging, Vol. 117, pp. 75-81, 1995.
49. Murakami M., et al., Heat Pipe Heat Sink, Proc. Int. Heat Pipe Conf., Grenoble, pp. 357-361, 1987.
50. Ochterbeck J. M. and Peterson G. P., Chapter 7 - Modeling of Heat Transfer in Heat Pipes, Modeling of Engg. Heat Trans. Phenomena, United Kingdom Press, pp. 175-212, 1999.
51. Peterson G. P., Duncan A. B. and Weichold M. H., Experimental Investigation of Micro Heat Pipes Fabricated in Silicon Wafers, J. Heat Transfer, Vol. 115, pp. 751-756, 1993.
52. Peterson G. P., An Introduction to Heat Pipes : Modeling, Testing, and Applications, ISBN: 0-471-30512-X, Series in Thermal Management of Microelectronic & Electronic Systems, Wiley, 1994.
53. Peterson G. P., Modeling, Fabrication and Testing of Heat Pipes: An Update, Applied Mechanics Review, Vol. 49, No. 10, Part 2, pp. 175-183, 1996.
54. Peterson G. P., Chapter No. 8 in Microscale Energy Transport, Series in Chemical and Mechanical Engineering, ISBN: 1-56032-459-7, Taylor and Francis, 1997.
55. Plesch D., Bier, W., Seidel, D. and Schubert, K., Miniature Heat Pipes for Heat Removal from Microelectronic Circuits. Micro-mechanical Sensors, Actuators and Systems, ASME-DSC 32, pp. 303-313, 1991.
56. Saez A. E. and Carbonell R. G., Hydrodynamic Parameters for Gas-Liquid Concurrent Flow in Packed Beds, A.I.Ch.E. Journal, Vol. 31, pp. 55-62, 1985.
57. Sarno C., et al., Use of Metal Matrix Composite Material Heat Pipes for the Thermal Management of High Integrated Electronic Packages, Proc. 11th Int. Heat Pipe Conf., Tokyo, 1999.
58. Schneider M., Yoshida M. and Groll M., Investigation of Interconnected Mini Heat Pipe Arrays for Micro Electronics Cooling, 11th Int. Heat Pipe Conf., Tokyo, 1999.
59. Schneider M., Khandekar, S., Schäfer, P., Kulenovic, R. and Groll, M., Visualization of Thermofluiddynamic Phenomena in Flat Plate Closed Loop Pulsating Heat Pipes, Proc. 6th Int. Heat Pipe Symp., Chiang Mai, 2000.
60. Sen M. and Yang K., Application of Artificial Neural Networks and Genetic Algorithms in Thermal Engineering, in: CRC Handbook of Thermal Engineering, Sec. 4.2, pp. 620-661, 2000.
61. Sotani J. et al., Feasibility Study of Printed Circuit Board Using Flat Plate Heat Pipes, Advances in Electronic Packaging, pp. 83-88, 1992.
62. Suo M. and Griffith P., Two-Phase Flow in Capillary Tubes, Trans. ASME, J. Basic Engg., pp. 576-582.
63. Swanepoel G., Taylor A. B. and Dobson R. T., Theoretical Modeling of Pulsating Heat Pipes, Proc. 6th Int. Heat Pipe Symp., Chiang Mai, 2000.
64. Tio K., Liu C. and Toh K., Thermal Analysis of Micro Heat Pipes Using a Porous-medium Model, Heat and Mass Transfer, Vol. 36, pp. 21-28, 2000.
65. Tong B., Wong T. and Ooi K., Closed-Loop Pulsating Heat Pipe, Applied Thermal Engineering, Vol. 21, pp. 1845-1862, 2001.
66. Udell K. S., Heat Transfer in Porous Media Considering Phase Change and Capillarity-the Heat Pipe Effect, Int. J. Heat Mass Trans., Vol. 28, pp. 485-495, 1985.

67. Wallis G., One Dimensional Two Phase Flow, ISBN: 0-0706-794-28, McGraw Hill, Inc, 1969.
68. Wang C., Groll, M., Rösler, S. and Tu, C., Porous Medium Model for Two-Phase Flow in Mini Channels with Applications to Micro Heat Pipes, Heat Recovery Systems & CHP, Vol. 14, No.4, pp. 377-389, 1994.
69. Wong, T. N., Tong, B., Lim, S. and Ooi, K., Theoretical Modeling of Pulsating Heat Pipe, Proc. 11th Int. Heat Pipe Conf., Tokyo, pp. 159-163, 1999.
70. Wu D., Peterson G. P. and Chang W. S, Transient Experimental Investigation of Micro Heat Pipes, J. Thermophysics , Vol. 5, No. 4, pp. 539-544, 1991.
71. Wu D. and Peterson G. P., Investigation of Transient Characteristics of a Micro Heat Pipe, J. Thermophysics, Vol. 5, No. 2, pp. 129-134, 1991.
72. Zaghdoudi M. C., Sartre V. and Lallemand M., Theoretical Investigation of Micro Heat Pipes Performance, Proc. 10th Int. Heat Pipe Conf., Stuttgart, 1997.
73. Zuo Z., North M. and Ray L., Combined Pulsating and Capillary Heat Pipe Mechanism for Cooling of High Heat Flux Electronics, Thermacore Inc., www.thermacore.com, 1998.