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Contemporary Perspectives
on
Flow BoilingInstabilities in Microchannels and Minichannels

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Rensselaer Polytechnic Institute

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CONTEMPORARY PERSPECTIVES ON FLOW INSTABILITIES IN MICROCHANNELS
YOAV PELES

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Foreword

It gives me great pleasure in presenting one of the first two books in the Series in Contemporary Perspectives in Emerging Technologies. The series was started to promote dissemination of the latest technological developments by leading researchers in the fields related to thermal and fluids aspects in engineering and biological sciences. It is expected to cover broader topics as further interest develops in this series.

Flow boiling in microchannels has been a topic of intense research for over a decade. Following the general belief that flow boiling is more efficient than single-phase flow, it was expected to achieve higher heat transfer coefficients and higher heat fluxes. However, the experiments performed by various researchers worldwide have indicated that flow boiling falls significantly below this expectation. One of the main obstacles in attaining higher heat fluxes has been identified to be flow boiling instabilities.

Professor Yoav Peles is an accomplished researcher in the field of microchannel heat transfer. He has been conducting research in this area covering single-phase enhancement, nucleation phenomena, flow boiling heat transfer, and flow boiling instabilities for over a decade. His work in the area of flow boiling instabilities in particular has been ground breaking in terms of providing theoretical backbone to this phenomenon, and validation through a complex set of experiments. This book is intended to present his work in a comprehensive way to aid in further developments in this field, with the ultimate objective of attaining heat fluxes well over 1 kW/cm^2 desired in electronics cooling applications.

The vision and foresight of our great friend William Begell in founding Begell House Publications to promote research in the fields of engineering and medicine has been the main driving force behind this effort. The impetus provided by him is further amplified by Yelena Shafeyeva, the President of Begell House. Her encouragement and support in founding this series is gratefully acknowledged. I am also thankful to the Vice President and Production Manager, Vicky Lipowski, who has been extremely patient and supportive in the entire process leading to publication of this book. The support and tireless efforts by all Begell House staff is also gratefully acknowledged.

Satish Kandlikar
Chief and Founding Editor,
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Preface

Because of its superior heat transfer characteristics, flow boiling in microdomains has received much attention in recent years. Over the course of this research initiative, it became clear that flow instabilities are a series problem that can hinder the realization of many practical miniature evaporators. Knowledge about the cause of these instabilities and methods to mitigate their deleterious effects must be effectively disseminated in order to enable development of technology related to flow boiling in diminishing length scales.

Literature concerning flow boiling instabilities in microchannels is available through quite a few journal and conference papers. However, these papers are scattered through assorted publication avenues and typically address one or several narrow aspects of flow instabilities. They generally target an audience with an extensive background and prior knowledge of the field. Practitioners who are not experts in flow instabilities and novice researchers to this fascinating field have difficulties comprehending the knowledge communicated in these papers. This book was written to bridge this gap and accelerate the learning process for these individuals.

There are many people to whom I owe a debt of gratitude for the roles they played in making this book possible. Satish Kandlikar, my friend and colleague, had the vision to develop this series of books dealing with contemporary perspectives in emerging technologies. Without his inspiration and support, this book would not have come to fruition. I would also like to thank Michael Jensen, my close collaborator. I benefited immensely from his scholarship and friendship.

The support of my research programs pertinent to flow boiling, including flow boiling instabilities, by the Office of Naval Research is also greatly appreciated. And of course, I feel honored to have worked with an outstanding group of graduate students and postdocs at Rensselaer Polytechnic Institute, including Ali Koşar, Chih-Jung Kuo, Santosh Krishnamurthy, Chandan Mishra, Eric Browne, Sidy Ndao, Tiejun Zhang, Junkyu Jung, Farzad Houshmand, Daren Elcock, Saptarshi Basu, Abhay Varghese Thomas, Catano Montoya Juan, Zhen Zhang, Yingying Wang, Abhra Chatterjee, Philip Meppen, Brandon Schneider, Shih-Chieh Chang, Gregory Michna, Hee Lee, and Zenghui Zhao.

Finally, I could not have done anything without the endless support of my wonderful family. This book is dedicated to my devoted parents, Yoram and Vera, to my loving wife and friend, Nirit, and to my two fabulous sons, Saar and Rom. To them I owe more than I can tell.

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NOMENCLATURE

a	speed of sound (m/s), Chapter 3
a_1, a_2, a_3	coefficients used in Eq. (9.2), Chapter 9
A	area (m^2) Chapters 2–9
A'	parameter to be used in Bowring correlation, Chapter 8
$A_{frontal}$	projected bubble area (m^2), Chapter 1
b	bubble height (m), Chapter 3
B	matrix, Chapters 4 and 7
b_1, b_2, b_3, b_4	experimentally obtained coefficients used in Kandlikar CHF correlation, Chapter 8
B_1, B_2	constants in Bowring correlation, Chapter 8
c	ratio between the liquid and vapor kinematic viscosity, dimensionless, Chapter 5
C	Shah's fitting coefficient, dimensionless, Chapter 5
C	constant that depends on the flow regime, dimensionless, Chapter 5
C'	parameter to be used in Bowring correlation, Chapter 8
C_1, C_2	constants, Chapter 3
Ca	capillary number, dimensionless, Chapter 8
C_D	drag coefficient, dimensionless, Chapter 1
Co	confinement number, dimensionless, Chapter 1
Co_{FG}	Fogg–Goodson confinement number, dimensionless, Chapter 3
c_p	specific heat (kJ/kg °C), Chapter 4
D	diameter (m), Chapters 4 and 8
D_b	bubble diameter (m), Chapter 1
D_h	hydraulic diameter (m), Chapters 1, 8, and 9
D_{he}	hydraulic diameter to be used in Ong and Thome CHF correlation (m), Chapters 1 and 8
D_{th}	hydraulic diameter (m), Chapters 1 and 8
f	friction factor, dimensionless, Chapters 3, 5, and 9
F	dimensionless parameter to be used with Taitel and Dukler, Chapter 2
F	shape factor, Chapter 3

F	force per unit channel length (N/m), Chapters 4, 6, and 7
F_1, F_2, F_3, F_4	constants used in Bowring correlation, Chapter 8
Fr	Froude number, dimensionless, Chapter 2
F_s	surface tension force (N), Chapter 1
g	gravitational constant (m/s^2), Chapters 1, 5, and 8
$g(x)$	function given in Eq. (9.2), Chapter 9
G	mass flux (kg/m^{2}s), Chapters 1, 4, 5, 6, 8, and 9
h	heat transfer coefficient (W/m^{2}K), Chapters 2, 3, and 8
h	channel height (m), Chapter 3
h	specific enthalpy (kJ/kg), Chapters 8 and 9
H	channel height (m), Chapter 8
h_{LG}	latent heat of vaporization (kJ/kg), Chapters 2–4 and 8
I	identity matrix, Chapter 7
j	superficial velocity (m/s), Chapter 2
k	thermal conductivity (W/m K), Chapter 3
k	constant, dimensionless, Chapter 4
K	dimensionless parameter to be used with Taitel and Dukler, Chapter 2
K	minor losses and losses across the valve, dimensionless, Chapters 3 and 5
K	parameter used in Eq. (8.2) (W/m^2), Chapter 8
$\mathrm{K}_{2,\mathrm{CHF}}$	Kandlikar number used in Kandlikar CHF correlation, Chapter 8
L	length (m), Chapters 1, 3, and 5–9
L^+	dimensionless length, dimensionless, Chapter 5
$\dot{m}$	mass flow rate (kg/s), Chapters 3, 4, 6,7, and 9
M	matrix, Chapter 7
M	pressure drop multiplier, Chapter 8
$\bar{M}$	molecular mass (g/mol), Chapter 8
n	polytropic constant, dimensionless, Chapter 6
n	constants to be used in Bowring correlation, Chapter 8
p	pressure (N/m^2), Chapters 2–9
Po	Poiseuille number, dimensionless, Chapter 5
q''	heat flux (W/m^2), Chapters 3, 4, and 8
q''_{co}	heat flux parameter used in Eq. (8.2) (W/m^2), Chapter 8
q''_{mkv}	predicted maximum heat flux from the kinetic theory (W/m^2), Chapter 8
Q	volumetric flow rate (m^3/s), Chapter 2
$\dot{Q}$	heat transfer rate (W), Chapters 2, 8, and 9

r	radius (m), Chapter 3
r	pressure drop ratio, dimensionless, Chapter 4
r_c	surface cavity's mouth radius (m), Chapter 3
R	radius of curvature (m), Chapters 2 and 3
$\overline{R}$	universal gas constant [kJ/(kmol K)], Chapter 8
Re	Reynolds number, dimensionless, Chapters 1, 3, 5, and 8
s	specific entropy (kJ/kg K), Chapter 2
s	pressure drop gradient (with respect to mass flow rate) (m^2/s), Chapter 7
t	time (s), Chapters 3, 4, 6, and 7
T	temperature (K or °C), Chapters 2–5 and 8
T	dimensionless parameter to be used with Taitel and Dukler, Chapter 2
u	velocity (m/s), Chapter 3
U	velocity (m/s), Chapters 1 and 5
v	specific volume (m^3/kg), Chapter 2
V	volume (m^3), Chapters 3–7
w	channel width (m), Chapter 3
W	channel width (m), Chapter 8
We	Weber number, dimensionless, Chapter 8
x	distance from channel's inlet (m), Chapter 3
x	mass quality, dimensionless, Chapters 5, 8, and 9
X	Martinelli parameter, dimensionless, Chapters 2 and 5
X	dependent variable, Chapter 4
X	mass flow rate perturbation vector, Chapter 7
y	perpendicular distance from heat transfer surface (m), Chapter 3
z	distance from channel's inlet (m), Chapters 2 and 4–7
z	bubble length (m), Chapter 3

Greek Symbols

α	void fraction, Chapter 5
β	ratio between channel height-to-width, dimensionless, Chapter 3
δ	boundary thickness (m), Chapter 3
Δ	difference, Chapters 2, 3, and 8
ϕ^2	two-phase frictional multiplier, dimensionless, Chapter 5
λ	eigenvalue of matrix B, Chapter 7
μ	dynamic viscosity (kg/m s), Chapters 1, 4, 5, and 8
ν	kinematic viscosity (m^2/s), Chapters 2–4
θ	dimensionless temperature, Chapter 3
θ	angle (rad), Chapter 5
θ_R	receding contact angle, 8

ρ	density (kg/m^3), Chapters 1 and 3–9
σ	surface tension (N/m), Chapters 1–3 and 8
τ	time constant (s), Chapter 3

Subscripts

a	accelerational
b	bubble
c	surface cavity's mouth, contraction, channel, critical pressure, mass quality of unity at the exit
CC	conventional scale channels
ch	cross-sectional
CHF	critical heat flux
CL	contact line
con	confinement
D	demand
D_h	based on hydraulic diameter
e	exit
f	frictional
F	Fanning
fd	fully developed
g	gravitational
G	gas
h	head
h	hydraulic
HFM	homogenous flow model
i	initial
in	in
j	index number
L	liquid
m	mean
MC	microchannel
microchannel	microchannel
ni	no instability (without instability)
ns	nucleation size
o	out
OFI	onset of flow instability
or	orifice
oriface	orifice
s	surface, surge tank
S	supply

sat	saturation
SFM	separated flow model
sp	single phase
sub	subcooled
T	thermal
T	total
tp	two phase
trans	transitional
visc	viscous
w	wall
∞	at the bulk

Chapter 1

Introduction

Flow boiling in microchannels is a key enabling technology for many high-power and high heat flux components and systems across diverse engineering disciplines, including electronics,[1–4] chemical reactors,[5–7] aerospace,[8] and miniature power systems [power micro electro-mechanical systems (MEMS)].[9–12] While typical modern electronic components, such as the central processing unit (CPU) used in personal computers, dissipate heat fluxes only in the 10 W/cm^2 range, methods to effectively dissipate heat fluxes in access of 1 kW/cm^2 over large surface areas and low surface temperature (e.g., 85°C for silicon-based electronic components) for high-end and future applications is currently being considered and studied. Single-phase liquid flow is a viable cooling method for many such applications, but its potential excessive pressure drop and power requirements are undesirable and often intolerable. Besides, ranges of applications (e.g., laser diodes) do not lend themselves well to large surface temperature variations typical of single-phase flow in channels. Flow boiling in microchannels, on the other hand, is a superior heat transfer mode with exceptionally high heat transfer coefficients. It can dissipate very high heat fluxes at approximately constant surface temperature with much lower mass flux rates than single-phase flow at potentially lower pressure drop (because of the low flow rates).

In their pioneering study on microchannel heat sinks, Tuckerman and Pease[13,14] had recognized the potential benefit of flow boiling for cooling electronic components. But, it took 10 more years before dedicated studies on flow boiling in microchannels have started to appear[15] and 10 additional years elapsed before some of the critical deleterious effects of flow boiling in diminishing length scale had been recognized and actively studied. Flow instabilities are perhaps the most pernicious phenomena hindering the practical realization of flow boiling systems in miniature heat exchangers. They are detrimental because they can compromise the structural integrity of the system leading to premature system failure; induce temperature (Fig. 1.1), pressure (Fig. 1.2), and flow rate (Fig. 1.3) oscillations;[16] cause system control problems; and, more importantly, trigger premature boiling crisis leading to an unfavorable heat transfer process. It should be noted, however, that flow oscillation might enhance the heat transfer coefficient under some limited cases[17] and can be considered as an active flow control method. However, allowing a system to operate with flow boiling oscillation should be very carefully considered since it is difficult to preciously predict and control its occurrence, and the heat transfer process can very quickly transition to unfavorable and possibly destructive conditions (i.e., to a condition known as the critical heat flux condition, which will be discussed later in this book).

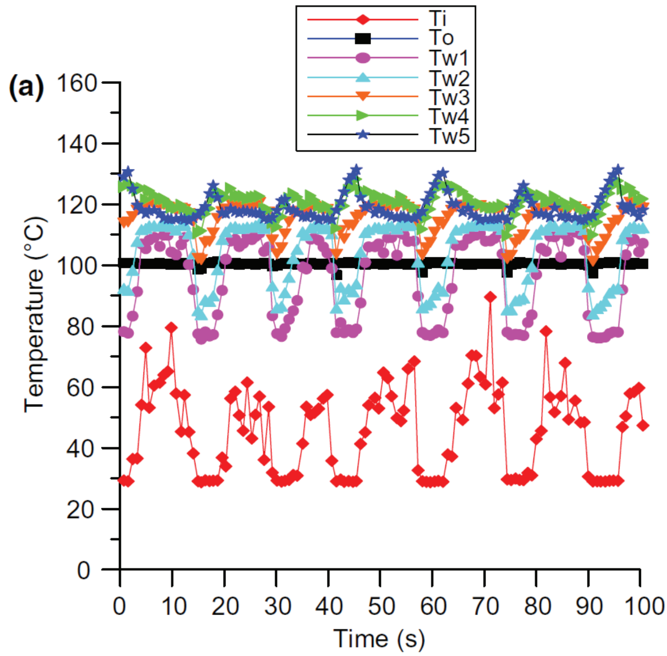

FIG. 1.1 A typical surface temperature fluctuation in microchannels: *Ti* and *To* are the inlet (to the microchannel) and exit (from the microchannel) water temperature, and *Tw1*–*Tw5* are the surface temperature measurements along the heated microchannel. Reprinted from Wu and Cheng with permission from Elsevier.[16]

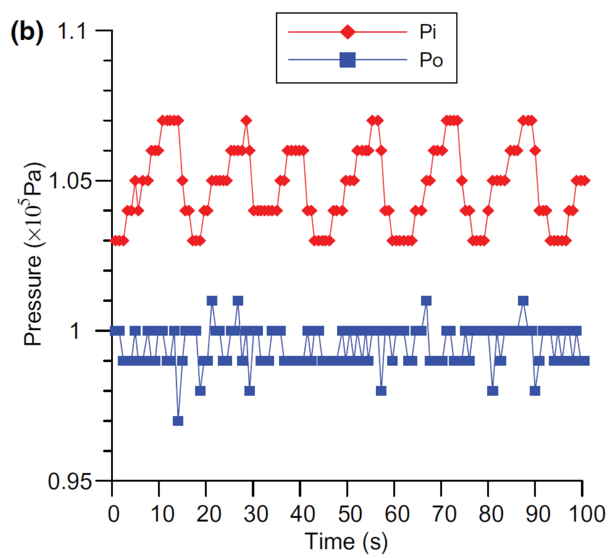

FIG. 1.2 Pressure oscillations under unstable conditions: *Pi* and *Po* are the inlet and exit pressures. Reprinted from Wu and Cheng with permission from Elsevier.[16]

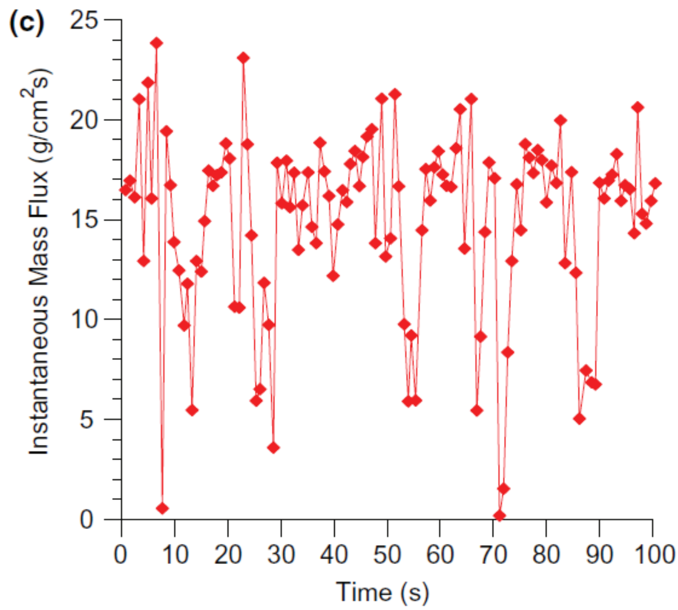

FIG. 1.3 Flow rate oscillations under unstable conditions. Reprinted from Wu and Cheng with permission from Elsevier.[16]

A formal definition of flow instabilities is given by Kakac and Bon[18] and Minorsky.[19] It states that "a flow is stable if, when disturbed, its new operating conditions tend asymptotically towards the original ones. Mathematically, it is to say that the original operating point is a solution to a system with the property that slight perturbations damp out to produce the original state."

Flow instabilities are generally classified into two main categories—static instabilities and dynamic instabilities. A flow is subjected to a static instability if, when disturbed, it moves to a different equilibrium condition, which can be stable or unstable—it can lead to a different steady-state condition or to a periodic behavior. The instability is driven by the steady-state characteristics and, therefore, can be predicted only through knowledge of the steady-state laws.

Simply put, dynamic instabilities are associated with flow (and temperature) oscillations. They are the result of interaction between the flow inertia and other feedback effects caused, for example, by the system compressibility and change to the rate of vapor generation. Dynamic instabilities are further categorized into four primary instability modes—*density wave* oscillations, *pressure drop* oscillations, *acoustic* oscillations, and *thermal* oscillations.

Density wave oscillations result from fluctuations in the void fraction (i.e., the cross-sectional area occupied by the vapor to the area occupied by the liquid) and have a characteristic frequency associated with the residence time of a particle in the channel. A momentary change in the flow rate in a channel will change the flow enthalpy and, as a result, the average density. This, in turn, will affect the pressure drop and heat transfer characteristics.

Pressure drop oscillations refer to a dynamic instability that is triggered by a static instability, which causes the pressure drop to oscillate. They are typical of systems having compressible volume upstream of the inlet or inside the channel.

Acoustic oscillations have very high frequencies that are related to the growth of acoustic waves in the channels and have a frequency related to the time required for a pressure wave to propagate through the system. With some exceptions[20] often they have little effect on the flow in conventional scale channels. However, in microchannels these types of oscillations, associated with the *rapid bubble growth* instability, can be very substantial.

Thermal oscillations are associated with large temperature fluctuation of the heated wall following dryout.[21] The flow pattern oscillates between annular flow, transition boiling, and droplet flow. This type of flow oscillation is triggered by density wave oscillations.

To obtain better knowledge and develop methods to suppress flow boiling oscillations in microchannels, much can be learned from the large body of knowledge developed over many years at the macro-scale. This is especially true since flow instabilities at the micro-scale and macro-scale share many similarities both in terms of the instability modes and their appearance. However, there are several distinct characteristics that distinguish their manifestation in diminishing length scales. These distinctive characteristics have been a subject of several studies and now much is known about the physical processes dominating flow oscillations at the micro-scale and methods have been developed to mitigate their destructive effects. Some of these techniques have unfavorable consequences, such as increased pressure drop. Much can still be done to develop better methods to suppress flow oscillations and to better understand the mechanisms controlling them.

From the various instability modes discussed in detail by Boure et al.[22] and in several later studies,[18,23,24] four have been identified and frequently reported in the open literature about flow boiling in microchannels;[25] namely, the *Ledinegg* (or *excursive*) instability, *parallel channel* instability, *upstream compressible volume* instability, and the *critical heat flux* (CHF) conditions. One notable exception that has not been explicitly identified in earlier studies at the macro-scale is the rapid bubble growth instability, which in many respects is unique to the small scales. These five instabilities are mapped in Table 1.1 according to the established instability classification discussed above.

TABLE 1.1: Classification of the five flow boiling instabilities dominating microchannels.

Type of Instability	Class
Ledinegg (or excursive) instability	Static instability
Parallel channel instability	Dynamic instability
Upstream compressible volume instability	Dynamic instability (pressure drop oscillations)
Critical heat flux (CHF) conditions	Static instability
Rapid bubble growth	Dynamic instability (acoustic oscillations)

Another important distinction between micro- and macro-scale channels concerns flow regimes. Because of the small channel's diameter, most flows in micro-domains are laminar, whereas turbulent flow dominates at the conventional scale. This distinction has significant effect on the fluid flow and heat transfer processes at the micro-scale. In addition, the geometrical configurations of flow domains at the micro-scale are often different than in the conventional scale. For instance, microchannels often have rectangular cross sections with three sides heated, whereas conventional scale channels are typically circular. These distinctions are directly related to the distinct manifestation of flow instabilities in microchannels.

Before continuing to detail flow instabilities in microchannels, it is important to present a discussion concerning the methods used to distinguish between various length scales; particularly between the micro-scale and mini-scale. An attempt to define transition criteria between various microchannel length scales was proposed by Kandlikar and Grande,[26] and is purely based on the channel hydraulic diameter, D_h (Table 1.2). While these transition criteria are not supported by any particular physical process, they set general guidelines for the various scale classifications for convective heat transfer and should be used as a coarse reference.

TABLE 1.2: Criteria for length scale transition.*

Size	Range
Conventional channel	$D_h > 3\text{mm}$
Minichannel	$3\text{mm} \geq D_h > 200\mu\text{m}$
Microchannel	$200\mu\text{m} \geq D_h > 10\mu\text{m}$
Transitional microchannels	$10\mu\text{m} \geq D_h > 1\mu\text{m}$
Transitional nanochannel	$1\mu\text{m} \geq D_h > 0.1\mu\text{m}$
Molecular nanochannel	$0.1\mu\text{m} \geq D_h$

* Reprinted from Kandlidar and Grande with permission from Elsevier. [26]

The bubble size-to-channel-diameter ratio is an important parameter that should be used when attempting to establish physically based transition criteria. These criteria are based on a balance between forces attempting to detach the bubble from the surface and forces resisting bubble departure. An early attempt was proposed by Kew and Cornwell[27] by defining the ratio between surface tension force (a force opposing bubble detachment) and gravitation force (promoting departure) according to the confinement number, Co:

$$\text{Co} = \left[\frac{\sigma}{g\left(\rho_L - \rho_G\right) D_h^2} \right]^2$$

where σ is the surface tension, g is the gravitational constant, ρ is the density, and D_h is the hydraulic diameter. This criterion is most applicable to pool boiling in confined spaces in normal gravity application, but not so much to flow boiling. To overcome the difficulty using the confinement number for flow boiling, Lee and Mudawar[28] proposed the ratio between the drag force on a bubble, which supports departure, and surface tension force. For laminar flow, the drag force on a bubble, F_D, is expressed as

$$F_D = C_D A_{\text{frontal}} \frac{1}{2}\rho_L U^2 = C_D \left(\frac{\pi D_b^2}{4}\right)\frac{1}{2}\rho_L U^2$$

where C_D is the drag coefficient, A_{frontal} is the projected bubble area, U is the velocity, and D_b is the bubble diameter. The surface tension force, F_s, is

$$F_s = \sigma L_{\text{CL}} = \sigma \pi D_b$$

where L_{CL} is the length of the solid–liquid contact line between the drag coefficient. Using the following drag coefficient expression for laminar flow:

$$C_D = \frac{24}{\text{Re}_{\text{trans}}}\left(1 + \frac{3}{160}\text{Re}_{\text{trans}}\right)$$

where Re_{trans} is the transitional Reynolds number and the transition diameter, D_{trans}, as

$$D_{\text{trans}} \le D_b$$

the following transition criterion from macro-to-micro can be formulated, using explicitly the mass flux, G[28]:

$$D_{\text{trans}} = \frac{160}{9}\left(\frac{\sigma\rho_L - 3\mu_L G}{G^2}\right) \tag{1.1}$$

where μ is the dynamic viscosity. Kew and Cornwell[27] criterion results in a transition channel diameter of several millimeters, depending on the type of fluid, while Lee and Mudawar[28] criterion results in diameters ranging from several tens of micrometers to several millimeters (Table 1.3), depending on the mass flux and type of fluid (i.e., fluid properties) and are more in-line with the common perception of a typical microchannel.

TABLE 1.3: Typical values for macro-to-micro transition diameter using Eq. 1.1.[28]

Fluid	Temperature (°C)	Mass flux $G = \rho V$ (kg/m²s)	Transition diameter from macro to micro
Water	99.6	500	3.99 mm
		1000	990 μm
		2000	243 μm
HFE 7100	59.6	500	1.49 mm
		1000	364 μm
		2000	86.3 μm

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