Micro-scale two-phase flow dynamics

Lecture 03 Macro-to-microscale transition criteria

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Outline

- Why microchannels
- Macro-to-microscale transition criteria
- Confinement number approach
- Bubble departure diameter approach
- Young-Laplace equation approach

Why Microchannels

- Ratio of surface to volume of a tube

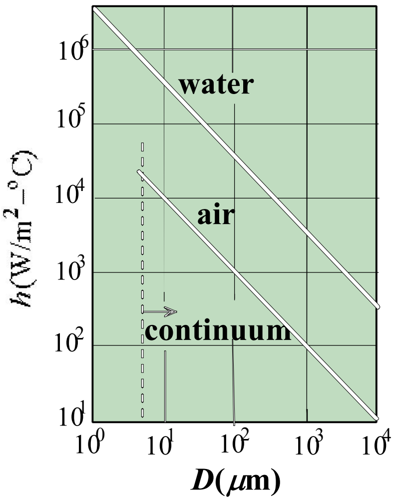
$$\frac{A}{V}=\frac{\pi DL}{\pi D^2 L/4}=\frac{4}{D}$$

- For D = 1 m, $A/V = 4\ (\mathrm{m}^{-1})$
- For D = 1 μm, $A/V = 4\times 10^{6}\ (\mathrm{m}^{-1})$

$$Nu=\frac{hD}{k}=3.66$$

$$h=3.66\frac{k}{D}$$

$$D\downarrow \quad h\uparrow$$



Latif Jiji. Heat Convection

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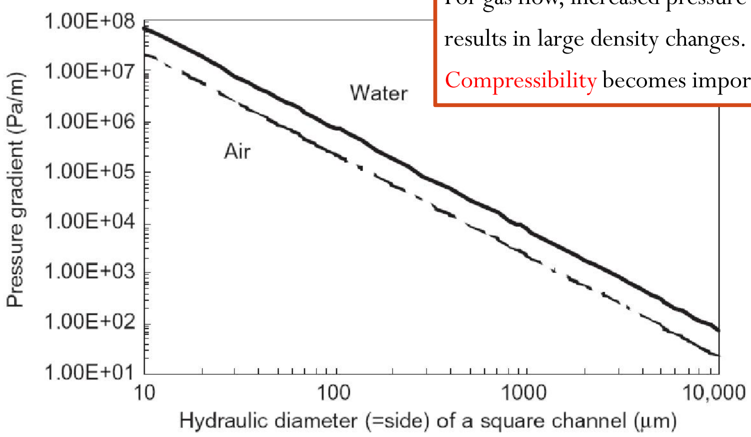
Why Microchannels

For gas flow, increased pressure drop results in large density changes. Compressibility becomes important



Heat Transfer and fluid flow in mini channels and micro channels.
Kandlikar S. et al.2006

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Micro-scale flow characteristics

	Viscosity / Pa.s	u/mm.s^{-1}	d	Re
Water	1.025×10^{-3}	1.0	100 nm ~ 100 μm	10^{-1} to 10^{-4}
Oxygen	20.317×10^{-6}	1.0	100 nm ~100 μm	10^{-5} to 10^{-2}

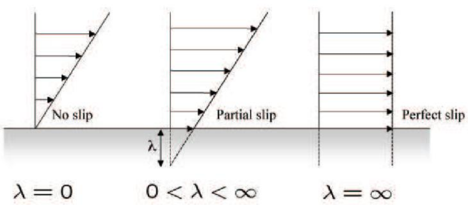
- Therefore, inertial forces are overwhelmed by **interfacial forces** in microfluidic devices. **Laminar flow** is expected in micro- and nanochannels, and not turbulent or random flow. Consequently, in simple geometries, **parabolic profiles** are expected in pressure-driven flows,
- In the microarea, the relative importance of forces, calculated in a water/oxygen two-phase microflow, is given by the following order:

buoyancy forces < inertial forces < gravitational forces

< viscous forces < interfacial forces

Boundary condition

- linear boundary condition (Navier 1823, Maxwell [109]),
  - the component of the fluid velocity tangent to the surface is proportional to the rate of strain (or shear rate) at the surface
  - The velocity component normal to the surface is naturally zero as mass cannot penetrate an impermeable solid surface



Boundary condition

- Gas flow in devices with dimensions that are on the order of the mean free path of the gas molecules shows significant slip

$$\frac{\lambda}{l_m} = \frac{2(2-p)}{3p}$$

- slip being important when Kn > 0.1

Boundary condition

- Newtonian liquids

Summary of slip results for pressure drop versus flow rate experiments

	Surfaces	Liquids	Wetting	Roughness	Shear rates	Slip length
Schnell [141]	Glass+DDS	Water	–	–	$10^2 - 10^3\ s^{-1}$	$1 - 10\ \mu m$
Churaev [34]	Quartz+TMS	Water	$70 - 90°$	–	$1\ s^{-1}$	30 nm
	"	Mercury	$115 - 130°$	–	$10^3 - 10^4\ s^{-1}$	70 nm
	"	CCl_4	Complete	–	–	no-slip
	"	Benzene	Complete	–	–	no-slip
Kiseleva [88]	Quartz+CTA(+)	CTAB solutions	$70°$	–	$10^2 - 10^3\ s^{-1}$	10 nm
Cheng [30]	Glass+photoresist	Water	–	5 Å (pp)	$10^2 - 10^4\ s^{-1}$	no-slip
	"	Hexane	–	"	"	10 nm
	"	Hexadecane	–	"	"	25 nm
	"	Decane	–	"	"	15 nm
	"	Silicon Oil	–	"	"	20 nm
Cheikh [29]	Poly(carbonate)+PVP	SDS solutions	$< 90°$	–	$0 - 10^5\ s^{-1}$	20 nm
Choi [32]	Silicon	Water	$\approx 0°$	11 Å (rms)	$10^3 - 10^5\ s^{-1}$	$0 - 10$ nm
	Silicon+OTS	Water	$\gtrsim 90°$	3 Å (rms)	"	$5 - 35$ nm

Microfluidics: The No-Slip Boundary Condition, 2005

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- Why microchannels
- Macro-to-microscale transition criteria
- Confinement number approach
- Bubble departure diameter approach
- Young-Laplace equation approach

Macro-to-microscale transition criteria

- What happens in micro-channels in two-phase flows can be quite different from single-phase flows.
- Macroscale methods for single-phase flow work well down to at least diameters of 5~10 micros and hence channels larger than this size can still be considered to macroscale.
- Macroscale two-phase flow methods usually do not work well at all when compared to data for channels below about 3mm diameter. It's very risky to extrapolate macroscale two-phase **flow pattern maps**, flow boiling heat transfer methods and two-phase pressure drop models to microchannels, except for specific documented cases.

Macro-to-micro transition criteria

- **lower boundary of the macroscale:** A well-proven criterion is required for predicting the limiting diameter above which **macroscale** methods and theory are applicable.
- **upper boundary of the microscale:** A well-proven criterion for predicting the limiting diameter below which **microscale** methods and theory are reliably applicable.
- **Mesoccale**: Methods are also required for predicting flow and thermal performance in channel sizes falling in between ().
- A further **nanoscale** two-phase flow and heat transfer domain may emerge as well for even smaller sizes of channels where yet other two-phase mechanisms control the process.

Macro-to-micro transition criteria

	Channel dimensions (μm)			
Gas	Continuum flow	Slip flow	Transition flow	Free molecular flow
Air	>67	0.67–67	0.0067–0.67	<0.0067
Helium	>194	1.94–194	0.0194–1.94	<0.0194
Hydrogen	>123	1.23–123	0.0123–1.23	<0.0123

Heat Transfer and fluid flow in mini channels and micro channels.
Kandlikar S. et al.2006

Macro-to-micro transition criteria

- As of today, there appears to be **no exact definition or proven criterion available** for definitively distinguishing the transition between macroscale and microscale for two-phase flows and heat transfer.
- International Conference on Microchaneels and Minichannels:

macrochannels	$> 3mm$	Kandlikar, 2001
minichannels	$0.6\sim3.0mm$	
microchannels	$< 0.6mm$	

Macro-to-micro transition criteria

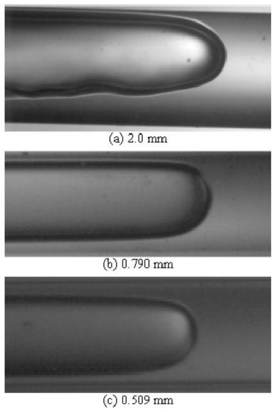
macrochannels	$> 6mm$	Mehendale and Jacobi, 2000
compact	$1\sim6mm$	
mesoscale	$100\mu m\sim1mm$	
microscale	$1\mu m\sim100\mu m$	

conventional channels	$> 3mm$	Kandlikar and Grande, 2003
minichannels	$200\mu m\sim3mm$	
microchannels	$10\mu m\sim200\mu m$	
nanoscale	$< 10\mu m$	

based merely on dimensions and not on physical behavior

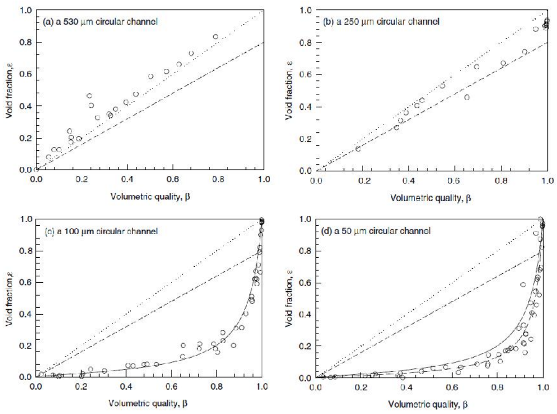
Evidence – Flow pattern

- In the 2.0mm channel, no stratified flow was observed while the difference in film thickness at the top compared to that at the bottom is quite noticeable.
- Similarly, the film thickness in the 0.79mm channel is still not uniform above and below the bubble.
- In contrast, in the 0.509mm channel, the film is quite uniform.
- Stratified-wavy and fully stratified flows disappear in small horizontal channels. This transition is perhaps an indication of the lower boundary of macroscopic two-phase flow (>2mm), while the upper boundary of microscale two-phase flow may be interpreted as the point in which the effect of gravity becomes insignificant.



The influence of channel size on the buoyancy effect on the elongated bubble with R134a at 30°C (Latif Jiji. Heat Convection)

Evidence – Void fraction



Chung & Kawaji, International Journal of Multiphase Flow 30 (2004) 735–761

$$\varepsilon = \frac{C_1 \beta^{0.5}}{1 - C_2 \beta^{0.5}}$$

The physical reason why the relationship between ε and β in a microchannel deviates from the conventional linear relationship for a minichannel may be explained as follows. In a microchannel, between β = 0 and 0.8, the void fraction data fell below traditional correlations developed for minichannels and conventional channels. At these volumetric qualities, short gas slugs and long liquid slugs appeared. The long liquid slugs would increase the pressure gradient which would in turn cause the short gas slugs to accelerate through the liquid evading capture by the video camera and decreasing their residence time in the microchannel, which results in a low time-averaged void fraction.

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- Confinement number approach
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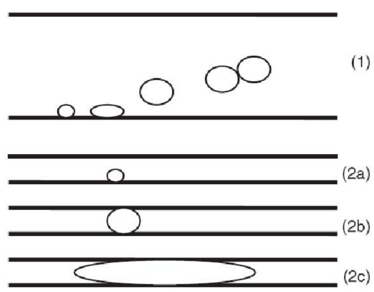
- Young-Laplace equation approach

Macro-to-micro transition criteria

- **Confinement number approach**
- The bubble confinement approach is based on the confined growth of a bubble in small channels (Ong & Thome, 2011).



Heat Transfer and fluid flow in mini channels and micro channels.
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Macro-to-micro transition criteria

- **Confinement number approach**
- In microchannels of the order of **a few μm to a few tens μm**, two-phase flow is believed to be influenced mainly by **surface tension, viscosity and inertia forces**. (Serizawa et al. 2002)
- Suo and Griffith (1964) derived the following criterion for tube diameter D:

$$Co = \frac{\lambda}{D} = \frac{1}{D}\sqrt{\frac{\sigma}{(\rho_l - \rho_g)g}} \geq 3.3$$

λ: Laplace constant: 2.7 mm for air–water flow at 0.1 Mpa (D = 818μm)

Macro-to-micro transition criteria

- **Confinement number approach**
- In the microscale, the influence of gravity is surpassed by that of surface tension, i.e., no stratified flow exists if the tube diameter is sufficiently small.

$$B_o = \frac{\rho a L^2}{\sigma} = \frac{(\rho_l - \rho_g)gd^2}{\sigma} < 4 \qquad d_h < 2\left(\frac{\sigma}{(\rho_l - \rho_g)g}\right)^{1/2}$$

Kew and Connwell, 1997

- This is apparently the first criterion proposed for the threshold to confined bubble flow and perhaps is thus the first macro-to-microscale two-phase flow transition criterion. Notably, this criterion also does not contain any flow forces, i.e., no superficial velocities nor shear effects on the bubble or annular films.

Macro-to-micro transition criteria

- **Confinement number approach**
- Kew and Connwell (1997) in fact proposed **bubble growth confinement within a channel as the parameter** to distinguish the macro-to-microscale transition in the form of the Confinement number:

$$Co = \frac{1}{D}\sqrt{\frac{\sigma}{(\rho_l-\rho_g)g}} \begin{cases} < 0.5 & \text{macro scale} \\ > 0.5 & \text{microscale} \end{cases}$$

- based on the flow boiling experiments for single channels with internal diameters of 1.10, 1.80, 2.80 and 3.60 mm and for a square channel of 2.0 × 2.0 mm.
- As an example, for R134a at T_{sat} = 0°C, the threshold diameter is given by this criterion to be 1.92mm and becomes smaller as the saturation pressure increases.

Macro-to-micro transition criteria

Table 6.2 Microchannel Transition Criteria

	Transition Diameter (mm) $T_{sat} = 50°C$	
	$Co > 0.5$	$L > D_H$
R-134a	1.39	0.69
R-404A	0.91	0.46
Propane	2.01	1.01
Ammonia	3.26	1.63
Water	5.30	2.65

Heat Transfer and fluid flow in mini channels and micro channels.
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Macro-to-micro transition criteria

- Thus, the practical value of such categorizations is somewhat limited—even a change in operating temperature for the same fluid could affect whether the channel should be treated as a microchannel **through the influence of temperature on surface tension and other properties**.
- What is more important is to recognize and account for the respective flow phenomena in the development of pressure drop and heat transfer models.
- For example, substantial differences due to channel size have been documented by several researchers at hydraulic diameters of a few millimeters, as noted by Palm (2001).

Macro-to-micro transition criteria

- **Confinement number approach**
- Kawaji and Chung (2003) reviewed the characteristics of two-phase flow and the available data and came up the following recommendation as a threshold criterion:

$$B_o = \frac{(\rho_l - \rho_g)gd^2}{\sigma} \ll 4 \qquad Ca_L = \frac{\mu_L U_L}{\sigma} \ll 1$$

$$We_{SL} = \frac{\rho_l U_L^2 d}{\sigma} \ll 1 \qquad Re_{SL} = \frac{\rho_l U_L d}{\mu_L} \ll 2000$$

$$We_{SG} = \frac{\rho_G U_G^2 d}{\sigma} \ll 1 \qquad Re_{SG} = \frac{\rho_G U_G d}{\mu_G} \ll 2000$$

- where U_L、U_G are superficial velocities

Macro-to-micro transition criteria

- **Confinement number approach**
- Ullmann and Brauner (2006) suggested the threshold to occur at Eo = 0.2 (for air-water this corresponds to a diameter of about 0.35mm:

$$E_o = \frac{(\rho_l - \rho_g)gd^2}{8\sigma} < 0.2 \qquad E_o = \frac{Bo}{8} = \frac{1}{8Co^2} \qquad E_o \approx 0.2 \sim Co \approx 0.79$$

- Eo number play an important role in flow pattern transitions and determining the characteristics length in **dispersed two-phase flows** in wall wetting effects in separated flows.
- Perhaps the earliest such transition criterion might be that of Bretherton (1961), who suggested a transition at **Eo < 0.84** as the threshold at which a Taylor bubble would no longer rise under only the influence of gravity in a vertical, water filled capillary tube.

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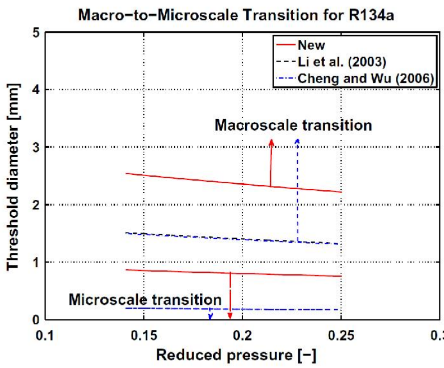
Macro-to-micro transition criteria

- **Confinement number approach**
- Ong & Thome (2011) observed that the two-phase flow patterns and transitions is a function of channel confinement, mass velocity, saturation temperature and flow pattern.
- Fluid properties such as surface tension, phase densities, and viscosity were found to affect the flow pattern transitions.
- lower boundary of macroscale (Co < 0.3–0.4)
- Upper boundary of symmetric microscale flow (Co > 1.0)



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C.L. Ong, J.R. Thome, Experimental Thermal and Fluid Science 35 (2011) 37–47

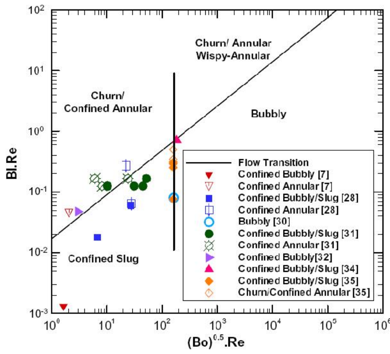
Macro-to-micro transition criteria

- **Confinement number approach**
- Harirchian & Garimella (2010) proposed a new criterion in term of convective confinement number that incorporates the effects of mass flux, as well as channel cross-sectional area and fluid properties:

$$Bo^{0.5} \times Re$$

$$= \left(\frac{(\rho_l - \rho_g) g d^2}{\sigma}\right)^{0.5} \frac{Gd}{\mu_f}$$

$$= \left(\frac{(\rho_l - \rho_g) g}{\sigma}\right)^{0.5} \frac{Gd^2}{\mu_f} \leq 160$$



T. Harirchian, S.V. Garimella / International Journal of Heat and Mass Transfer 53 (2010) 2694–2702

Macro-to-micro transition criteria

- **Bubble departure diameter approach**

$$d_{bub} = 0.0208\beta\left(\frac{\sigma}{(\rho_l - \rho_g)g}\right)^{1/2}$$

Fritz, 1935
(β is contact angle in °)

$$d_{bub} = \left[0.12 + 0.08\left(\frac{c_{pL} T_{sat}}{h_{LG}}\right)^{2/3}\right]\left(\frac{\sigma}{(\rho_l - \rho_g)g}\right)^{1/2}$$

Nishikawa et al., 1976

$$d_{bub} = \left[0.25(1 + 10^5 K_1)^{1/2}\right]\left(\frac{\sigma}{(\rho_l - \rho_g)g}\right)^{1/2}$$

$$K_1 = \left(\frac{\rho_L c_{pL}(T_w - T_{sat})}{\rho_G h_{LG} Pr_L}\right)^2 \left[\frac{\mu_L^2\left[(\rho_l - \rho_g)g\right]^{1/2}}{\rho_L \sigma^{2/3}}\right]$$

Kutateladze and Gogonin, 1979

Macro-to-micro transition criteria

- **Bubble departure diameter approach**

- It's interesting to notice the role played by the **Bond number** in all these relations, which are only strictly valid for **pool boiling**.

- The flow in microchannel will tend to **promote the detachment of the bubble** before it completely spans the channel. Thus, a macro-to-microscale criterion set equal to the passive bubble detachment diameter will probably **overestimate the value of the channel diameter** of the macro-to-microscale threshold.

Macro-to-micro transition criteria

- **Young-Laplace equation approach**

$$d_{crit} = 0.224 L_{cap}$$
$$d_h = 1.75 L_{cap}$$
$$L_{cap} = \left(\frac{\sigma}{(\rho_l - \rho_g)g}\right)^{1/2}$$

Li and Wang, 2003

$$\begin{cases} \text{Effect of gravity is insignificant} & d \le d_{crit}\ (Co > 4.46) \\ \text{Effeict of gravity is visible but surface tentionis dominated} & d_{crit} \le d \le d_{th}\ (0.57 < Co < 4.46) \\ \text{Effect of surface tension will be small with respect to gravity} & d \ge d_{th} (Co < 0.57) \end{cases}$$

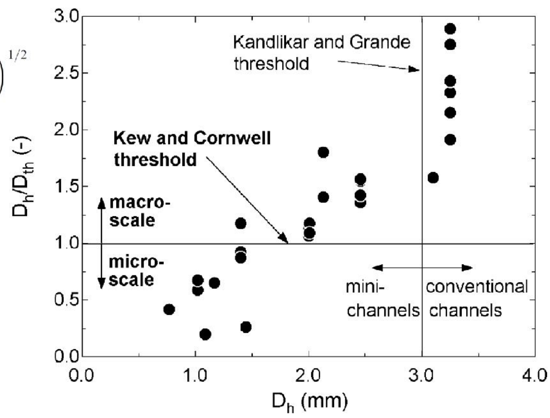
Young-Laplace equation

Thomas Young
1773 – 1829
English polymath
who developed the qualitative theory of surface tension in 1805

Pierre-Simon Laplace
1749 – 1827)
French mathematician and astronomer
who completed the mathematical description in the following year

Macro-to-micro transition criteria

$$D_{\mathrm{th}} = \left(\frac{4\sigma}{g(\rho_L - \rho_V)}\right)^{1/2}$$



Comparison between the experimental hydraulic diameters, Dh, included in the present pressure drop database and the threshold diameter criteria of Kew and Cornwell [1997], given by Dh/Dth = 1, and of Kandlikar and Grande [2003], given by Dh = 3 mm. (Experimental Thermal and Fluid Science 31 (2006) 1–19)

Macro-to-micro transition criteria

Table 1. The different criteria for small tubes

Parameters	Air / water	R-134a		
Pressure (MPa)	0.10	0.60	1.00	1.40
Temperature (^{o}C)	25.0	21.6	39.4	52.5
	Critical Diameter (mm)			
Criterion based on Eö=1	17.1	5.3	4.7	4.3
Criterion based on Co=0.5	5.4	1.7	1.5	1.4
Criterion based on Eö=100	1.71	0.53	0.47	0.43
Criterion based on Bo=0.3	0.81	0.25	0.23	0.20

L. Chen, Y. S. Tian, and T. G. Karayiannis.
The Effect of Tube Diameter on Vertical Two-phase Flow Regimes in Small Tubes

Exercise 04

- Compare the transition diameter for air-water two-phase flow in 25^{o}C under different macro-to-micro transition:
- $\sigma = 0.072\text{N/m}, \rho_g = 1.293\text{kg/m}^3$

$$Co = \frac{1}{D}\sqrt{\frac{\sigma}{(\rho_l-\rho_g)g}} \begin{cases} < 0.5 & \textit{macro scale} \\ > 0.5 & \textit{microscale} \end{cases}$$

$$B_o = \frac{\rho a L^2}{\sigma} = \frac{(\rho_l-\rho_g)gd^2}{\sigma} < 4$$

$$E_o = \frac{(\rho_l-\rho_g)gd^2}{8\sigma} < 0.2$$

$$Bo^{0.5} \times Re \le 160$$

$$d_{crit} = 0.224 L_{cap}\text{ , where } L_{cap} = \left(\frac{\sigma}{(\rho_l-\rho_g)g}\right)^{1/2}$$

To be continued……