Karlsruhe Institute of Technology

Flow of Taylor bubbles in narrow channels

Dr.-Ing. Martin Wörner

Karlsruhe Institute of Technology
Institute for Nuclear and Energy Technologies

SPP 1506 Summer School,
CSI Darmstadt, July 8-9, 2010

Transport processes at fluidic interfaces

DFG SPP 1506

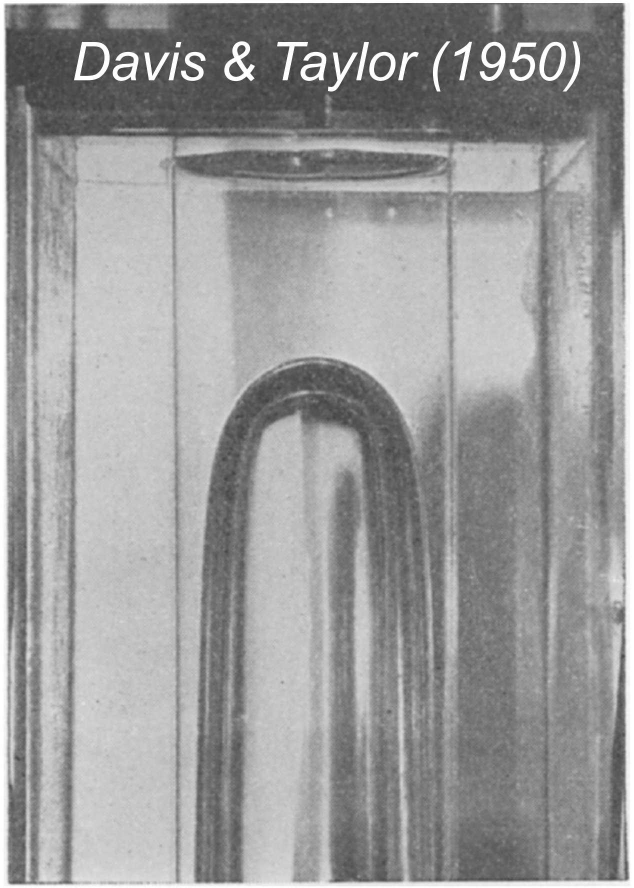

FIGURE 8. Emptying a glass tube 7·9 cm. diameter.

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Taylor bubbles – a short history

A.H. Gibson, On the motion of long air-bubbles in a vertical tube. Philosophical Magazine 26 (1913) 952-965.

… when the diameter is about 0.75 that of the tube the bubble begins to adopt a more or less cylindrical form with an ogival head and a flat stern, and the motion becomes steady. Any further increase in the volume is mainly effective in increasing the length of the cylindrical portion of the body, the form of the head remaining sensibly unchanged, and the mean diameter, although increasing with length, not altering greatly.

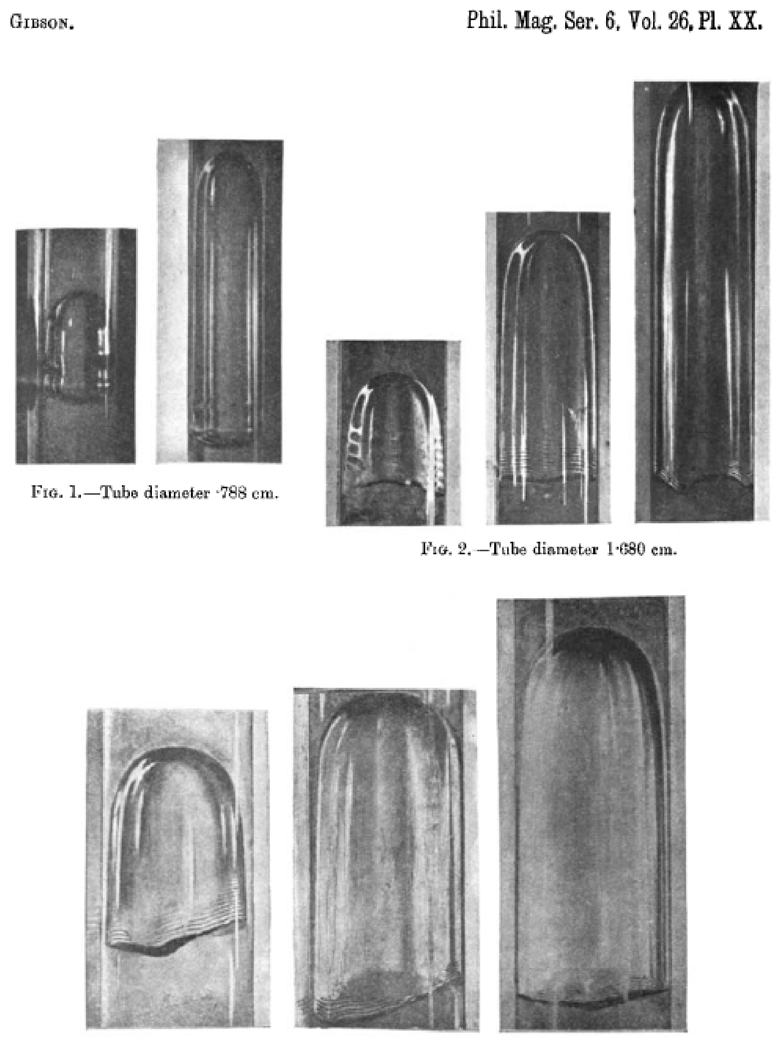


FIG. 1.—Tube diameter ·788 cm.
FIG. 2. —Tube diameter 1·680 cm.
FIG. 3.—Tube diameter 2·695 cm.

Taylor bubbles – a short history

D.T. Dumitrescu, Strömung an einer Luftblase im senkrechten Rohr, Z. angew. Math. Mech, Vol. 23 (1943) p. 139–149.

Mitarbeiter of KWI, from left Thirot, Görtler, Oswatitsch, Dumitrescu,

Dumitru T. Dumitrescu (1904–1984)
(a student of Ludwig Prandtl)

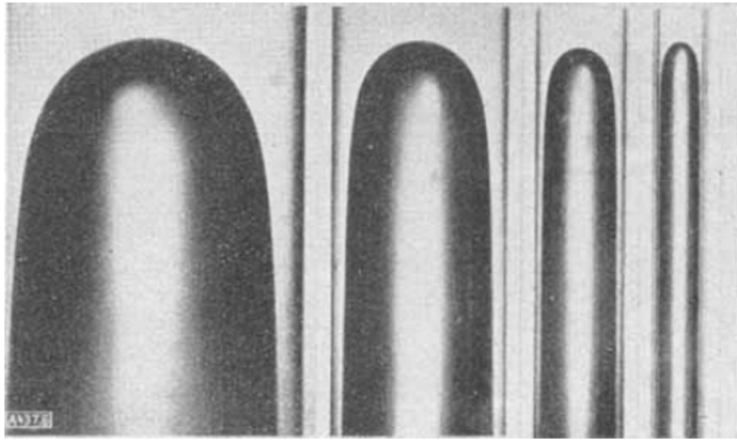


Bild 6. Blasen, in halber Größe wiedergegeben.

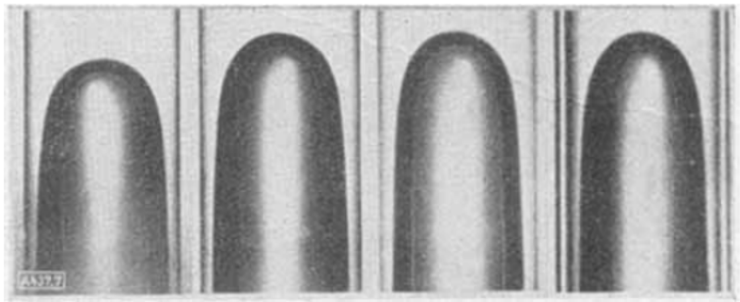


Bild 7. Dieselben Blasen wie in Bild 6, jedoch auf gleichen Maßstab gebracht.

Taylor bubbles – a short history

R.M. Davis & G.I. Taylor, The mechanics of large bubbles rising through extended liquids and through liquids in tubes. Proc. Roy. Soc. Series A Vol. 200 (1950) p. 375-390.

Geoffrey Ingram Taylor
(1886 –1975)

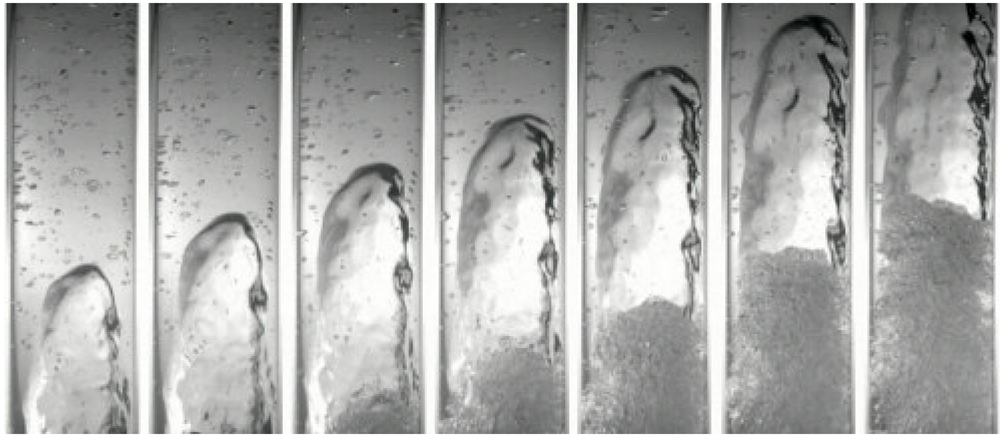
- Taylor-Couette flow
- Rayleigh-Taylor instability
- Taylor-Proudman theorem
- Taylor dispersion
- Taylor microscale
- Taylor number
- …
- *but not Taylor series*

Taylor bubbles and Taylor flow

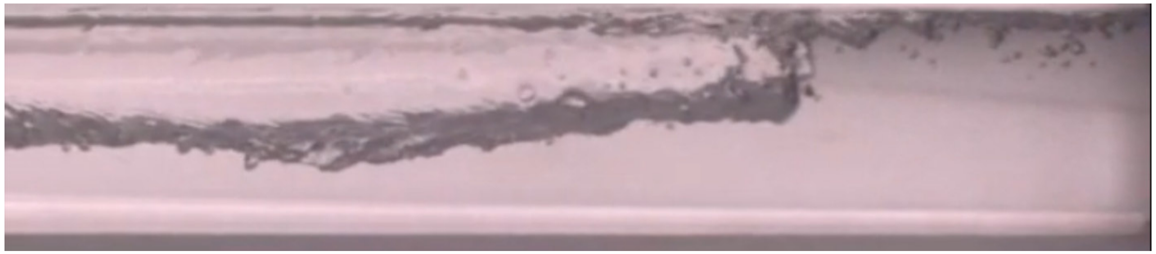
- Taylor bubble
  - an elongated bullet-shaped bubble that almost fills the entire cross-section of a channel
  - usually buoyancy driven flow in a vertical channel
- Taylor flow (segmented flow, bubble-train flow)
  - pressure driven flow of a <u>sequence of Taylor bubbles</u>
  - any channel orientation (vertical, horizontal, inclined)
  - usually narrow channel (small hydraulic diameter)
  - individual Taylor bubbles are separated by liquid slugs which are free from gas entrainment
  - … a special kind of slug flow

Slug flow and Taylor flow

(IAHR Multimedia Library)

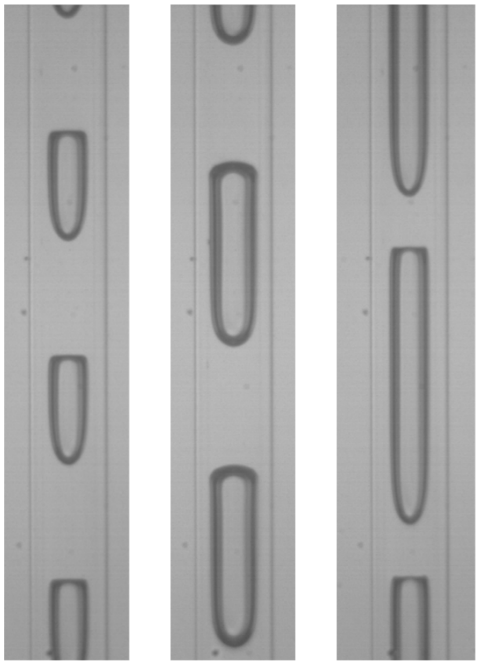


Vertical slug flow (air-water)
http://www.youtube.com/watch?v=L9KRvAG-c5E&feature=related



Horizontal slug flow (air-water)
http://www.youtube.com/watch?v=_07Pg1ZWscY

Co-current downward Taylor flow in a square channel, Squalane-nitrogen (1mm ×1mm)



TECHNISCHE UNIVERSITÄT DRESDEN

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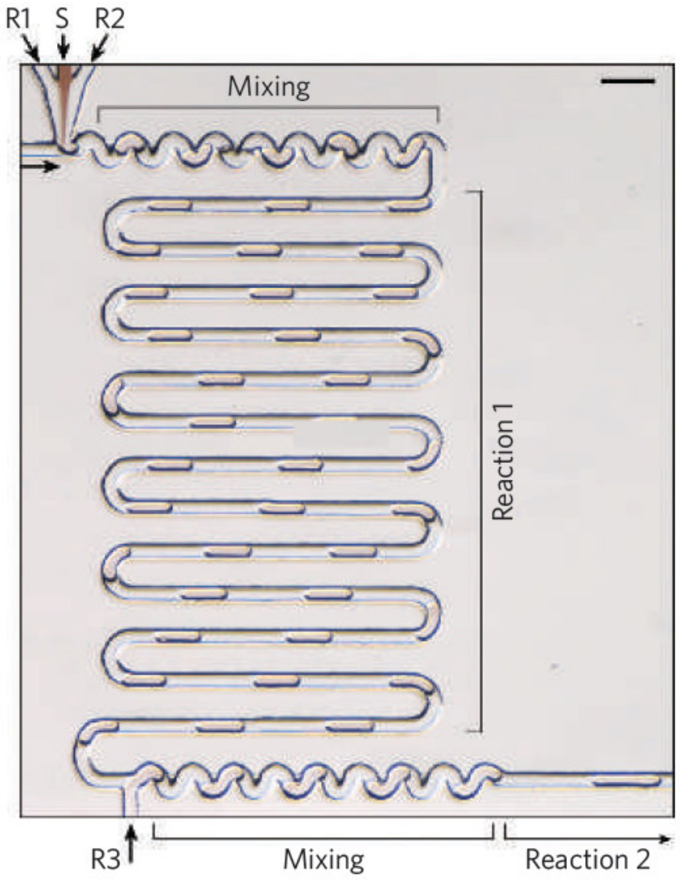
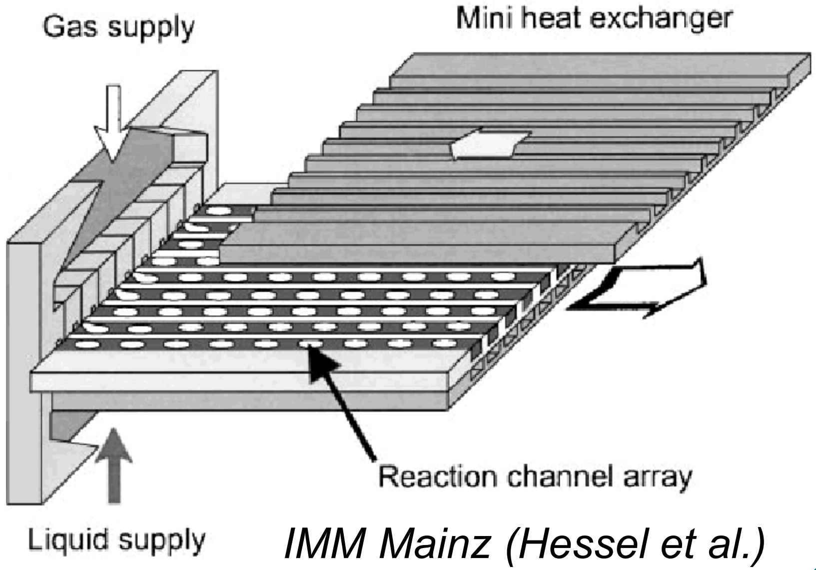
Chemical micro process engineering

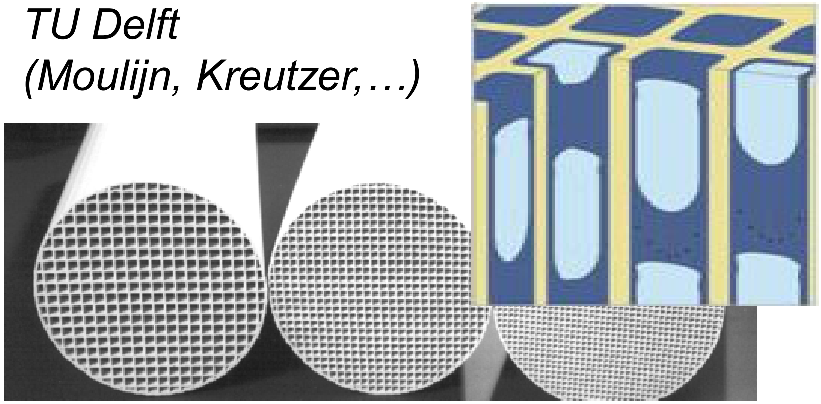


Okushima et al., Langmuir 20 (2004) 9905



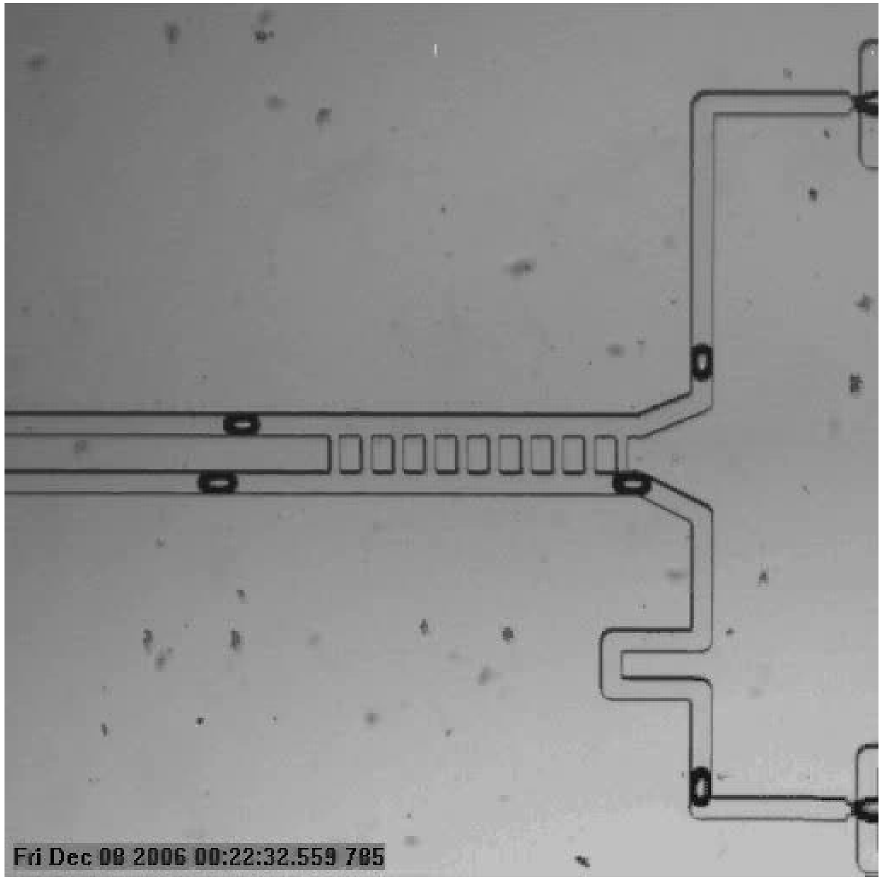
IMM Mainz (Hessel et al.)

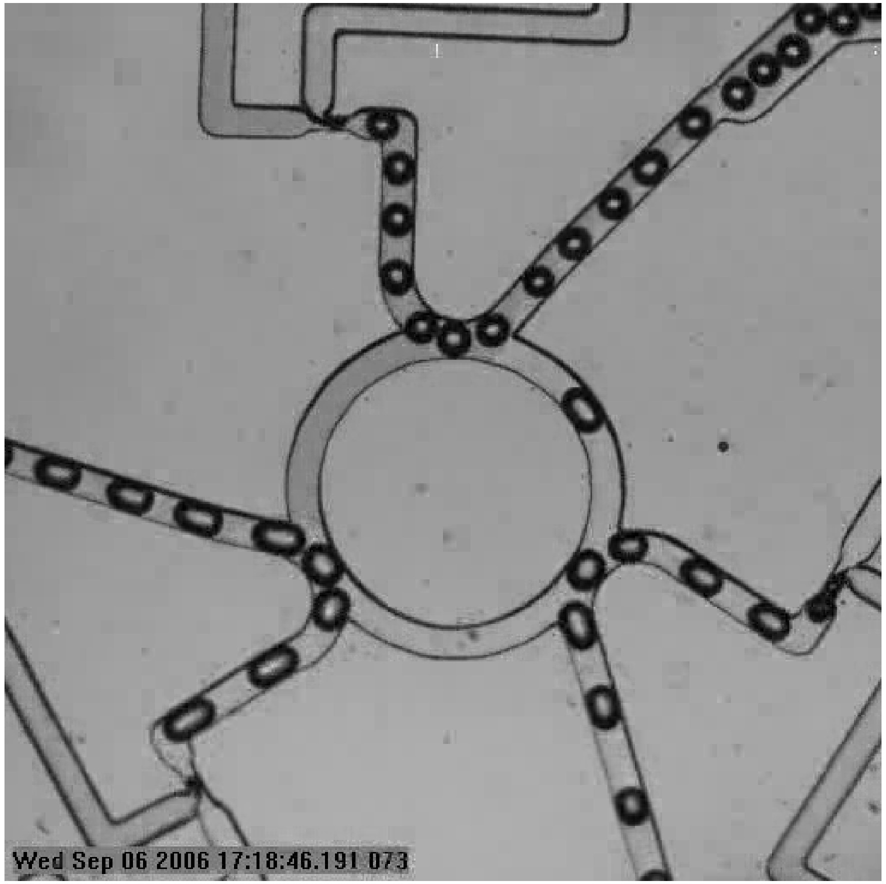
TU Delft (Moulijn, Kreutzer,…)



Microfluidics and lab-on-a-chip

Rectangular channels (height = 70 μm)

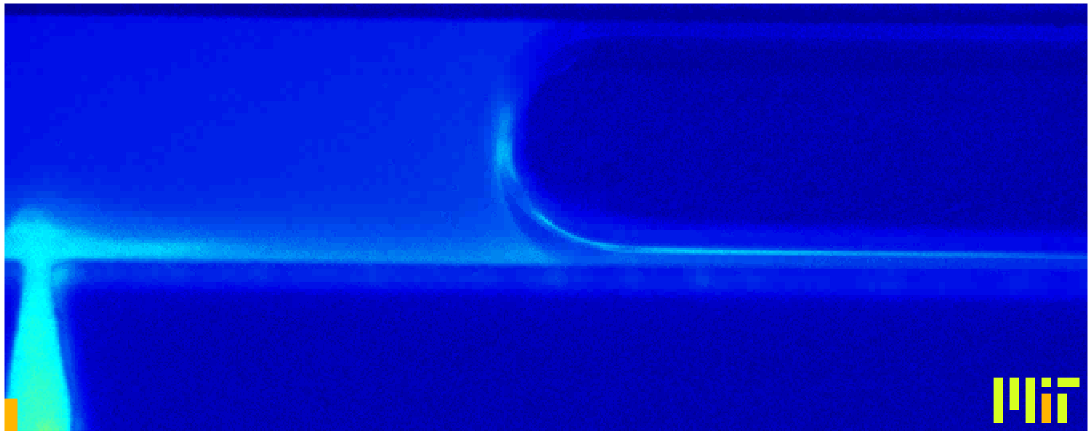




M. Prakash, N. Gershenfeld, Science 315 (2007) 832

Key advantages of Taylor flow

- Good mixing of species within the bubble
- Large interfacial area per unit volume and thin liquid film between bubble and wall ⇒ efficient heat and mass transfer
- Axial segmentation of liquid ⇒ reduced axial dispersion
- Recirculation in liquid slug ⇒ good mixing in liquid slug and wall-normal convective transport in laminar flow



Channel cross section: 400 μm × 280 μm

Movie of Günther et al. Langmuir ***21*** *(2005) 1547-1555*

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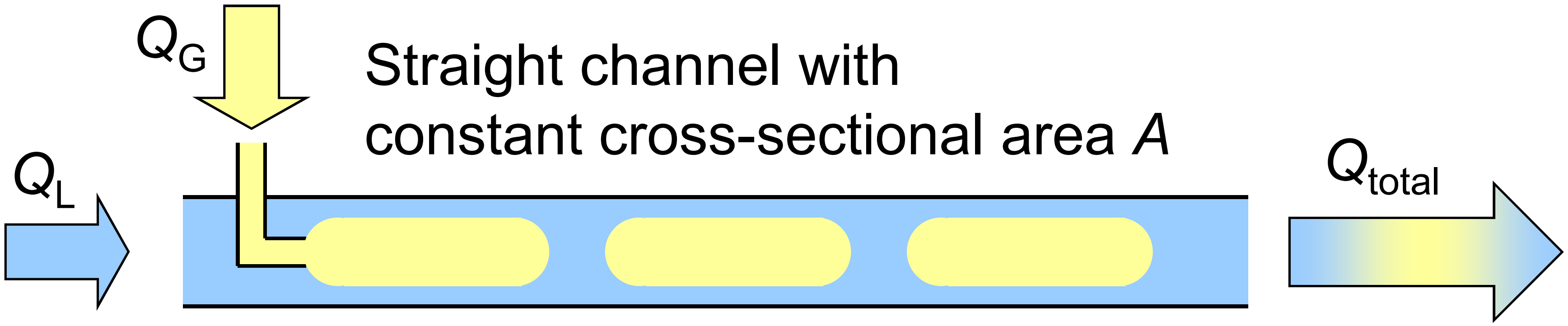
Some basic definitions



Total volumetric flux: $Q_{total} = Q_L + Q_G$ [m³/s]

Superficial velocities:

- Gas: $J_G \equiv Q_G / A$ [m/s]
- Liquid: $J_L \equiv Q_L / A$ [m/s]
- Total: $J_{total} \equiv (Q_G + Q_L) / A = J_G + J_L$ [m/s]

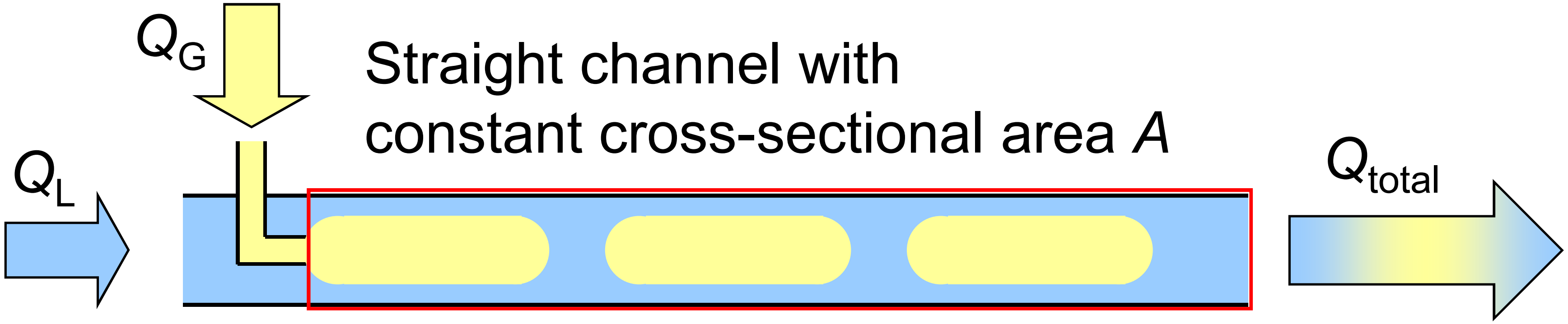
Volumetric flow rate ratio of the phases:

- Gas: $\beta_G \equiv Q_G / (Q_G + Q_L) = J_G / (J_G + J_L) = \beta$ [-]
- Liquid: $\beta_L \equiv Q_L / (Q_G + Q_L)$ [-]

$$\beta_G + \beta_L = 1$$

Some basic definitions

Straight channel with
constant cross-sectional area *A*



Volumetric phase fraction within the red control volume:

Gas: $\alpha_G \equiv V_G / (V_G+V_L) = \alpha = \varepsilon$ [-]

Liquid: $\alpha_L \equiv V_L / (V_G+V_L)$ [-] $\alpha_G + \alpha_L = 1$

Mean velocity within the control volume:

Gas: $U_G = Q_G / (\alpha_G A) = J_G / \alpha_G$ [m/s]

Liquid: $U_L = Q_L / (\alpha_L A) = J_L / \alpha_L$ [m/s]

Total: $U_{total} = U_G\alpha_G + U_L\alpha_L = J_G + J_L = J_{total}$ [m/s]

Slip: $S \equiv U_G / U_L$ (S = 1: homogeneous flow)

$\Rightarrow$ $\beta = J_G / (J_G+J_L) = \varepsilon / (\varepsilon + (1-\varepsilon)/S)$ (only for S=1 it is $\beta=\varepsilon$)

Forces in fluid dynamics

- Pressure force: drives flow from high to low pressure
- Inertia force: resists a change of actual state of motion
- Viscous force: diminishes velocity differences
- Gravity/Buoyancy force: drives flow in gravitational field
- Surface tension force: tends to minimize interfacial area

		Magnitude of	
Force	type	force	force per unit volume
Pressure force	surface force	$F_{\mathrm{P}} \propto \mathcal{A}\Delta p$	$f_{\mathrm{P}} \propto \Delta p L^{-1}$
Inertia force	volume force	$F_{\mathrm{I}} \propto \mathcal{V}\rho U^2 L^{-1}$	$f_{\mathrm{I}} \propto \rho U^2 L^{-1}$
Viscous force	surface force	$F_{\mathrm{V}} \propto \mathcal{A}\mu U L^{-1}$	$f_{\mathrm{V}} \propto \mu U L^{-2}$
Gravity force	volume force	$F_{\mathrm{G}} \propto \mathcal{V} g \rho$	$f_{\mathrm{G}} \propto g\rho$
Buoyancy force	volume force	$F_{\mathrm{B}} \propto \mathcal{V} g \Delta\rho$	$f_{\mathrm{B}} \propto g\Delta\rho$
Surface tension force	line force	$F_{\mathrm{S}} \propto \mathcal{C}\sigma$	$f_{\mathrm{S}} \propto \sigma L^{-2}$

Non-linear

Dominant forces at small length scales

Non-dimensional groups

- Reynolds number $$Re \equiv \frac{F_\mathrm{I}}{F_\mathrm{V}} = \frac{\rho_\mathrm{c} D_\mathrm{h} U_\mathrm{B}}{\mu_\mathrm{c}}$$ *(characteristic scales: $L = D_\mathrm{h}$ = hydr. diam. $U = U_\mathrm{B}$ = bubble vel.)*
- Capillary number $$Ca \equiv \frac{F_\mathrm{V}}{F_\mathrm{S}} = \frac{\mu_\mathrm{c} U_\mathrm{B}}{\sigma}$$ *(ratio of the two forces that are dominant at small length scales)*
- Eötvös number $$E\ddot{o} \equiv \frac{F_\mathrm{B}}{F_\mathrm{S}} = \frac{g(\rho_\mathrm{c} - \rho_\mathrm{d}) D_\mathrm{h}^2}{\sigma}$$
- Weber number $$We \equiv \frac{F_\mathrm{I}}{F_\mathrm{S}} = \frac{\rho_\mathrm{c} D_\mathrm{h} U_\mathrm{B}^2}{\sigma}$$
- Froude number $$Fr \equiv \sqrt{\frac{F_\mathrm{I}}{F_\mathrm{B}}} = \frac{U_\mathrm{B}}{\sqrt{g D_\mathrm{h} (\rho_\mathrm{c} - \rho_\mathrm{d}) / \rho_\mathrm{c}}}$$

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Rise velocity of a Taylor bubble

- Rise of a single Taylor bubble in a vertical pipe due to buoyancy
- Inertia dominated regime $Re \gg 1$

$$F_{\mathrm{B}} \cong F_{\mathrm{I}} \rightarrow Fr \equiv \sqrt{\frac{F_{\mathrm{I}}}{F_{\mathrm{B}}}} = C_{\mathrm{I}} = const.$$

$$\boxed{Fr = 0.35}$$

Dumitrescu (1943)

- Viscous regime $Re \ll 1$

$$F_{\mathrm{B}} \cong F_{\mathrm{V}} \rightarrow Fr \equiv \sqrt{\frac{F_{\mathrm{I}}}{F_{\mathrm{B}}}} \cong C_{\mathrm{V}} \sqrt{\frac{F_{\mathrm{I}}}{F_{\mathrm{V}}}} = C_{\mathrm{V}} \sqrt{Re}$$

$$\boxed{Fr = 0.1\sqrt{Re}}$$

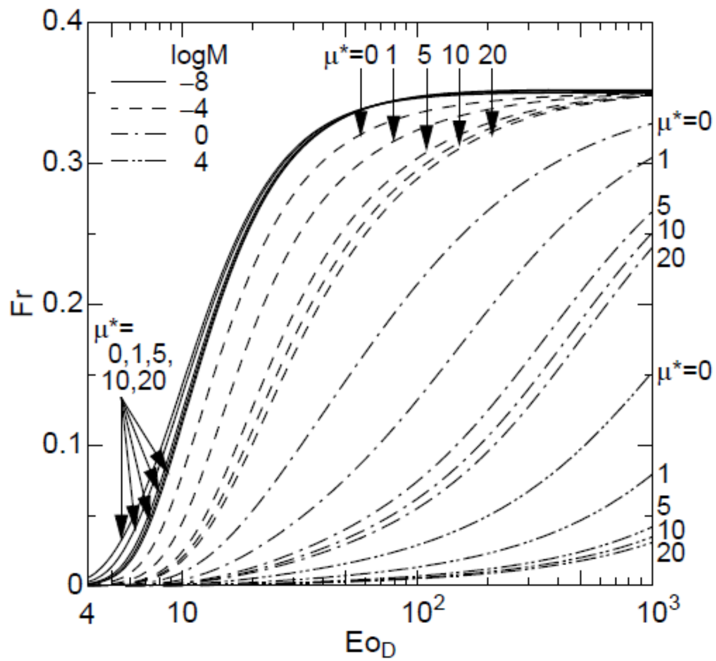
Wallis (1969)

General correlation

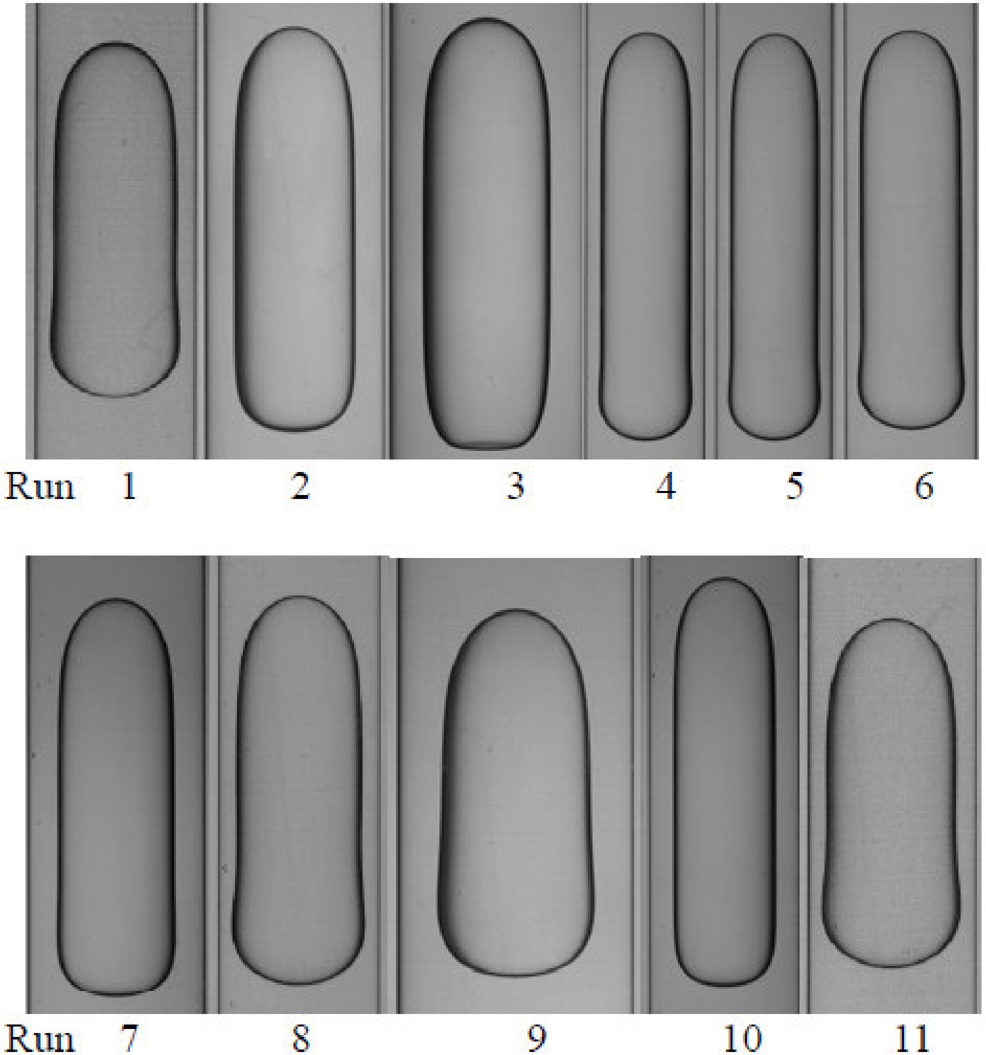
- Valid for single Taylor bubbles and Taylor drops

$$Fr = \sqrt{\dfrac{0.0089\left(1+\dfrac{41}{E\ddot{o}^{1.96}}\right)^{-4.63}}{0.0725+\dfrac{1-0.11Re^{0.33}}{Re}\,\dfrac{1+1.75\dfrac{\mu_{\mathrm{D}}}{\mu_{\mathrm{C}}}}{1+0.27\dfrac{\mu_{\mathrm{D}}}{\mu_{\mathrm{C}}}}}}$$

K. Hayashi, R. Kurimoto, A. Tomiyama,
7th Int. Conf. Multiph. Flow,
Tampa, FL USA, 2010



Shapes of Taylor drops



Pipe diameters in experiments:
D = 11.0, 20.1, 26.1 and 30.8 mm

K. Hayashi, R. Kurimoto, A. Tomiyama,
7th Int. Conf. Multiph. Flow, Tampa,
FL USA, 2010

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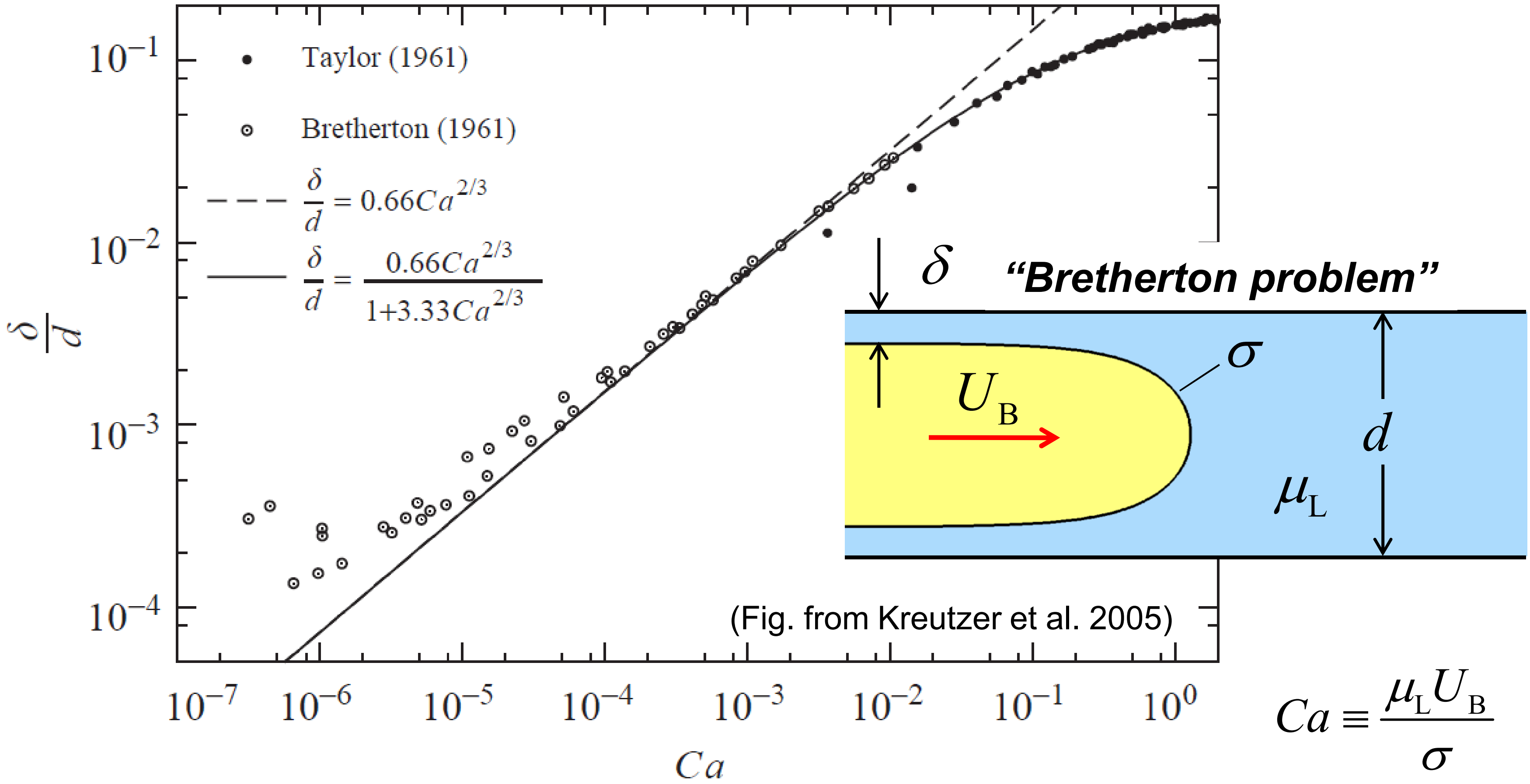
Displacement of liquid by a gas

G.I. Taylor, Deposition of a viscous fluid on the wall of a tube, J. Fluid Mech. 10 (1961) 161–165
F.P. Bretherton, The motion of long gas bubbles in tubes, J. Fluid Mech. 10 (1961) 166–188
P. Aussilous, D. Quére, Quick deposition of a fluid on the wall of a tube, Phys. Fluids 12 (2000) 2367–2371

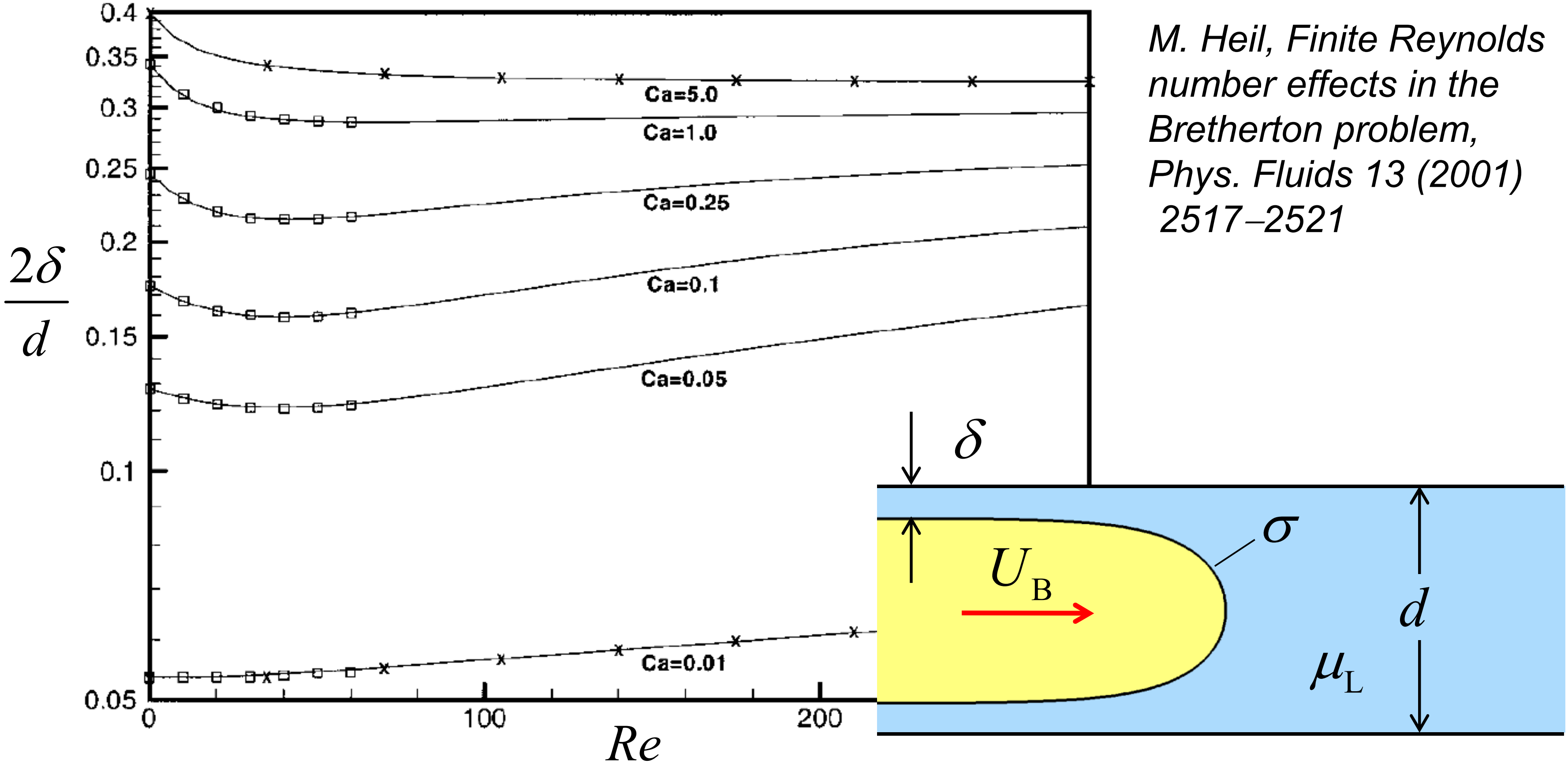


(Fig. from Kreutzer et al. 2005)

$$Ca \equiv \frac{\mu_L U_B}{\sigma}$$

Displacement of liquid by a gas

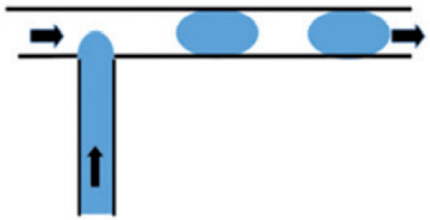
- Inertial effects on liquid film thickness in 2D (planar) Bretherton problem (numerical results, inviscid bubble)

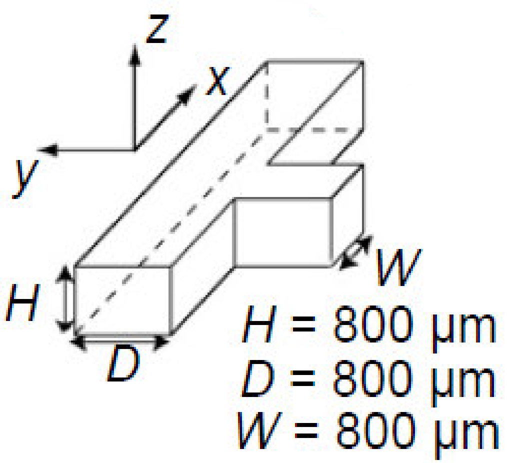


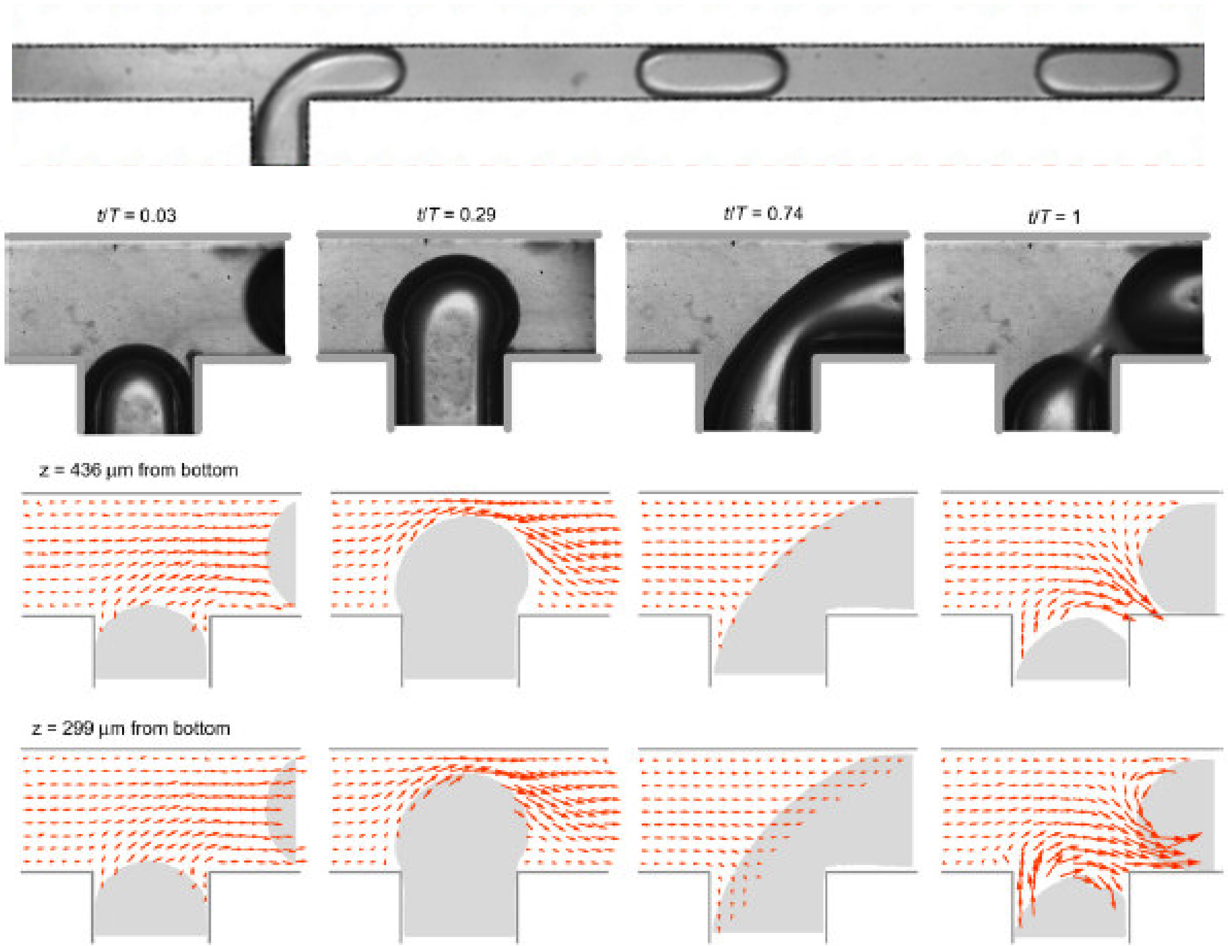
M. Heil, Finite Reynolds number effects in the Bretherton problem, Phys. Fluids 13 (2001) 2517–2521

Generation of Taylor flow

- T-junction





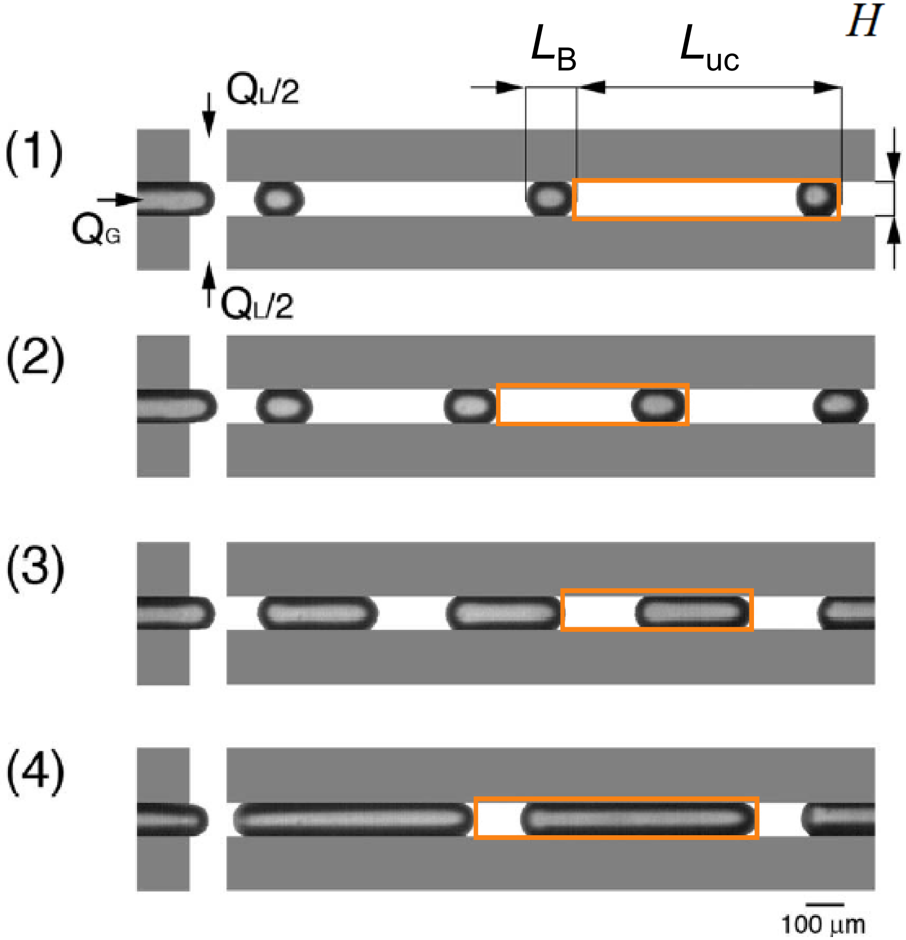


μPIV measurements by *van Steijn et al. Chem. Eng. Sci. 62 (2007) 7505*

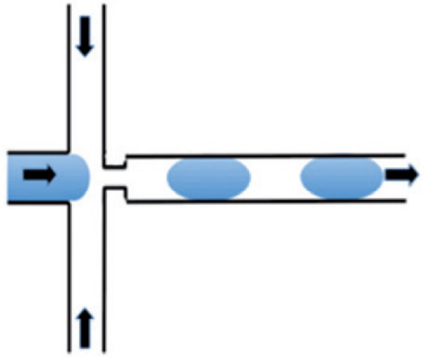
Generation of Taylor flow

- Flow focusing

$$\frac{L_B}{H} \propto \frac{Q_G + Q_L}{Q_L} = \frac{1}{\beta_L}$$



H = 100 µm

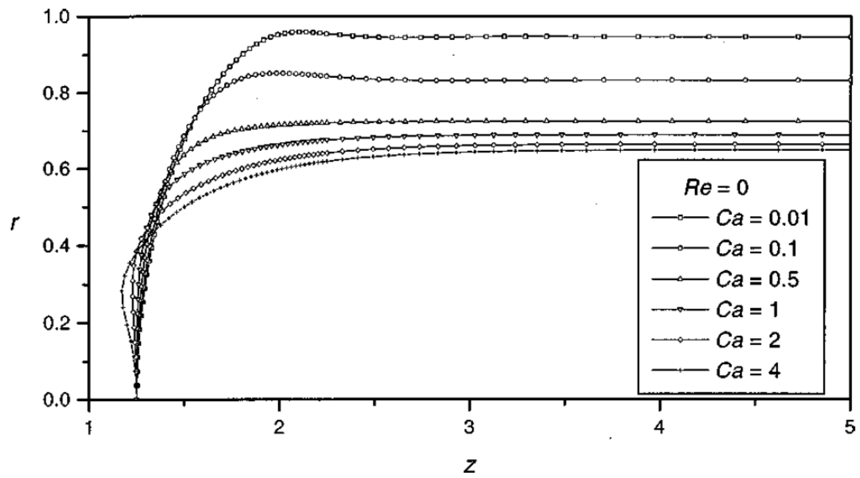


Square channel 100µm × 100µm

Cubaud et al. Phys. Rev. E 72 (2005) 037302

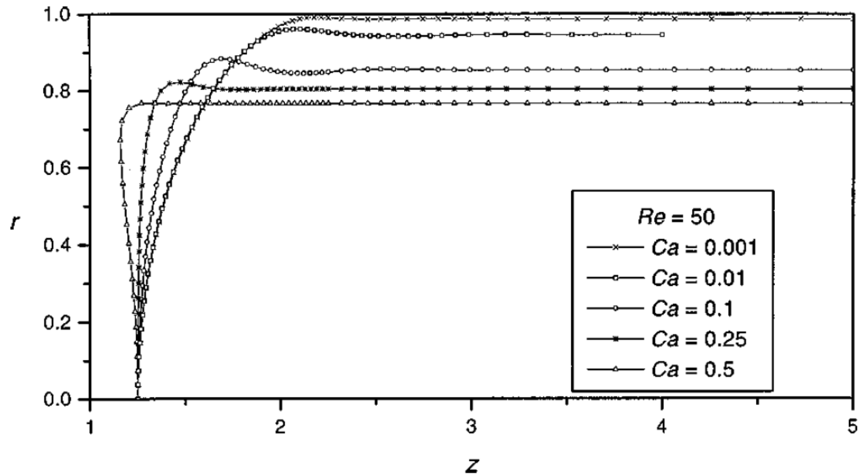
FIG. 1. Bubble formation for different water and air superficial velocities. (1) J_L=28.6 cm/s, J_G=11.3 cm/s, α_L=0.72; (2) J_L=26 cm/s, J_G=19.3 cm/s, α_L=0.57; (3) J_L=22 cm/s, J_G=72.4 cm/s, α_L=0.23; (4) J_L=18.1 cm/s, J_G=109.9 cm/s, α_L=0.14. Liquid inlet pressure was kept constant while gas inlet pressure was increased.

Shape of the rear meniscus



Numerical study (inviscid bubble)

M.D. Giavedoni, F.A. Saita, The rear meniscus of a long bubble steadily displacing a Newtonian liquid in a capillary tube, Phys. Fluids 11 (1999) 786–794



- The rear meniscus shows a complex shape depending on the values of *Ca* and *Re*
- Of primary influence is the value of the capillary number

Bubble shape – effect of *Re*

M. Kreutzer, Ph.D thesis, Delft University of Technology, 2003

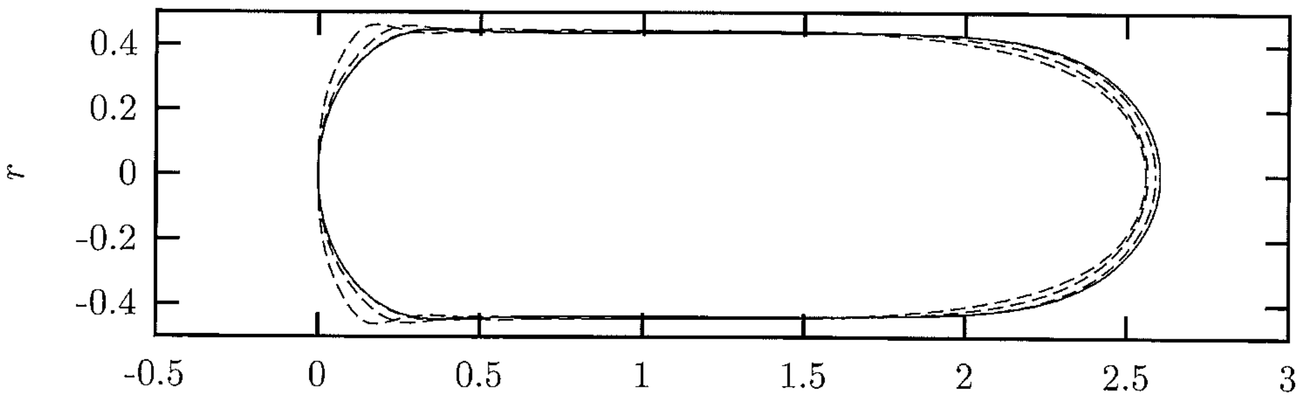


Figure 2.9: Shape of the gas–liquid interface for Re =1,10,100,200 at Ca =0.04

- *Re* and *Ca* are linearly related by the Laplace number *La*

$$Re = La \cdot Ca, \qquad La \equiv \frac{\sigma \rho_L D_h}{\mu_L^2}$$

- For a given fluid pair and channel size a change in *Ca* goes along with a change in *Re*

Liquid mass balance

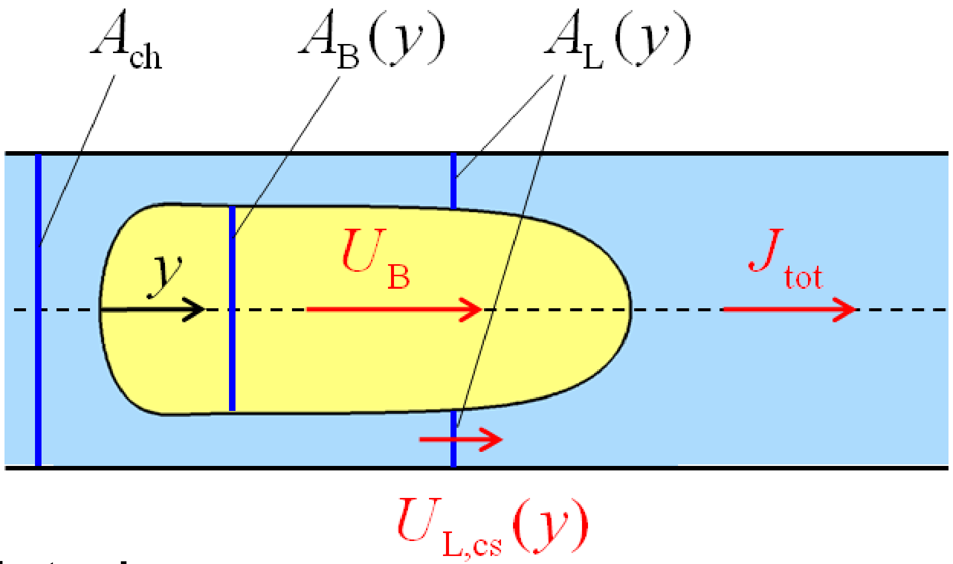
- A mass balance for the liquid phase in a frame of reference moving with the bubble at an arbitrary axial position *y* yields

$$(J_{\text{tot}} - U_{\text{B}})A_{\text{ch}} = \left[U_{\text{L,cs}}(y) - U_{\text{B}}\right]A_{\text{L}}(y)$$

so that

$$\frac{A_{\text{L}}(y)}{A_{\text{ch}}} = \frac{\psi - 1}{\psi - U_{\text{L,cs}}(y)/J_{\text{tot}}}$$

where $\psi \equiv \dfrac{U_{\text{B}}}{J_{\text{tot}}}$



- A_{L} and $U_{\text{L,cs}}$ are closely related
- in general A_{L} is not uniform but varies along the bubble

Bubble diameter / film thickness

- For a stagnant liquid film ($U_{L,cs}$=0) one obtains

$$\frac{A_B}{A_{ch}} = \frac{1}{\psi} \qquad \frac{A_L}{A_{ch}} = 1 - \frac{1}{\psi} \qquad \psi \equiv \frac{U_B}{J_{tot}}$$

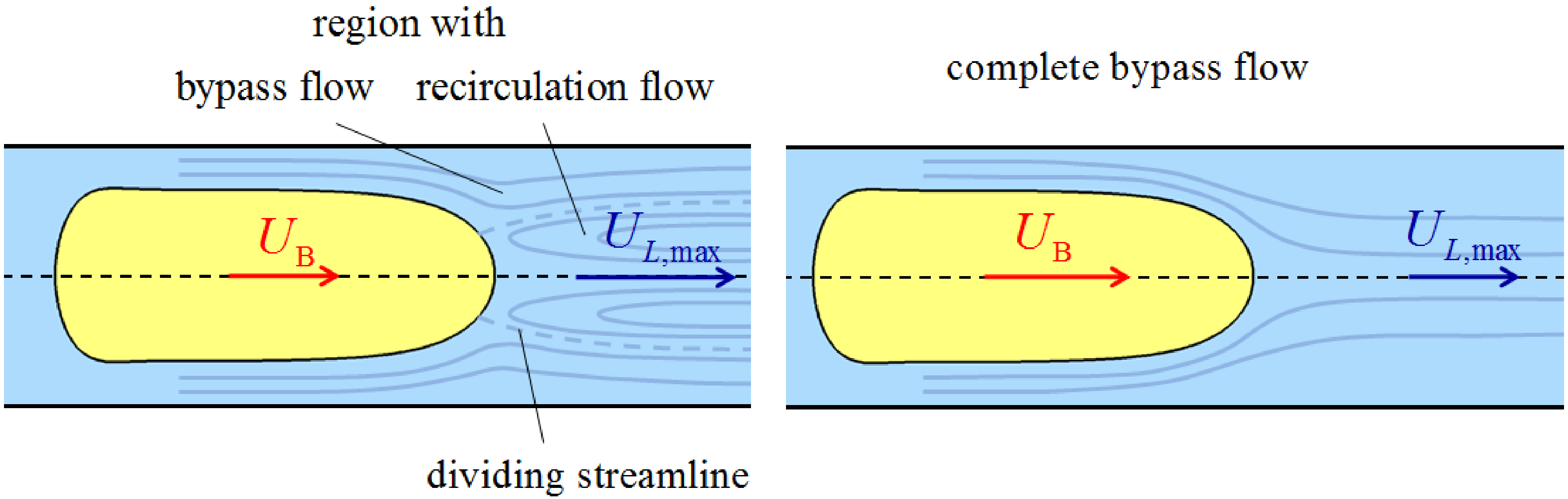
- For a circular channel with diameter D it follows for the bubble diameter D_B and the liquid film thickness δ_F

$$\frac{D_B}{D} = \frac{1}{\sqrt{\psi}} \qquad \frac{\delta_F}{D} = \frac{1}{2}\left(1 - \frac{1}{\sqrt{\psi}}\right)$$

- For a rectangular channel (aspect ratio $\chi \equiv H/B$) with an axisymmetric bubble and a stagnant liquid film it follows

$$\frac{D_B}{B} = 2\sqrt{\frac{\chi}{\pi\psi}} \qquad \frac{D_B}{H} = \frac{2}{\sqrt{\pi\chi\psi}} \qquad \frac{D_B}{D_h} = \frac{1+\chi}{\sqrt{\pi\chi\psi}}$$

Recirculation and by-pass flow



Fully developed laminar flow: $U_{L,\max} = C U_{L,\text{mean}} \quad (C_{\bigcirc} = 2;\ C_{\square} = 2.096)$

In Taylor flow it is: $U_{L,\text{mean}} = J_{\text{tot}}$ *(velocity profile in liquid slug is fully developed i.e. parabolic for $L_{sl}/D_h > 1.5$)*

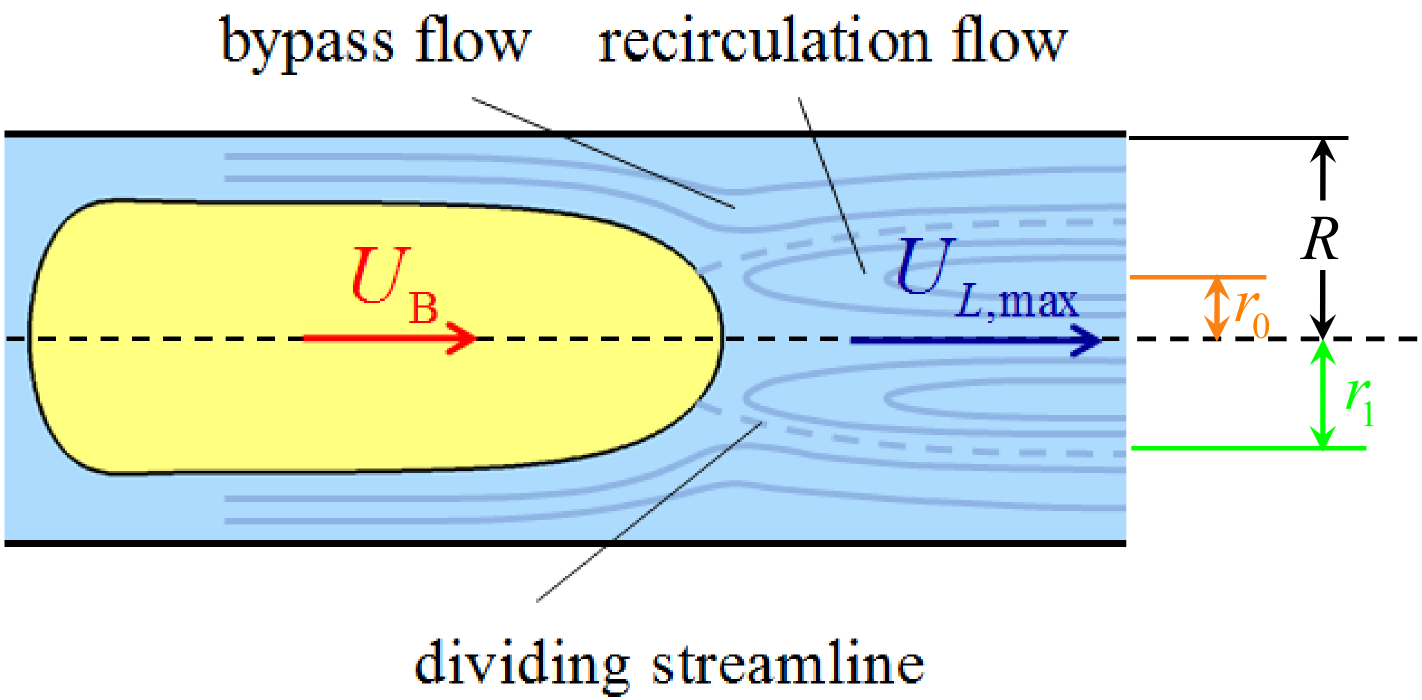
Condition for recirculation flow is	Condition for bypass flow is
$\psi \equiv U_B / J_{\text{tot}} < C$	$\psi \equiv U_B / J_{\text{tot}} \geq C$

Sketches in moving frame of reference after G.I. Taylor, J. Fluid Mech. 10 (1961) 161–165

Recirculation area and recirc. time

- Relations for a circular pipe of radius R

  Thulasidas, Abraham, Cerro, Chem. Eng. Sci. 52 (1997) 2947



$$\psi \equiv \frac{U_B}{J_{tot}}$$

$$\frac{r_0}{R} = \sqrt{\frac{2-\psi}{2}}$$

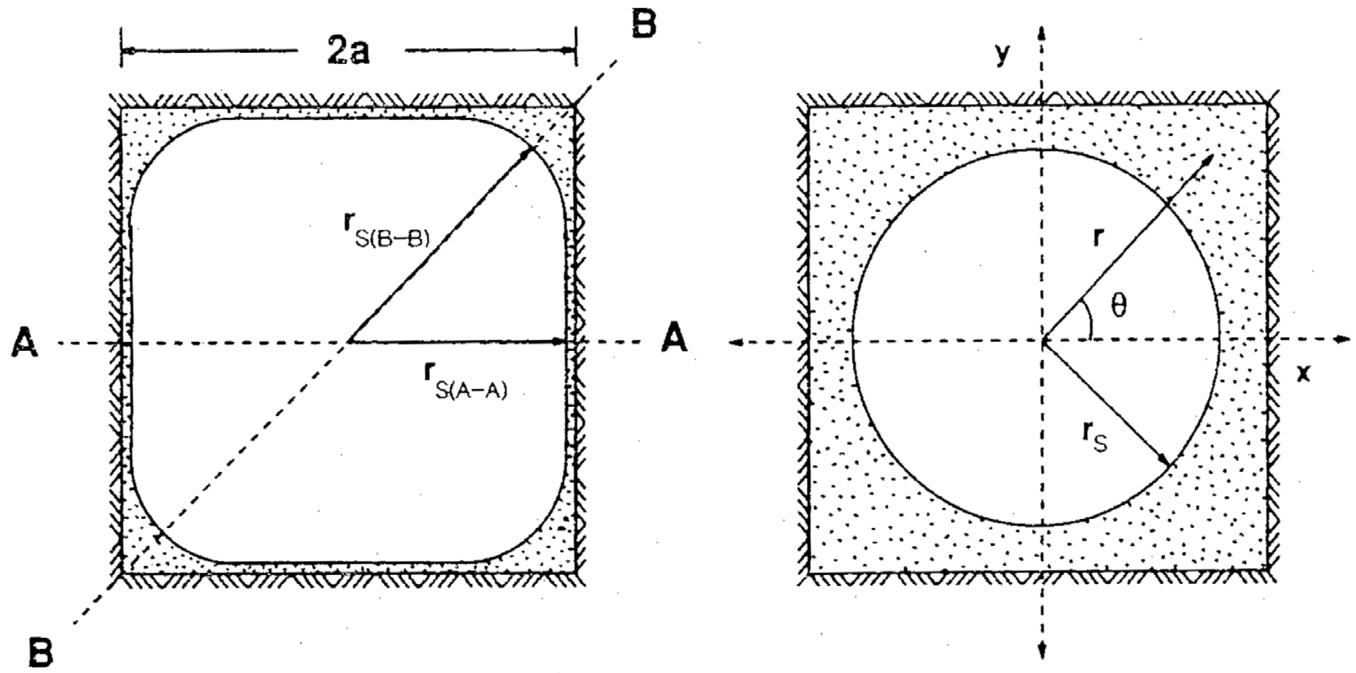
$$\frac{r_1}{R} = \sqrt{2-\psi}$$

$$\tau = \left(\frac{1}{\psi} - \frac{1}{2}\right)^{-1}$$

For the dependence of A_0/A_{ch}, A_1/A_{ch} and τ on ψ and χ in rectangular channels see Kececi et al. Catalysis Today 147S (2009) S125

Taylor flow in a square channel

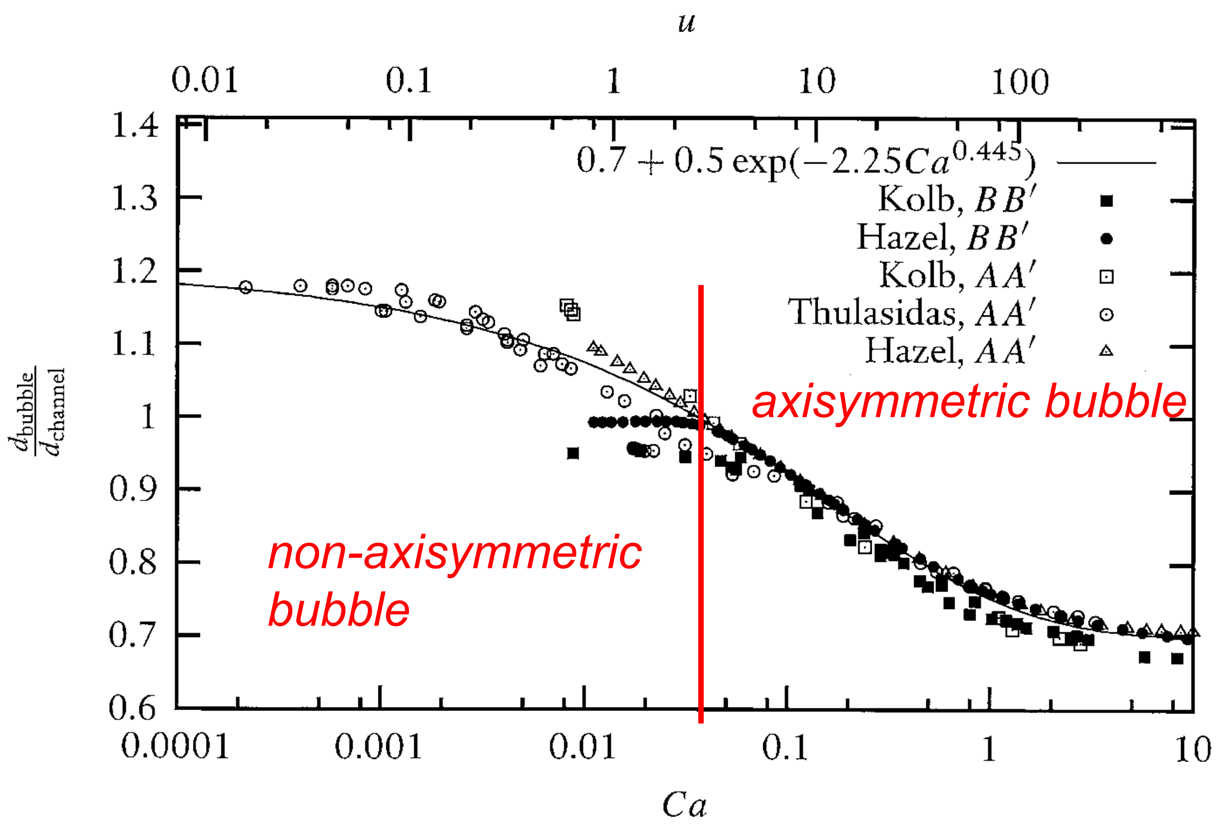
- Cross-section of a bubble in a square channel
  - Which shape corresponds to a smaller capillary number?

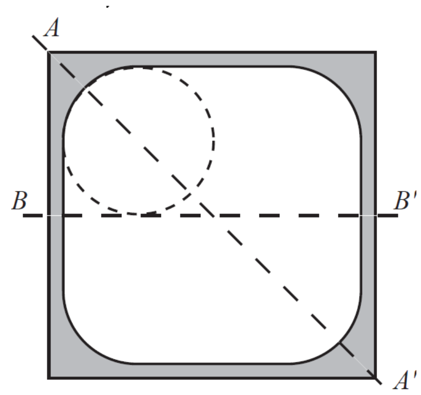


$$Ca \equiv \frac{\mu_L U_B}{\sigma}$$

Figure from Kolb & Cerro, J. Colloid. Interf. Sci. 159 (1993) 302–311

Bubble diameter in square channel





transition occurs at Ca ≈ 0.04

Figure 4.2: Bubble diameter versus *Ca* in square capillaries. Experimental data from Thulasidas *et al.* (1995*a*) and Kolb & Cerro (1991), numerical data from Hazel & Heil (2002). On the top axis, the velocity of the bubble is plotted, assuming water-like properties $\mu_L = 10^{-3}$ Pa s and $\gamma = 0.073$ N m^{-1}.

M. Kreutzer, Ph.D thesis, Delft University of Technology, 2003

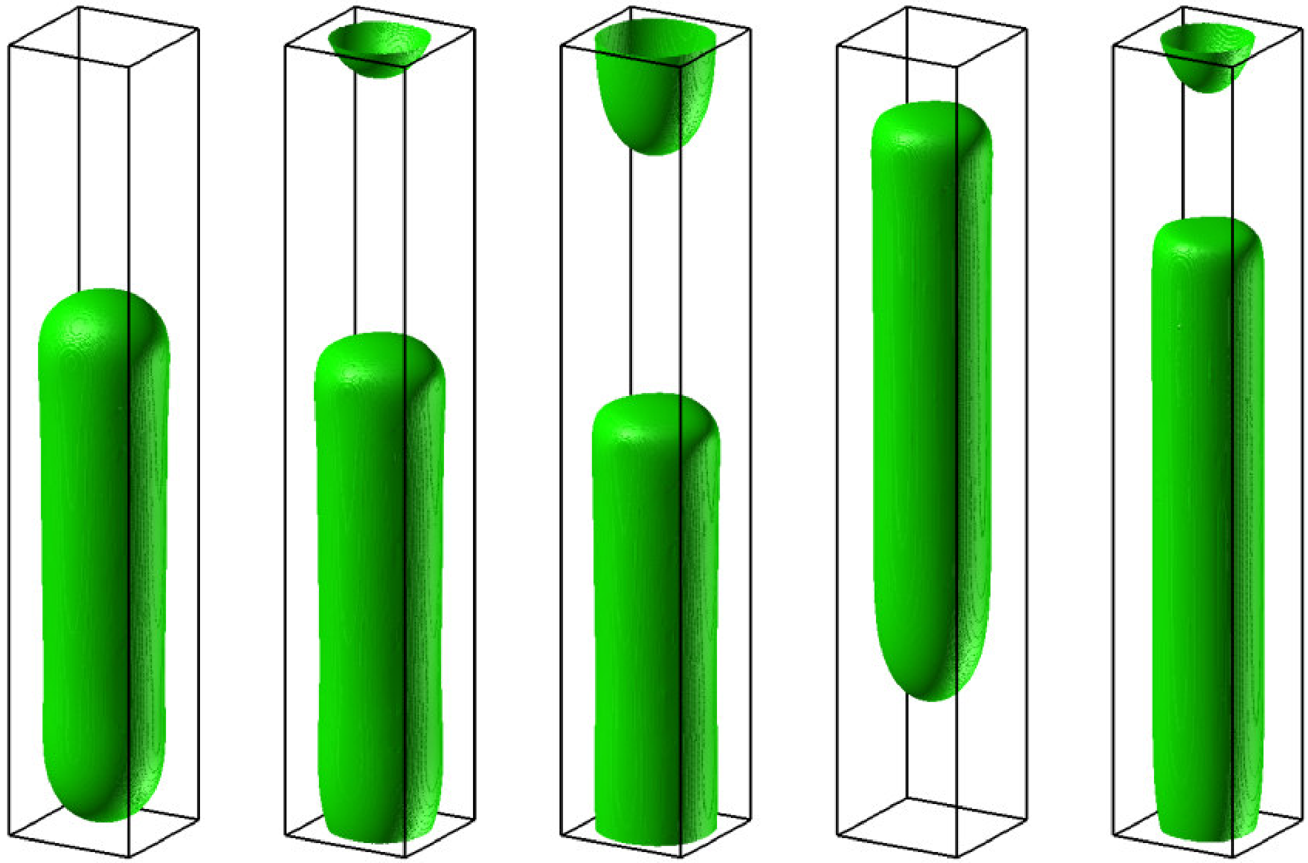
Downward Taylor flow (square channel)

$$1\,\mathrm{mm}\times 1\,\mathrm{mm}$$
$$L_{uc} = 6\,\mathrm{mm}$$
$$\varepsilon_G = 0.4$$

$$\frac{Re}{Ca} = \frac{\sigma \rho_L D_h}{\mu_L^2} \equiv La = 27.27$$

$$Ca \equiv \frac{\mu_L U_B}{\sigma}$$

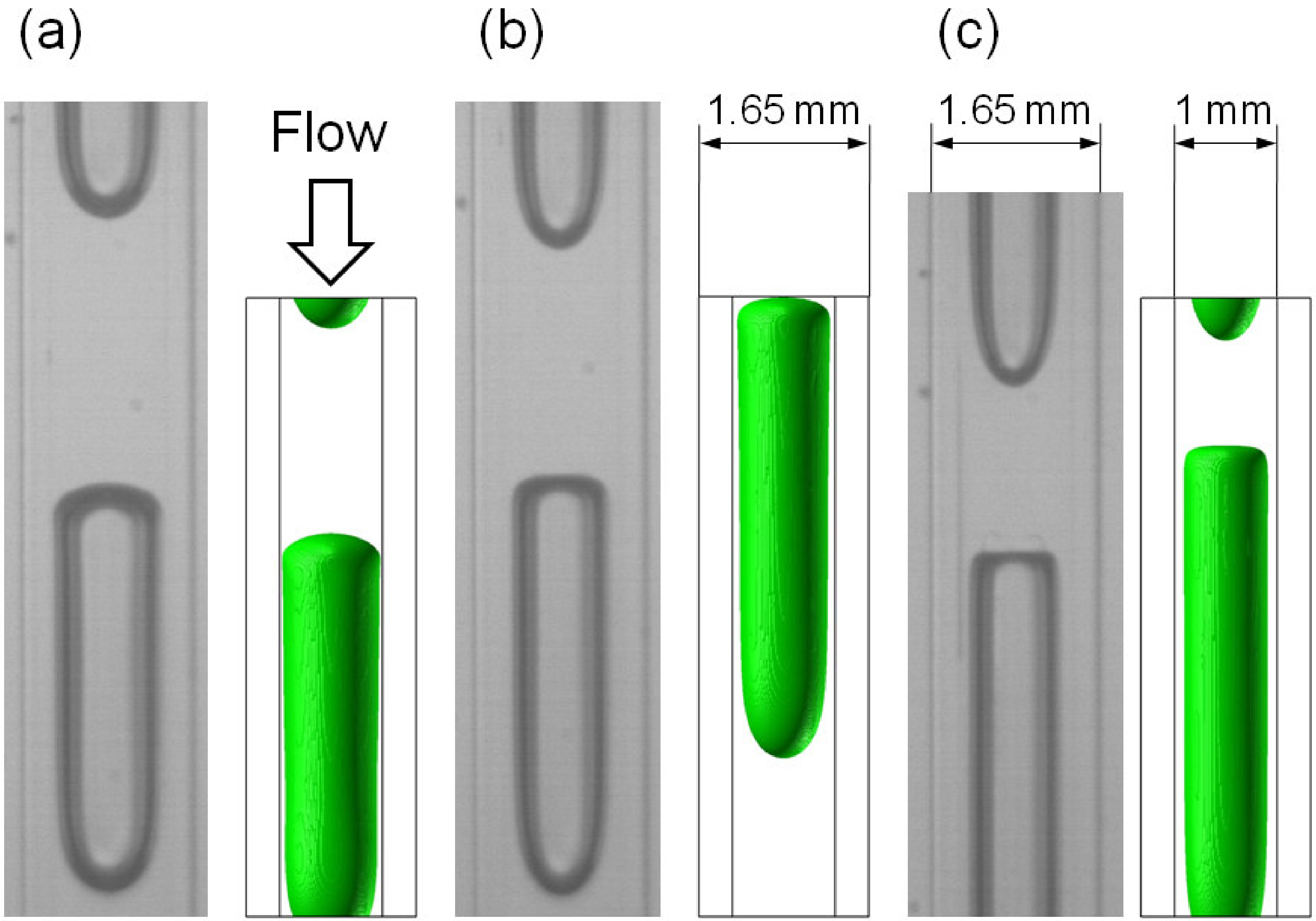
$$Re \equiv \frac{\rho_L D_h U_B}{\mu_L}$$



$Ca =$	0.045	0.12	0.17	0.26	0.49
$Re =$	1.22	3.19	4.64	7.16	13.4

M. Wörner, 7th Int. Conf. Multiph. Flow, Tampa FL USA, 2010

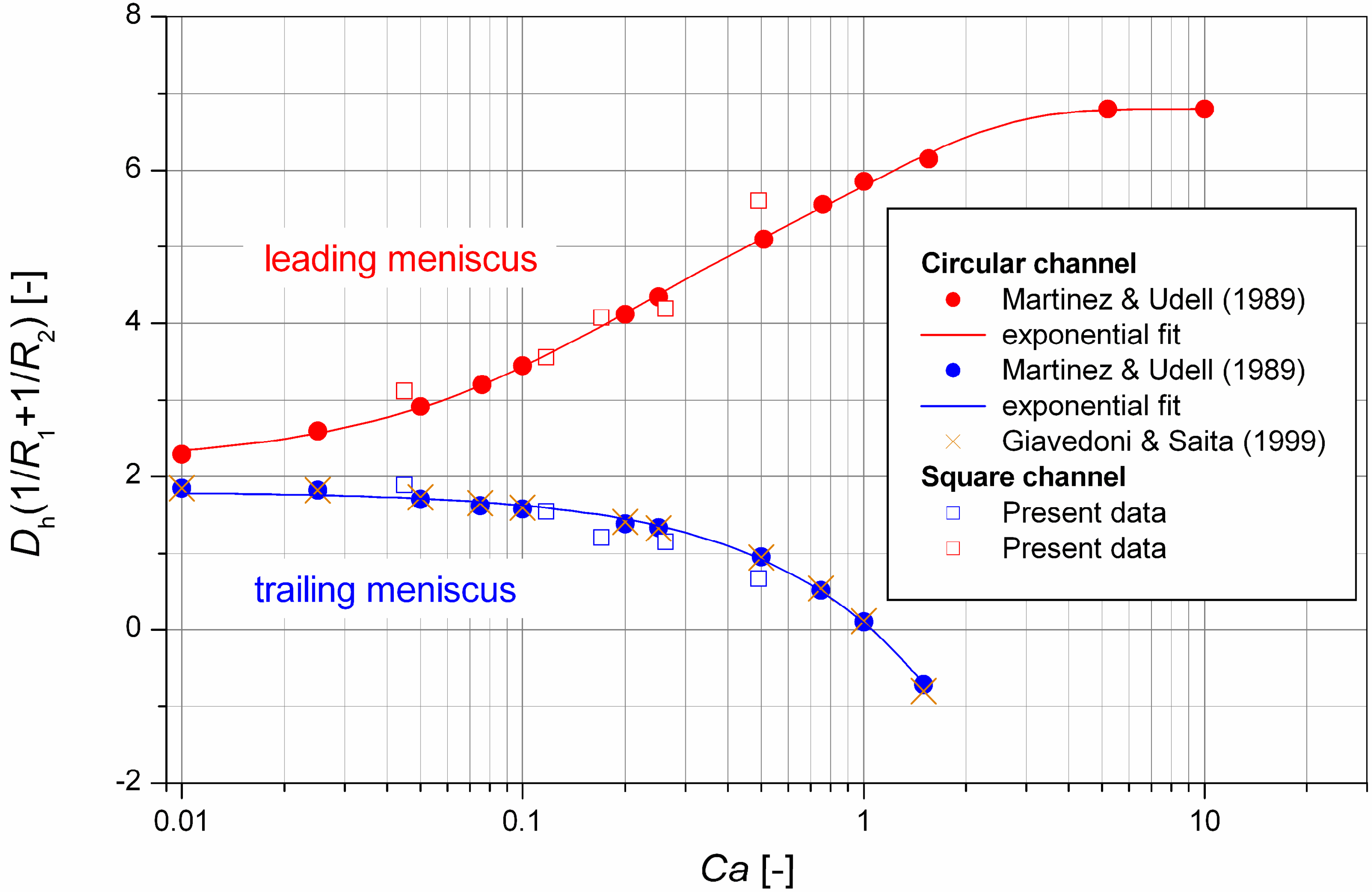
Validation of bubble shape



Experiments by Bauer & Lange

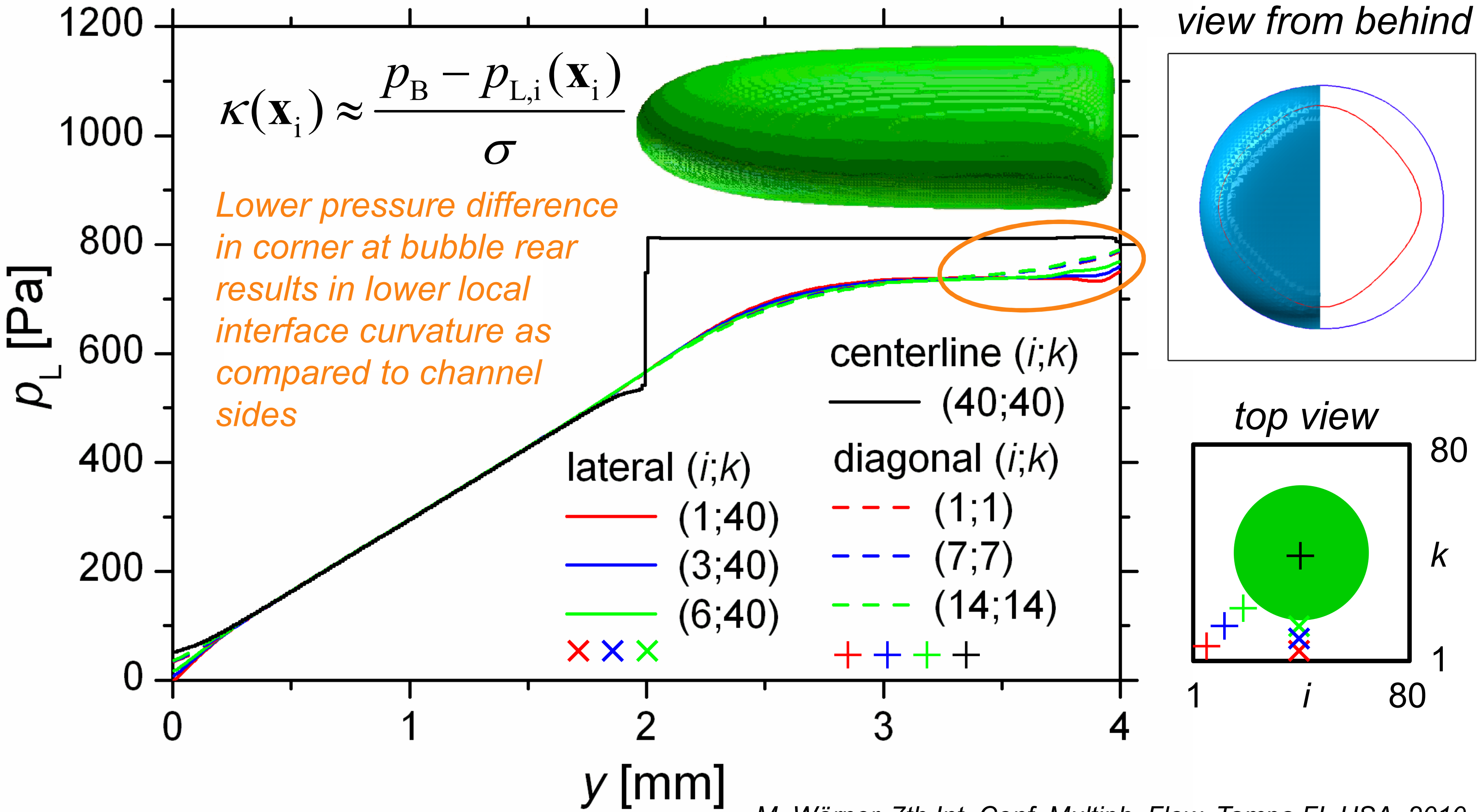
Keskin et al., AIChE J. 56 (2010) 1693–1702

Front and rear curvature



Pressure drop

$$\kappa_{\text{tip}} - \kappa_{\text{rear}} \approx \frac{p_{\text{L,rear}} - p_{\text{L,tip}}}{\sigma}$$



M. Wörner, 7th Int. Conf. Multiph. Flow, Tampa FL USA, 2010

Non-axisymmetric bubble regime

- Advanced measurements of local instantaneous liquid film thickness in a square channel (D_h = 0.3, 0.5, 1 mm) by a laser-focus-displacement meter for three different liquids

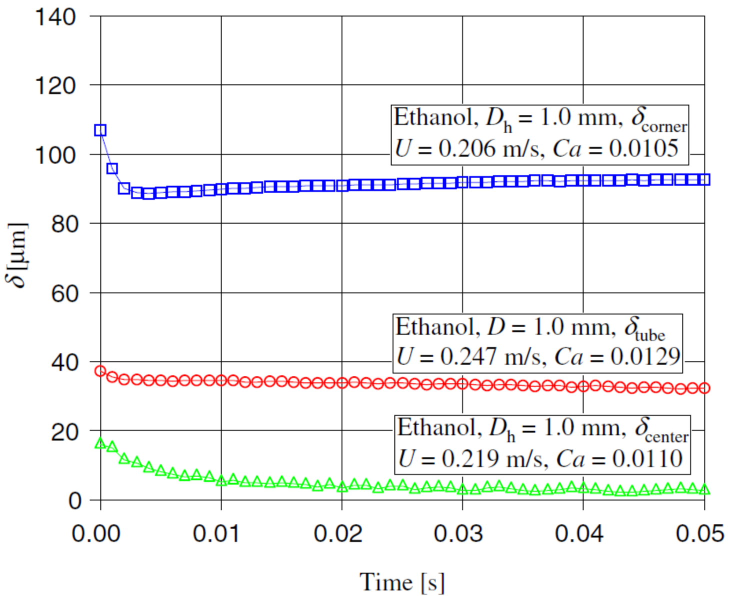


Fig. 6. Variation of liquid film thickness with time at low capillary number.

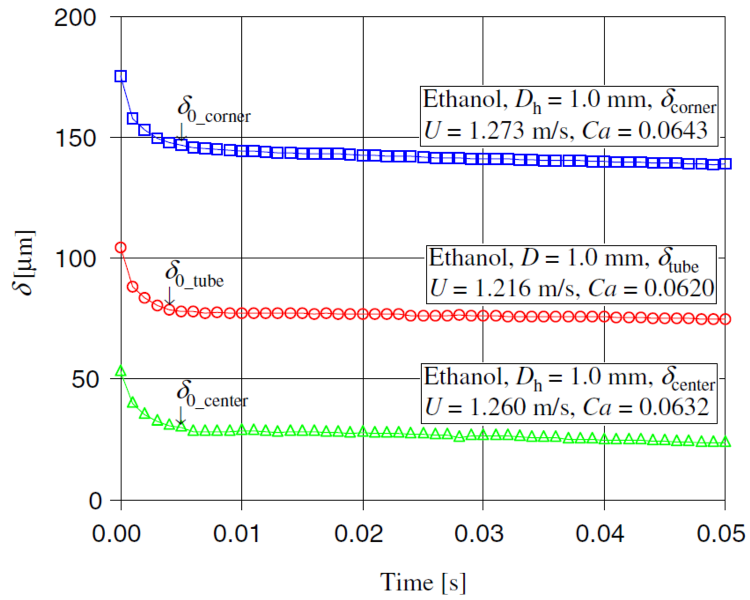


Fig. 10. Variation of liquid film thickness with time at high capillary number.

Y. Han, N. Shikazono, Measurement of liquid film thickness in micro square channel, Int. J. Multiph. Flow 35 (2009) 896–903
Y. Han, N. Shikazono, Measurement of liquid film thickness in micro tube slug flow, Int. J. Heat Fluid Flow 30 (2009) 842–853

Non-axisymmetric bubble regime

- Dimensionless bubble diameter

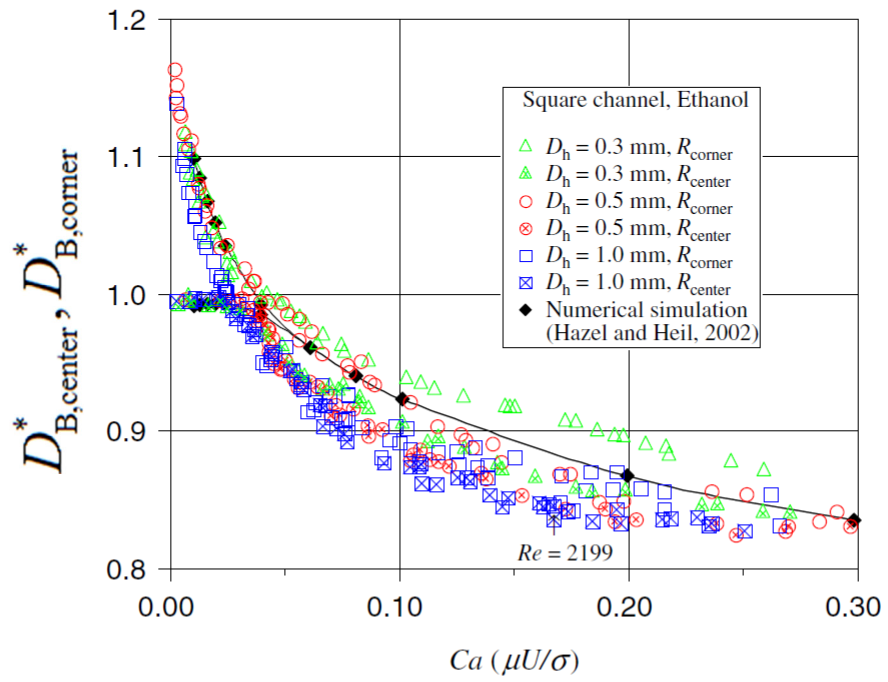
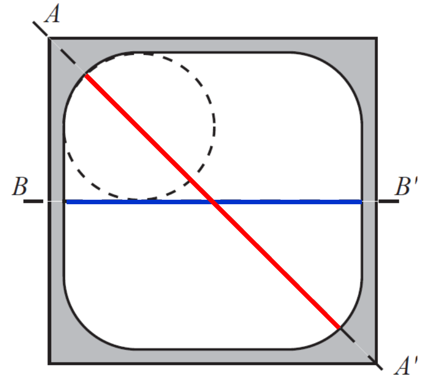


Fig. 14. Dimensionless bubble diameter against capillary number for the ethanol/air experiment.



$$D^*_{\mathrm{B,center}} = \frac{D_{\mathrm{B,center}}}{D_{\mathrm{h}}} = 1 - \frac{2\delta_{\mathrm{center}}}{D_{\mathrm{h}}}$$

$$D^*_{\mathrm{B,corner}} = \frac{D_{\mathrm{B,corner}}}{D_{\mathrm{h}}} = \sqrt{2} - \frac{2\delta_{\mathrm{corner}}}{D_{\mathrm{h}}}$$

Y. Han, N. Shikazono, Measurement of liquid film thickness in micro square channel, Int. J. Multiph. Flow 35 (2009) 896–903

Outline

- What are Taylor bubbles and Taylor flow?
  - Some historical publications
  - Where is Taylor flow of practical relevance?
- Some fundamentals of two-phase flows
  - Definitions, forces, non-dimensional groups
- What is the current state of knowledge?
  - Taylor bubbles driven by buoyancy
  - Taylor bubbles and Taylor flow in narrow channels
- **Why is Taylor flow of interest for this SPP?**
- What is the goal of the proposed experiment?

Taylor flow and SPP 1506

- Taylor flow is of practical technical relevance
- Taylor flow is of fundamental physical interest as it constitutes a prototypical problem for the non-linear interaction between viscous, inertial and surface tension forces under geometric constraints
- Taylor flow allows to increase the complexity of the flow and bubble shape by variation of one main control parameter (the bubble velocity)
- Thus, Taylor flow allows to study complex interfacial hydrodynamics in a relatively simple set-up, and is very well suited for validation of numerical methods and computer codes

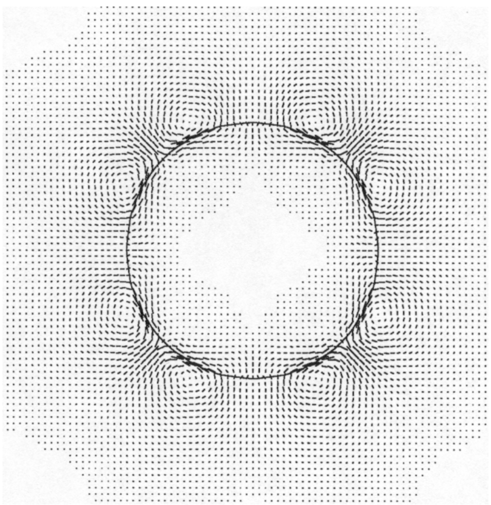
Taylor flow: a numerical challenge

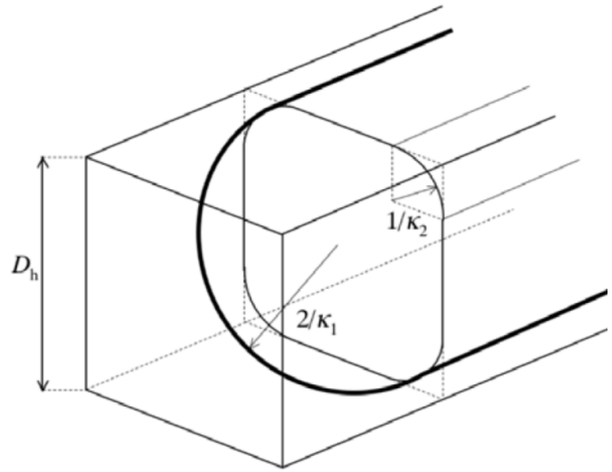
Karlsruhe Institute of Technology

- Large density and viscosity ratio of the phases
- Moving deformable interface
- Thin liquid film (non-uniform thickness in square ch.)
- Complex flow field in laminar flow (recirculation pattern in liquid slug, vortices in bubble wake)
- Transport phenomena at and across the interface (heat and mass transfer, Marangoni effects, see later)
- Large local interface curvature (in corner of square channel and at the rear meniscus)
- Spurious currents (artificial currents, parasitic flow)

Spurious currents

- Artificial non-physical flow at the interface due to
  - Imbalance in the numerical implementation of the discrete pressure gradient and surface tension force
  - Inaccurate computation of local interface curvature
  - For a spherical bubble or drop the amplitude of the spurious currents is proportional to σ / μ_L





Outline

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Experiments on Taylor flow

- Provide detailed data which allow for a <u>quantitative</u> validation of numerical methods and computer codes
- Perform experiments under well defined and well documented experimental conditions which allow a detailed recalculation
  - Thermo-physical properties of both fluids
  - Volume of the Taylor bubble
  - Liquid and gas volumetric flow rates
  - Boundary conditions for computational domain
  - …
- Experiments in 2D (pipe) and 3D (square channel)

Experiments on Taylor flow

- Approximate range of parameters*
  - Variation of capillary number by a least two orders of magnitude (0.01 – 1) maybe even three (0.001 – 1)
  - Variation of Reynolds number by at least two orders of magnitude (0.1 – 100) may be even three (0.1 – 1000)
  - Vertical channel (hydraulic diameter in range 1 – 5 mm)
  - Variation of liquid viscosity (very viscous / less viscous)
- Quantities to measure (if possible)
  - Three-dimensional bubble shape
  - Liquid film thickness (axial and circumferential)
  - Local velocity profiles (in liquid film and liquid slug)

** See also the appendix in the proposal for SPP 1506*

Experiments on Taylor flow

- Mass transfer from gas into liquid phase
  - Measurement of local concentration field

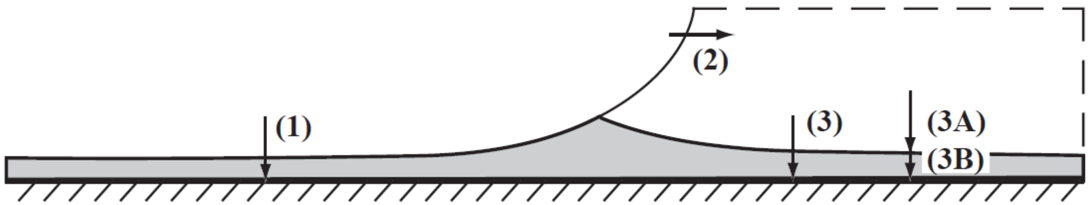
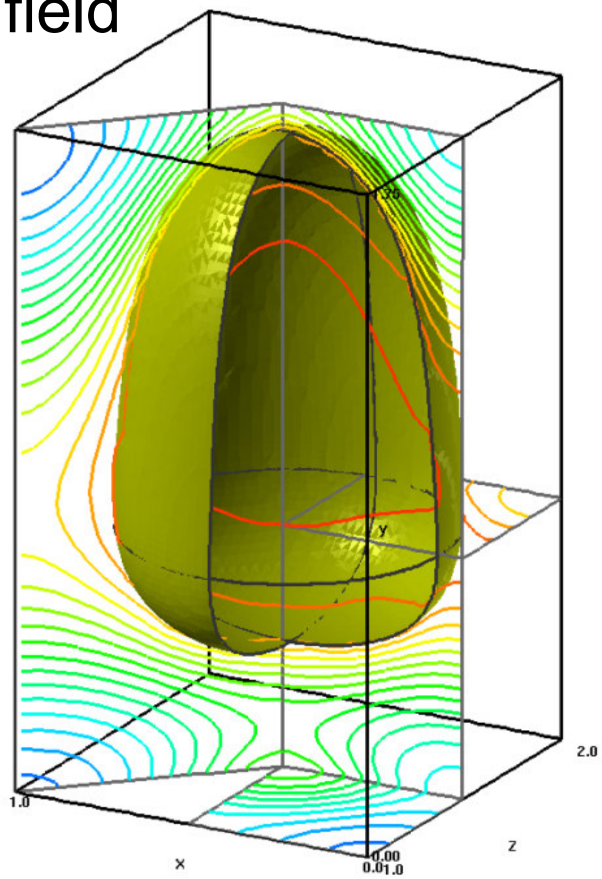


Fig. 15. Different mass transfer steps in Taylor flow. (1) From the bubble directly to the wall, (2) from the bubble to the vortex region in the slug, (3) from the vortex region to the wall. Note that the third step may be decomposed into a convective–diffusive contribution in the vortex region and a pure diffusive contribution in the film region.

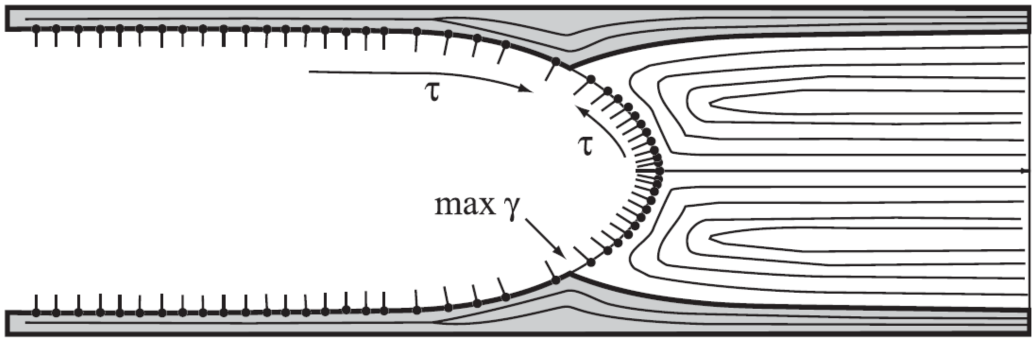
(Fig. from Kreutzer et al. 2005)



Numerical simulations of Onea et al. Chem. Eng. Sci. 64 (2009) 1416–1435

Possible future extensions

- Variable surface tension (Marangoni effects)
  - Temperature dependent: lateral heating of the channel
  - Concentration dependent: addition of a surfactant



(Fig. from Kreutzer et al. 2005)

Fig. 7. Schematic representation of the surface concentrations and the interaction with the fluid flow (after Ratulowski and Chang, 1989).

- Horizontal channel (break of symmetry by gravity)
- Defined contact and coalescence of Taylor bubbles
  - Two bubbles of different volume have a relative velocity

Further literature

Karlsruhe Institute of Technology

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