Karlsruhe Institute of Technology

Survey Lecture:

Benchmark Test Taylor bubbles

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SPP 1506 Annual Conference
Regensburg, April 11-12, 2011

Transport processes at fluidic interfaces
DFG SPP 1506

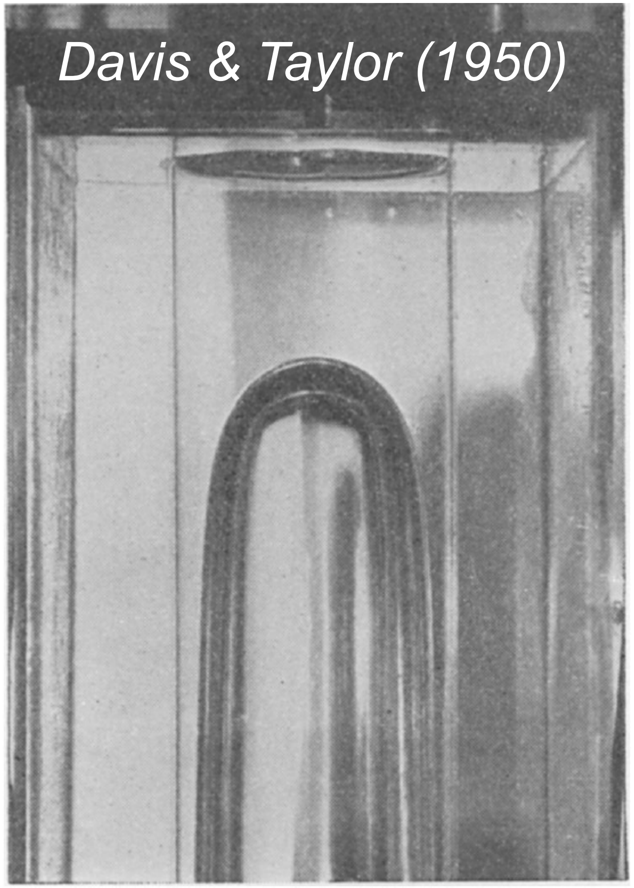


FIGURE 8. Emptying a glass tube 7·9 cm. diameter.

Outline

- Taylor bubbles and Taylor flow
  - Recalling some essential facts
- Taylor flow and SPP 1506
  - Why Taylor flow as validation experiment?
  - Validation data base: what should be measured?
- Benchmark test cases as starting point
  - Bretherton problem
  - Buoyancy driven rise of a Taylor drop in a circular pipe
  - Taylor flow in a square mini-channel

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

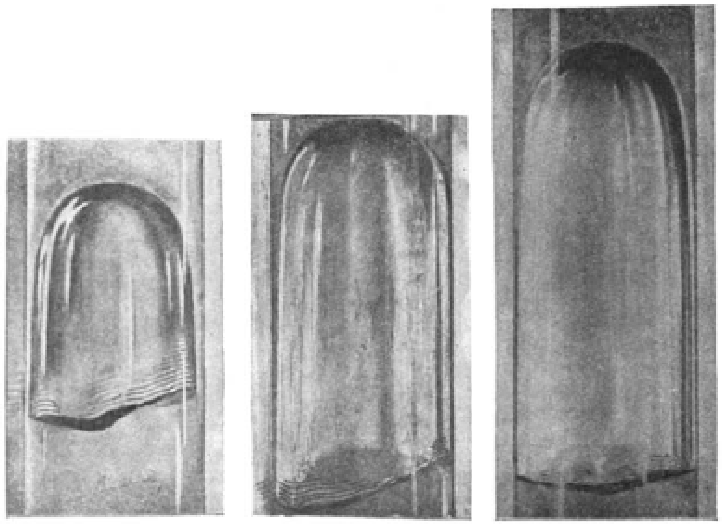
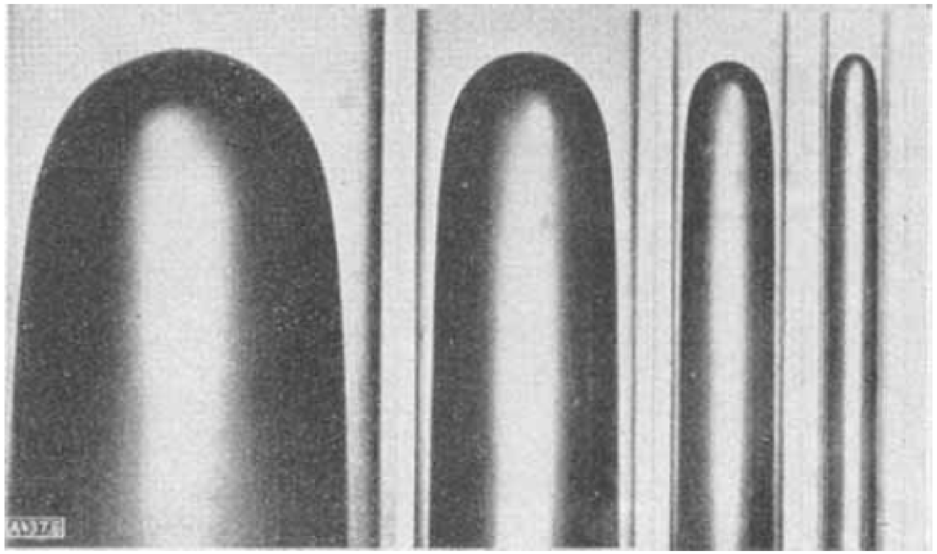


FIG. 3.—Tube diameter 2·695 cm.

Gibson (1913)

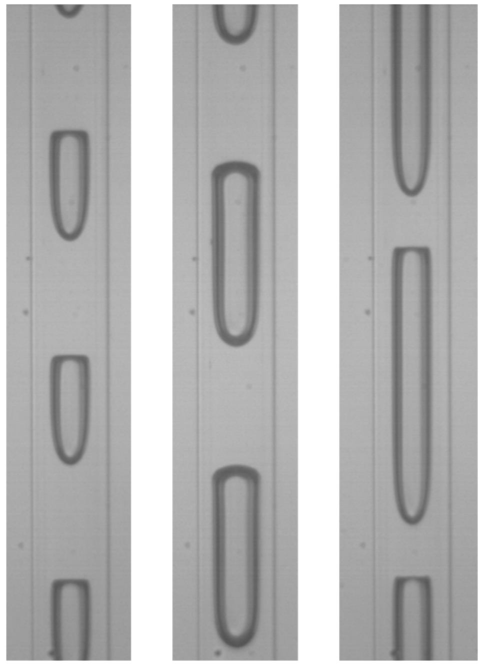


Dumitrescu (1943)

Taylor flow (segmented flow, bubble-train flow)

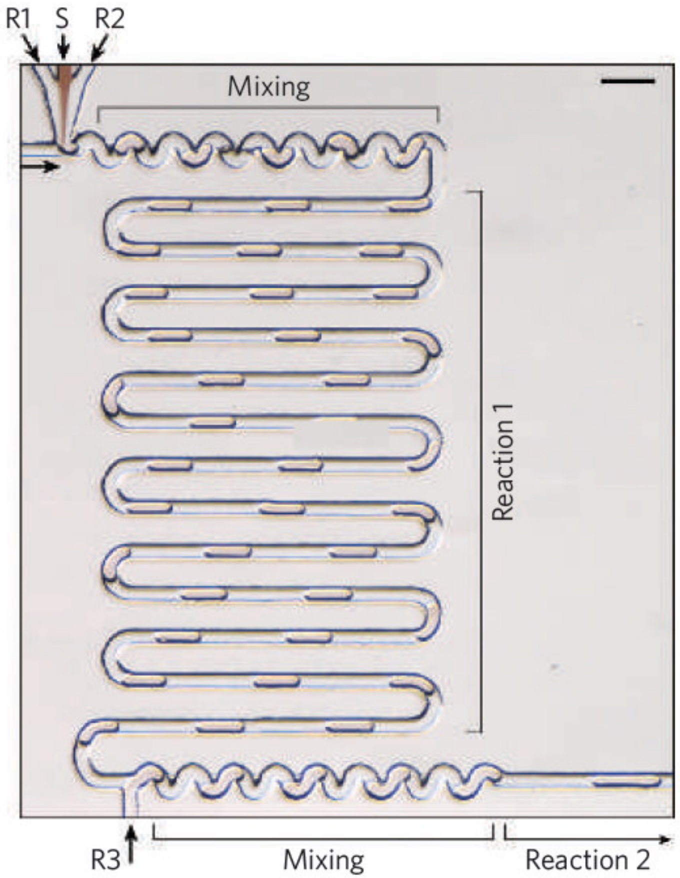
- Pressure driven flow of a sequence of Taylor bubbles
- Any channel/flow orientation (vertical up/down, horizontal)
- Usually narrow channel (small hydraulic diameter)
- Individual Taylor bubbles are separated by liquid slugs which are free from gas entrainment

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

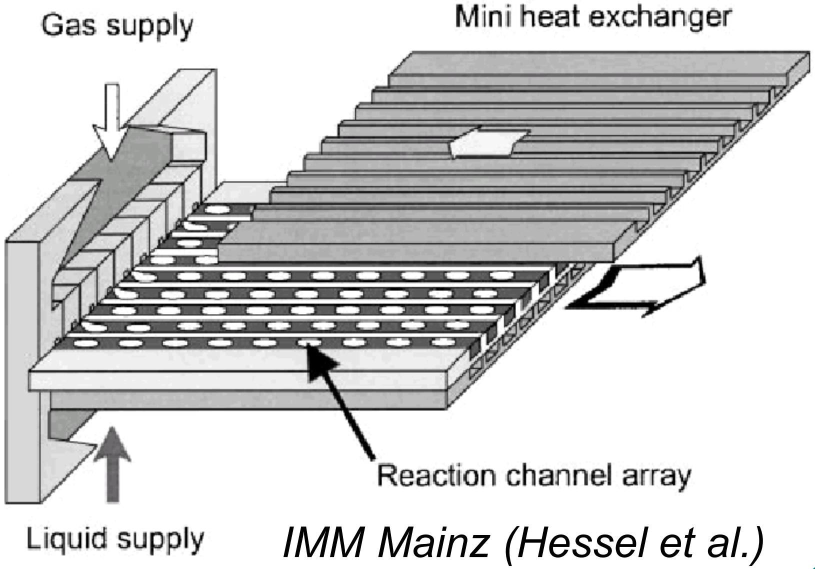


TECHNISCHE UNIVERSITÄT DRESDEN

Applications of Taylor flow

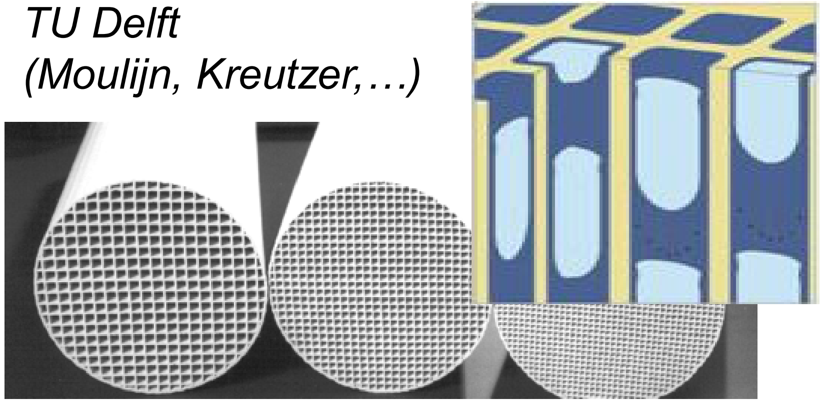


Okushima et al., Langmuir 20 (2004) 9905



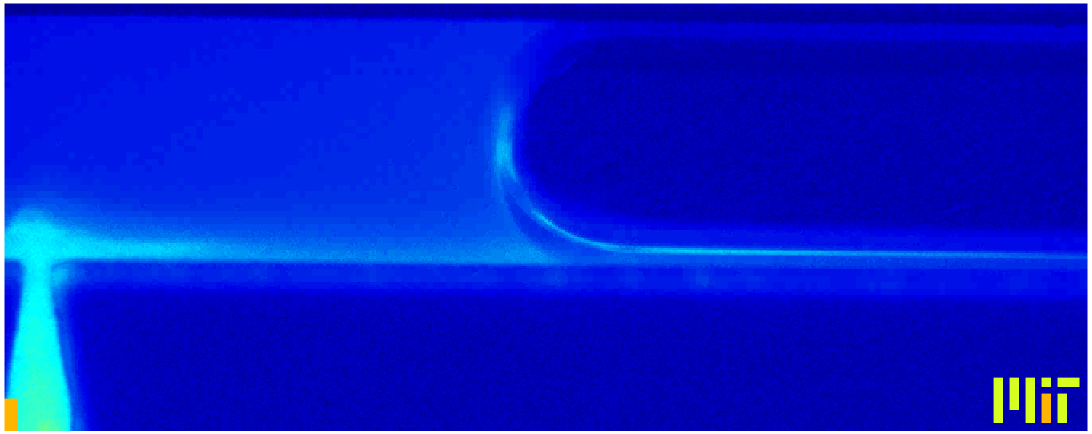
IMM Mainz (Hessel et al.)

TU Delft
(Moulijn, Kreutzer,…)



Key advantages of Taylor flow

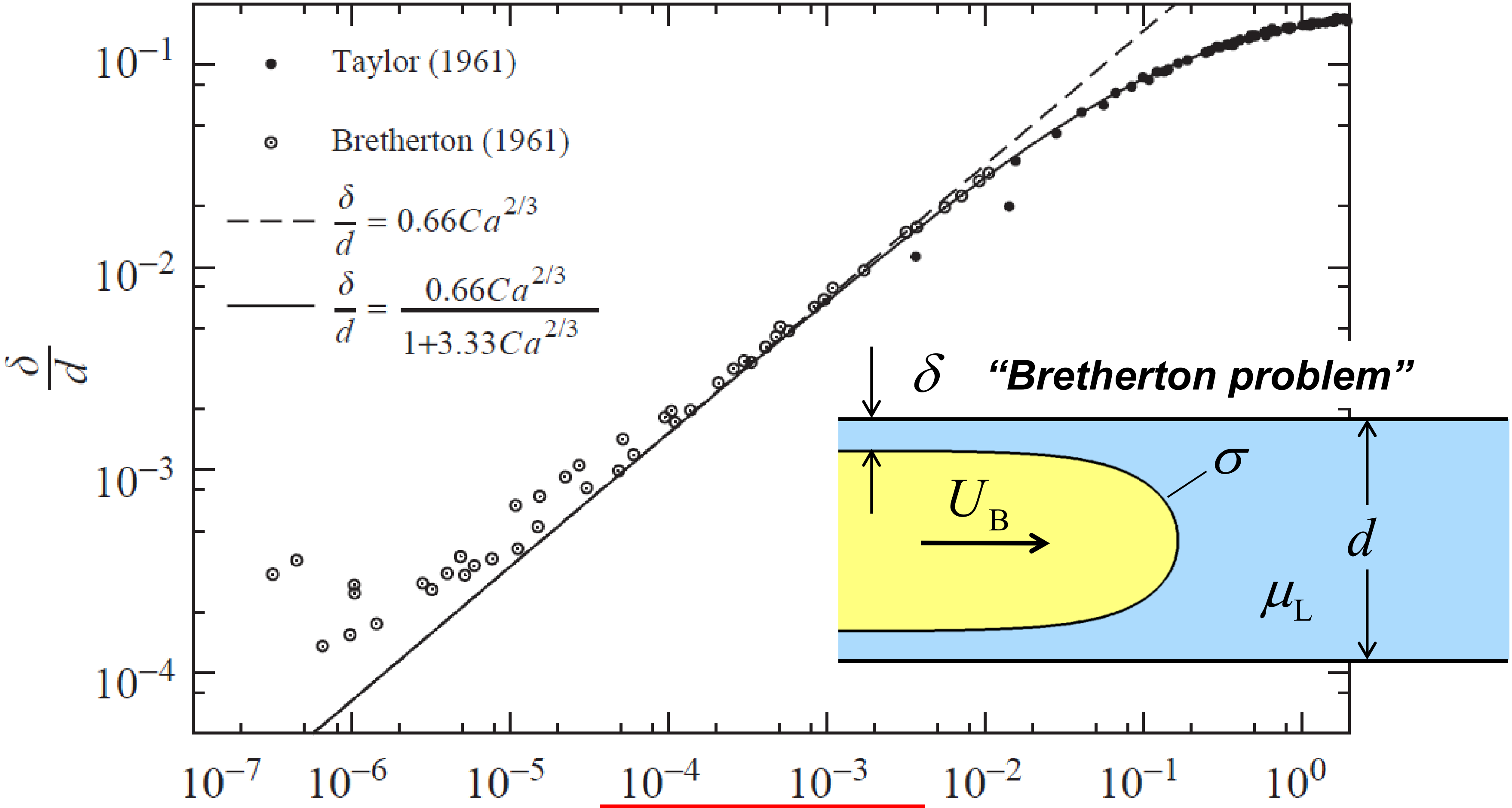
- Good mixing of species within the bubble
- Large interfacial area per unit volume and thin liquid film between bubble and wall $\Rightarrow$ efficient heat and mass transfer
- Axial segmentation of liquid $\Rightarrow$ reduced axial dispersion
- Recirculation in liquid slug $\Rightarrow$ good mixing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



Channel cross section:
400 μm $\times$ 280 μm

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

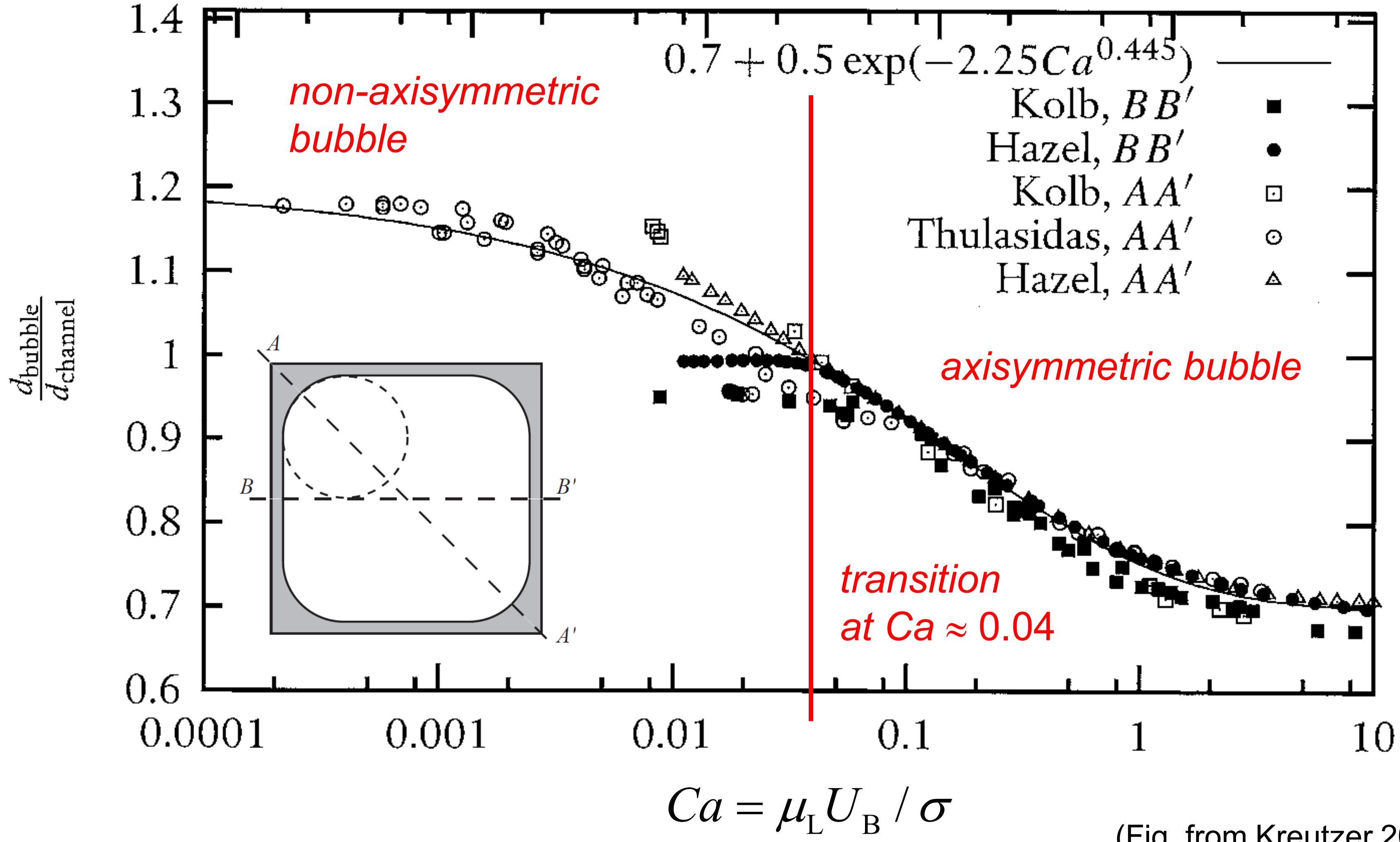
Liquid film thickness (circular tube)



capillary number $\boxed{Ca = \mu_L U_B / \sigma}$

(Fig. from Kreutzer et al. 2005)

Bubble diameter in a square channel



(Fig. from Kreutzer 2003)

Bubble shape – effect of *Re*

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

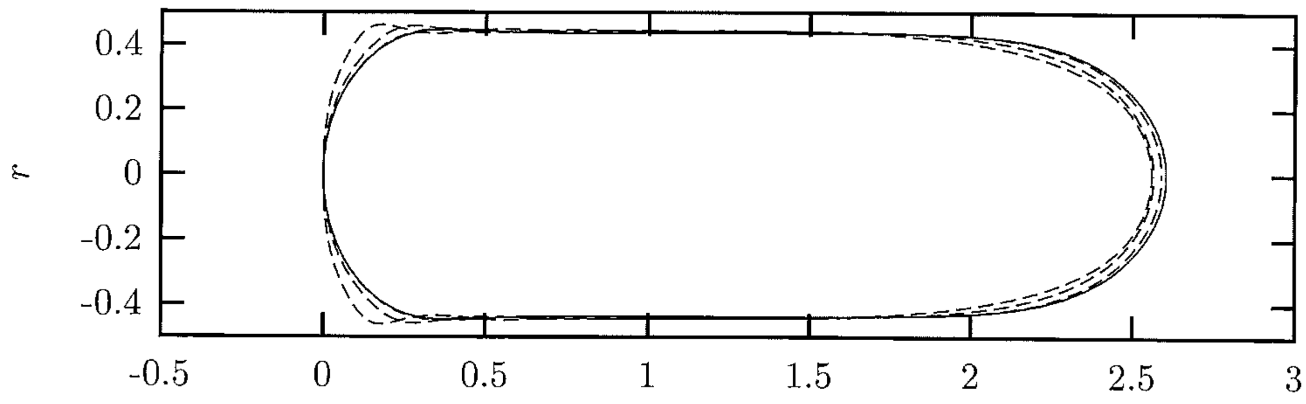
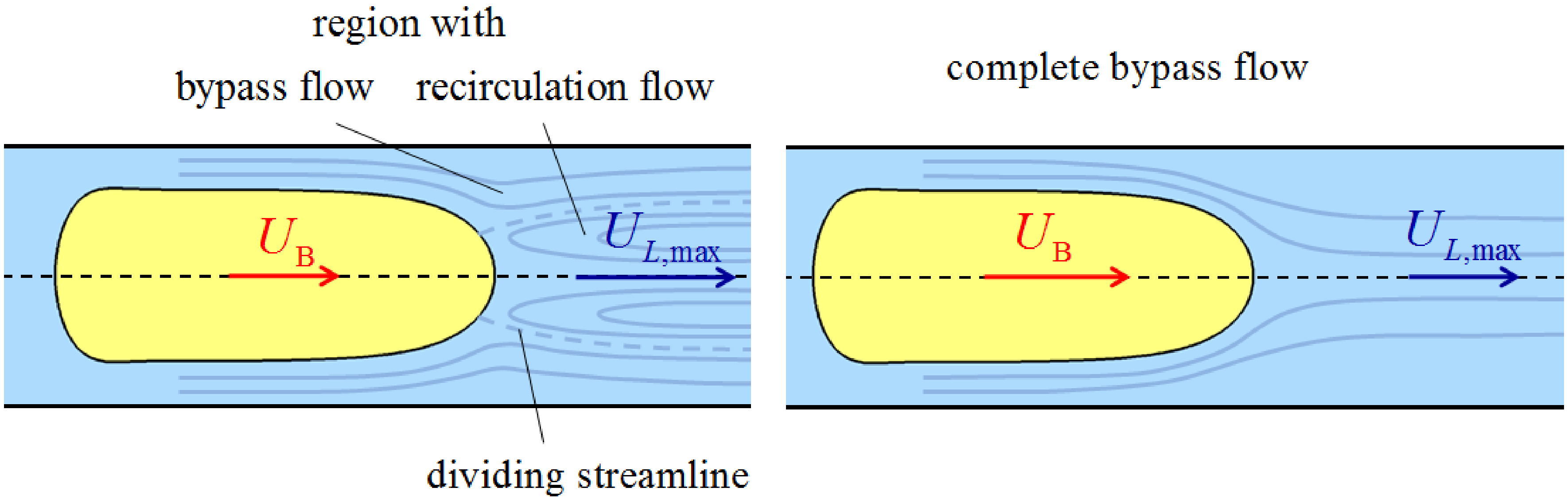


Figure 2.9: Shape of the gas–liquid interface for Re =1,10,100,200 at Ca =0.04

- For fixed channel size and fluid properties a change in *Ca* goes along with a change in *Re* (both are linearly related by the Laplace number *La* which is constant then)

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

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
$U_B / J_{\text{tot}} < C$	$U_B / J_{\text{tot}} \geq C$

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

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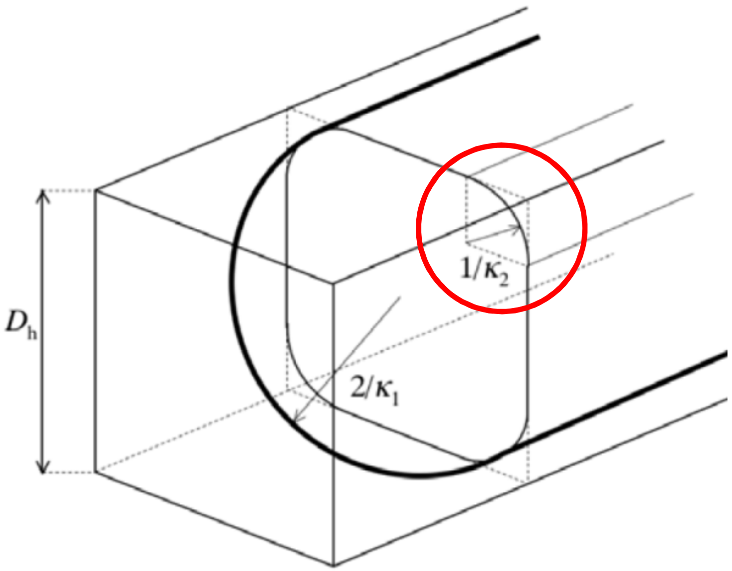
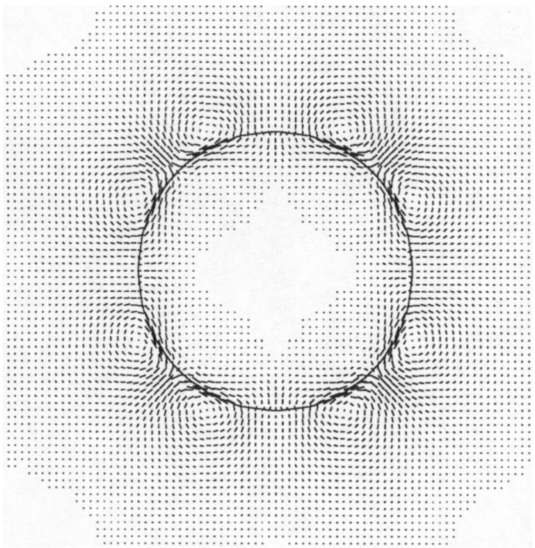
Why Taylor flow?

- 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** (bubble velocity respectively *Ca*)
- Thus, Taylor flow allows to study complex interfacial hydrodynamics in a relatively simple set-up, and is well suited for validation of numerical methods and computer codes

Taylor flow: a numerical challenge

- Thin liquid film (non-uniform thickness in square ch.)
- Complex flow field in laminar flow (recirculation pattern in liquid slug, vortices in bubble wake)
- Complex bubble shape with large local interface curvature (in corners of square channel) $\rightarrow$ spurious currents





Experiments on Taylor flow

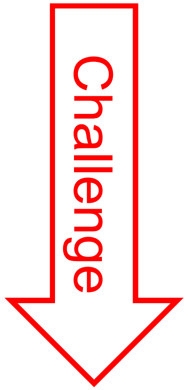
- <u>Goal:</u> Provide detailed data which allow for a **quantitative validation** of numerical methods and computer codes
- Perform experiments under well defined and documented experimental conditions which allow a detailed recalculation
  - Thermo-physical properties of both fluids
  - Volume of the Taylor bubble
  - Liquid and gas volumetric flow rates
  - Boundary conditions for computational domain
  - …
- Validation data base should not only serve members of SPP 1506 by the entire international CFD community
  - Set-up of a web database with experimental data (see presentation by C. Meyer)

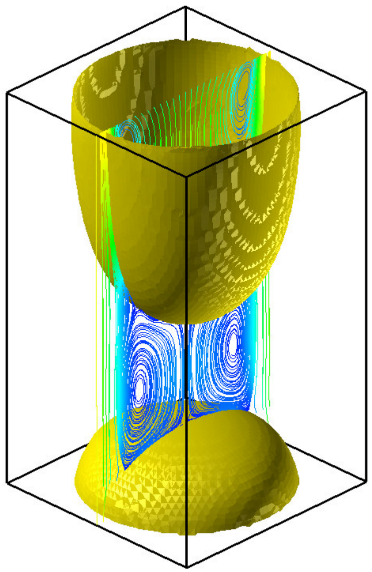
Exp. setup and parameters

- Experiments in circular and square vertical channel
  - Hydraulic diameter = 2 mm
  - Co-current upward Taylor flow
  - “Perfect” Taylor flow (identical bubbles/slugs; reproducibility!)
- Approximate range of parameters
  - Variation of capillary number by a least two orders of magnitude (0.005 – 1)
  - Variation of Reynolds number by at least two orders of magnitude (1 – 500)
  - Realization of this parameter range by variation of liquid viscosity (water/glycerol mixture) and gas/liquid flow rates
  - *see the following two presentations on experiments …*

Quantities to measure (*if possible*)

- Bubble shape
  - minimum liquid film thickness (lateral and diagonal)
  - axial profile of liquid film thickness (lateral and diagonal)
  - interface curvature at the bubble front and rear
  - interface curvature in the corners of square channel
  - full three-dimensional bubble shape (tomography?)
- Local velocity profiles
  - in liquid film (lateral and diagonal, corner flow)
  - close to bubble front and rear (dividing streamline)
- Pressure drop
- Local concentration field in mass transfer





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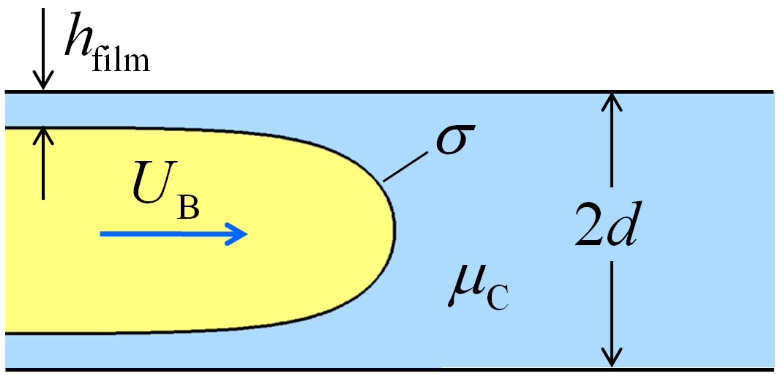
Benchmark cases as starting point

- Validation data from Taylor flow experiments in SPP 1506 are not available yet …
- Interested groups may want to start right now with simulation of Taylor flow in order to gain experience
- For this purpose three test cases are proposed
  - Bretherton problem
  - Buoyancy driven rise of a Taylor drop in a circular pipe
  - Taylor flow in a square mini-channel
- These are shortly introduced; for details see SPP homepage (Benchmark simulation of Taylor flows.pdf)

1. Planar Bretherton problem

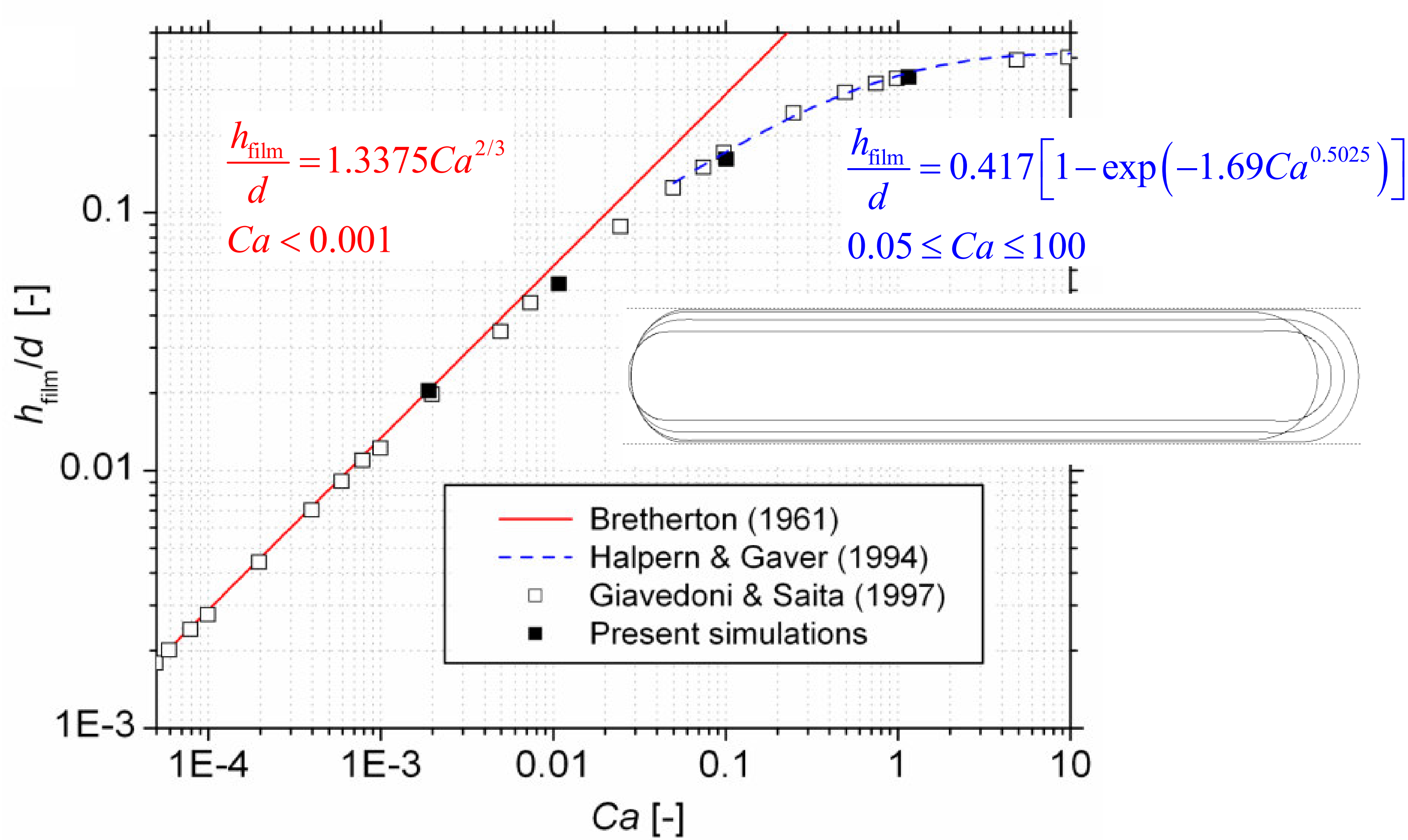
- Planar Bretherton problem: displacement of a viscous Newtonian liquid between two plates (distance 2*d*) by an inviscid semi-infinite gas bubble moving with velocity U_B
- Analytical solution by lubrication theory for small *Ca*

$$\frac{h_{\mathrm{film}}}{d} = 1.3375 Ca^{2/3}$$



- Set-up of benchmark case
  - Long viscous bubble instead of semi-infinite inviscid one
  - Computational domain: $2d$ = 1mm, length $20d$ = 10 mm
  - Properties: $\rho_c = \rho_d = 1000$ kg/m^3, $\mu_c = 10^{-2}$ Pa s, $\mu_c = 10^{-5}$ Pa s, $g = 0$
  - Four different values of σ, $Ca = 0.0019 - 1.15$, $Re \approx 0.1$

1. Planar Bretherton problem



Öztaskin et al. Phys. Fluids **21** (2009) 042108

2. Rise of a single Taylor drop

- Experimental and numerical study of the buoyancy driven rise of a Taylor drop in a vertical circular pipe (diameter *D* = 11.0, 20.1, 26.1, 30.8 mm) by Tomiyama's group
- 34 experimental cases with different parameters / physical properties are considered (pure and contaminated systems)
- Here: selection of three cases with characteristic bubble shape (all for pure system)

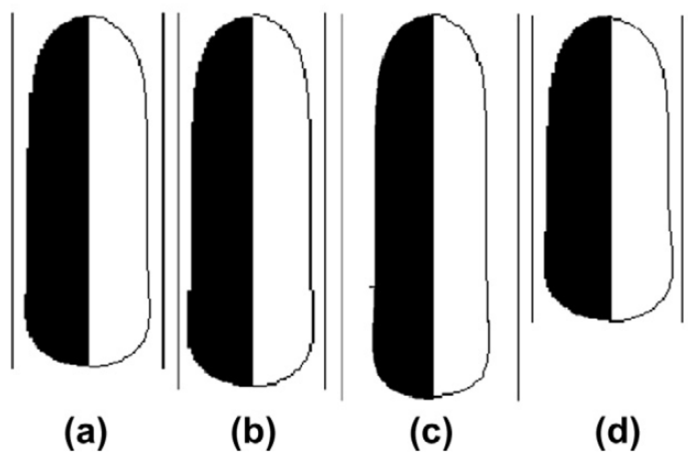
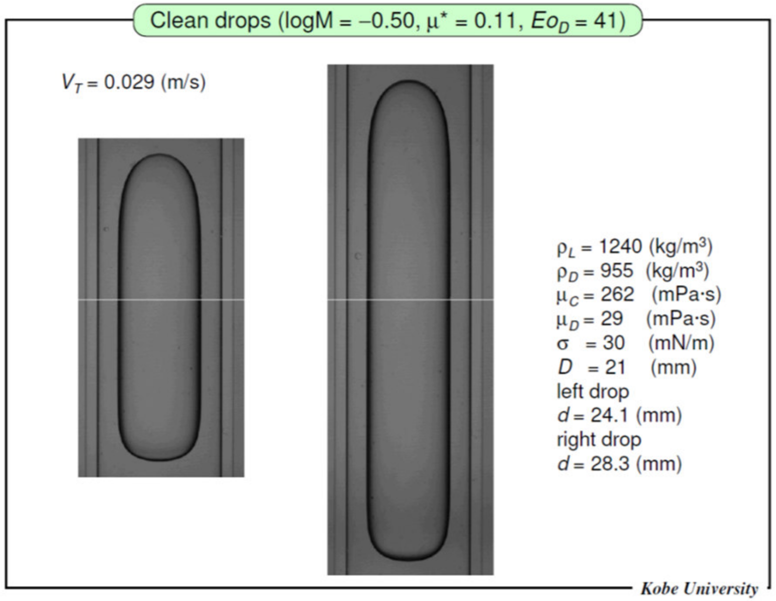


Fig. 17. Comparisons between measured and predicted shapes (left: measured, right: predicted)

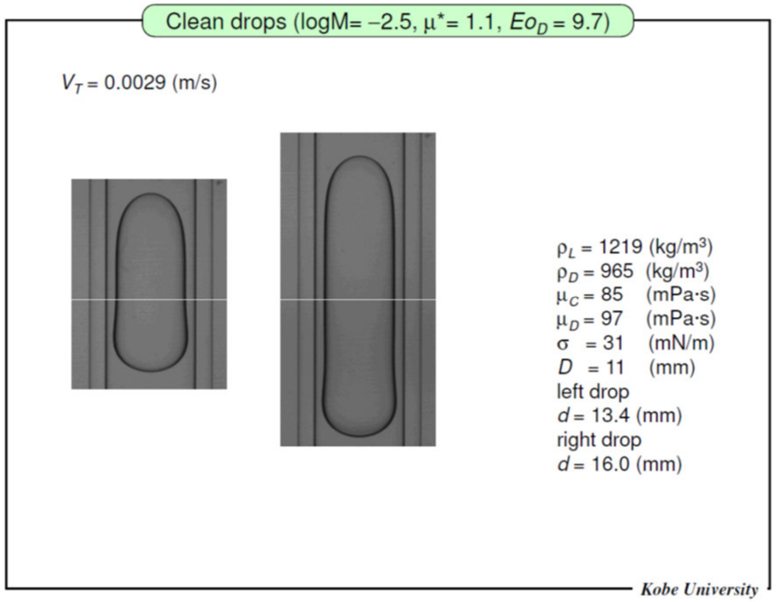
Hayashi, Kurimoto, Tomiyama, Int. J. Multiph. Flow 37 (2011) 241–251
(see also Hayashi, Kurimoto, Tomiyama, 7th Int. Conf. Multiph. Flow, Tampa, FL USA, 2010
Kurimoto, Hayashi, Tomiyama, 7th Int. Conf. Multiph. Flow, Tampa, FL, USA, 2010

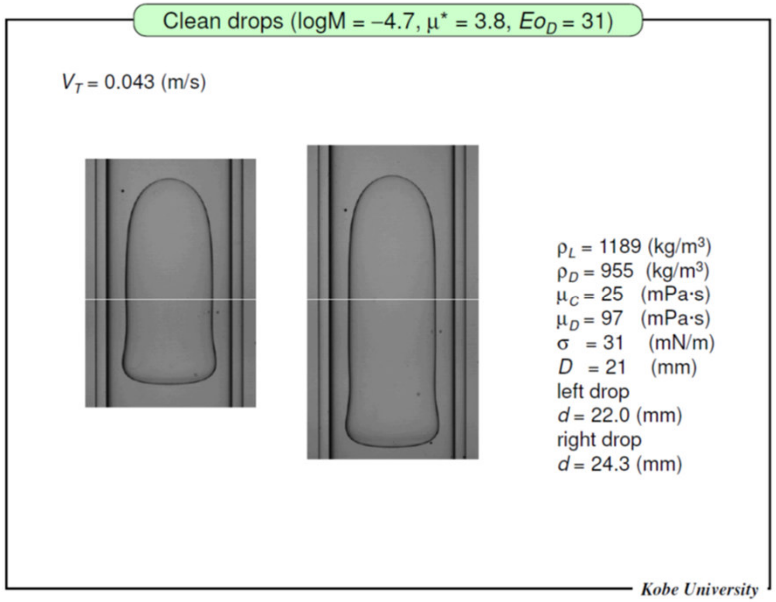


$$M = \frac{g\mu_c^4(\rho_c - \rho_d)}{\rho_c^2\sigma^3}, \quad \mu^* = \frac{\mu_d}{\mu_c}$$

$$Eo_D = \frac{g(\rho_c - \rho_d)D^2}{\sigma}$$

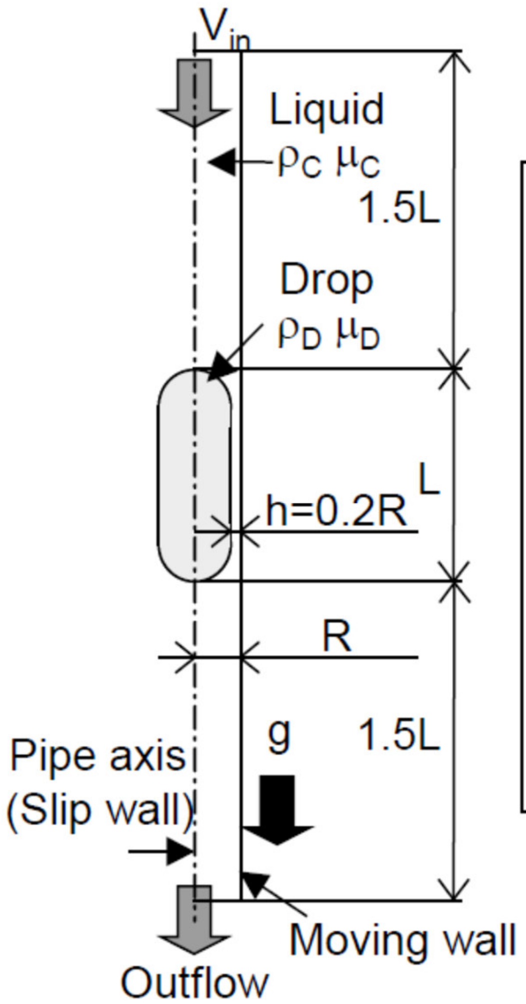
d = volume-equivalent drop diameter
(for each case two drops of
different size are shown)





Computational set-up

- Frame of reference moving with the drop
- 2D axi-symmetric computations
- Inflow and outflow boundary conditions
- Experimental data available for validation
  - terminal drop velocity
  - shape of Taylor drop



Initial drop:

Length L

h=0.2R

d/D=1.25

Domain size:

R x 4L

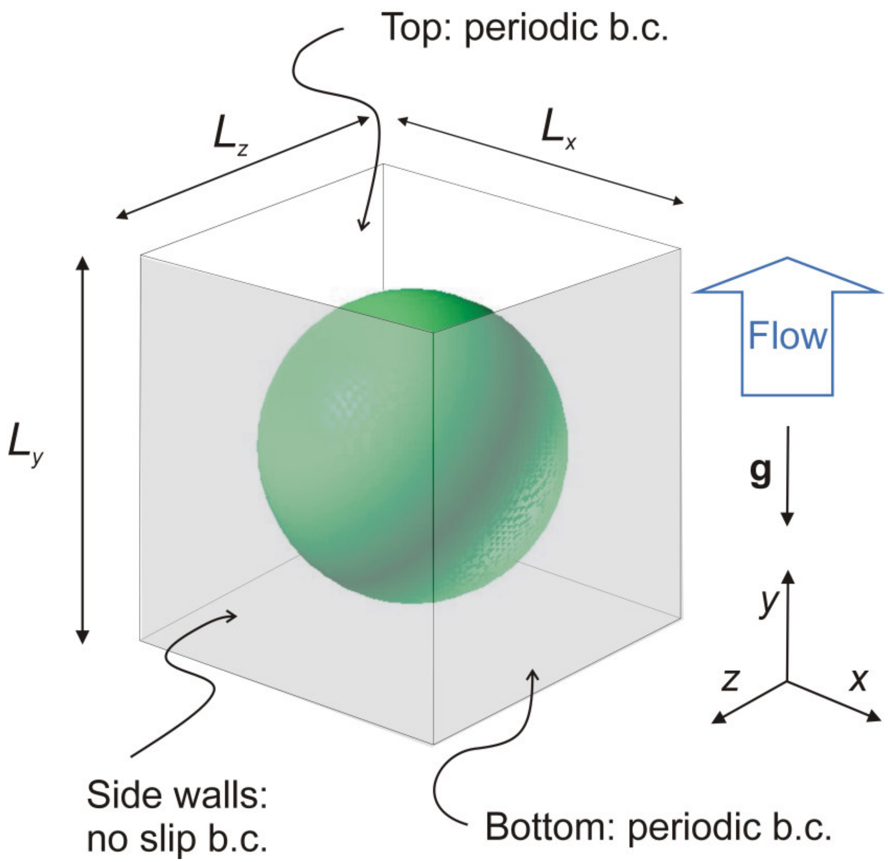
(32 x 588 cells)

$\Delta r = \Delta z$

Hayashi, Kurimoto, Tomiyama, Int. J. Multiph. Flow 37 (2011) 241–251

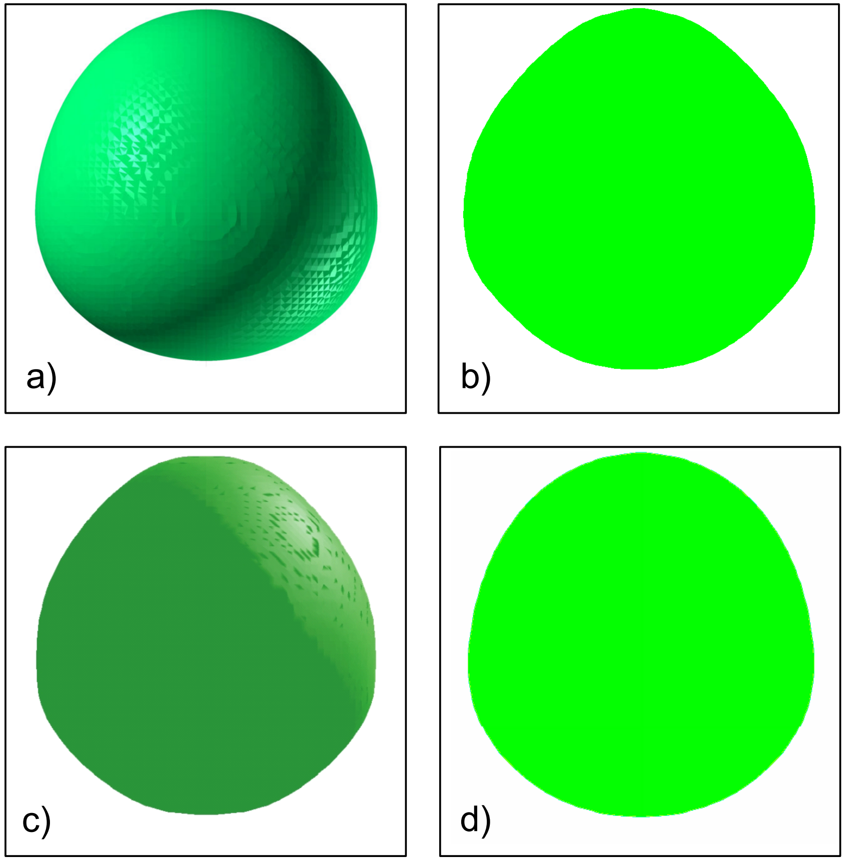
3. Taylor flow in a square channel

- Code-to-code comparison
  $\rightarrow$ no experimental data available for comparison
  $\rightarrow$ no strict validation!
- Domain 2mm × 2mm × 2mm
- Co-current upward Taylor flow ("bubble-train" flow)
- Periodic boundary conditions in vertical direction
- Grid: 48 × 48 × 48 (or 64^3)



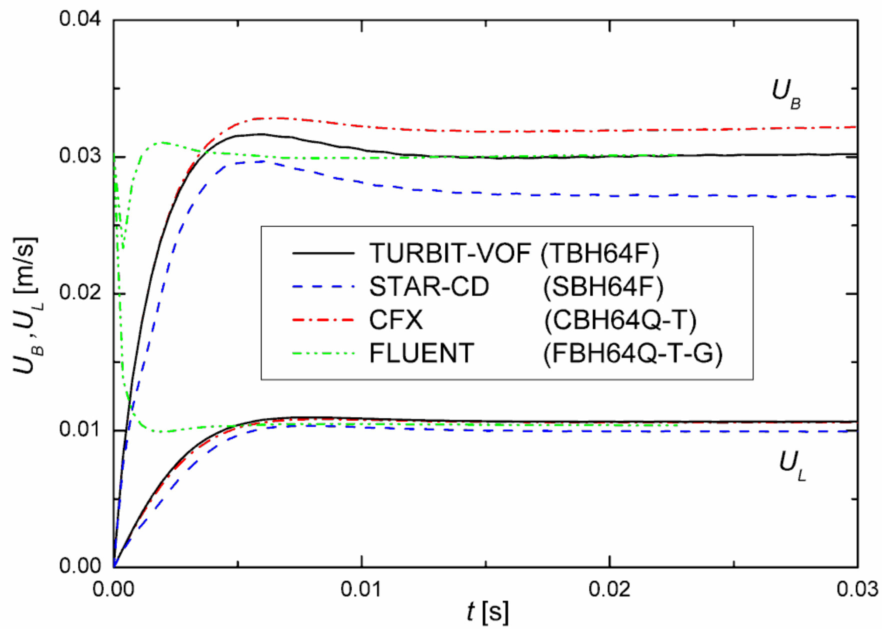
Buoyancy driven flow

TURBIT-VOF STAR-CD



FLUENT CFX

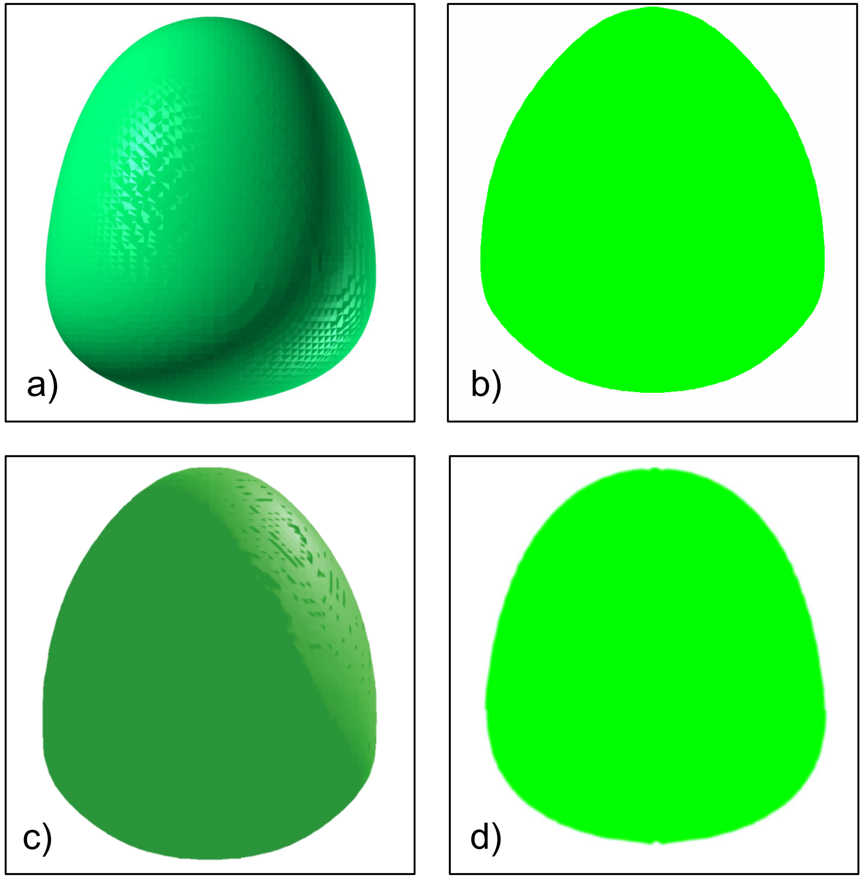
CODES	Terminal Bubble Diameter DB (mm)
TURBIT-VOF	1.711
STAR-CD	1.756
CFX	1.704
FLUENT	1.709



Özkan et al., Int. J. Num. Meth. Fluids 55 (2007) 537

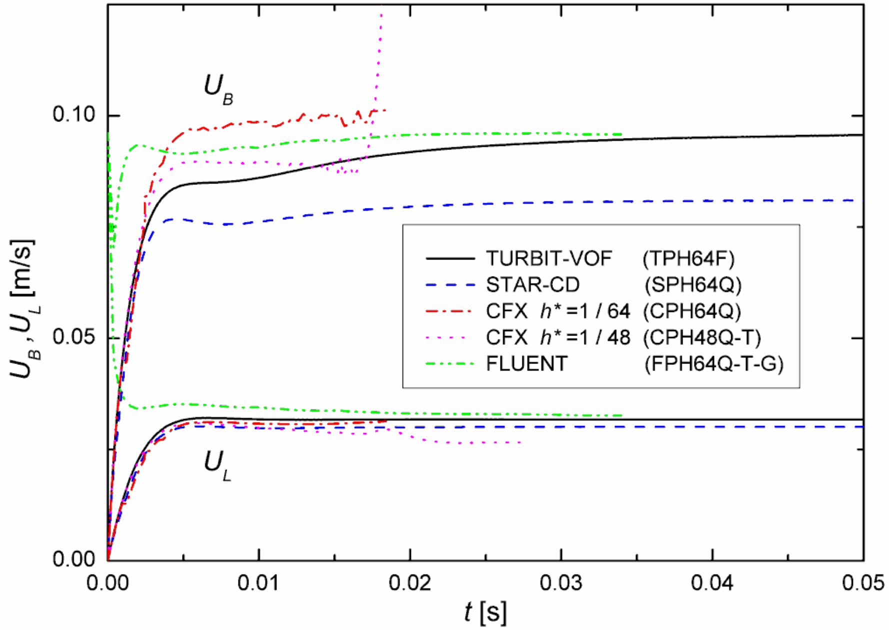
Pressure driven flow

TURBIT-VOF STAR-CD



FLUENT CFX

CODES	Terminal Bubble Diameter DB (mm)
TURBIT-VOF	1.629
STAR-CD	1.693
CFX	1.641
FLUENT	1.634



Özkan et al., Int. J. Num. Meth. Fluids 55 (2007) 537

For further details see SPP web page (internal)

If you have questions regarding the test cases or you need some support you are welcome to contact me

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