DFG Priority Program 1506 “Transport Processes at Fluidic Interfaces“

Research project “Experimental investigation of Taylor flow in a mini-channel”

1 Introduction

Taylor flow, which is also known as segmented flow or bubble train flow, is characterized by the presence of elongated gas bubbles which flow along a capillary channel and are separated from each other by liquid slugs. The gas bubbles occupy most of the capillary cross section and are separated from the channel wall by a thin liquid film. Taylor flow has advantageous mass transfer characteristics and is of interest for micro process engineering [1], monolith reactors [2] and for micro-fluidics applications in the life sciences. In all these applications, the channel cross section is often not circular but square or rectangular. Recent reviews on Taylor flow can be found in [3] and [4]. A lack of knowledge exists in particular with respect to the effects of variable surface tension and non-circular channels [4].

Beside its technical relevance, experiments on Taylor bubbles or Taylor flow offer several advantages for validation of the mathematical models and numerical methods to be developed in the context of the priority program “Transport Processes at Fluidic Interfaces”. One distinct advantage is that many aspects of the hydrodynamics of Taylor flow such as the liquid film thickness and the shape of the front meniscus depend mainly on one single control parameter, i.e. the capillary number $Ca = \mu_L U_B / \sigma$ (μ_L = the liquid viscosity, U_B = bubble velocity, σ = coefficient of surface tension). For higher values of the bubble Reynolds number $Re = \rho_L D_h U_B / \mu_L$ inertial effects become also important, and influence in particular the shape of the rear meniscus (ρ_L = liquid density, D_h = hydraulic channel diameter). While in circular channels the thickness of the liquid film along the circumference of the bubble is uniform, it is non-uniform otherwise. In square channels the bubble shape is axisymmetric for $Ca > 0.04$ but becomes increasingly complex for $Ca < 0.04$ when the bubble expands in the corners of the channel and loses its axial symmetry.

2 Suggestions for a basic experimental set-up

The main parameters for hydrodynamic validation of mathematical models and numerical methods will be the three-dimensional bubble shape for different values of the capillary number Ca together with information about the local liquid velocity field. In the following, some suggestions regarding different aspects of the experimental set-up are made.

- Channel orientation: at first vertical (due to gravitational effects the problem will not be symmetric for a horizontal channel when the hydraulic channel diameter is in the millimeter range)
- Shape of channel cross-section:
  - at first circular (in computations then for a vertical channel axisymmetry can be assumed)
  - later square (expansion of the bubble in the corners of the channel; to reduce CPU time consideration of 1/4 or 1/8 of the channel is possible for vertical orientation)
- Range of capillary number: Variation of Ca by two to three orders of magnitude within a range of about 0.005 − 1 (the lower limit covers the expansion of the bubble in the corners of the square channel; the upper limit covers the transition from recirculation flow to by-pass flow in the liquid slug)
  - Realization of this range for Ca by variation of U_B and by consideration of liquids with different viscosity (low Ca e.g. water, high Ca e.g. silicon oil or water-glycerol mixture). For low values of Ca severe numerical problems are to be expected because of parasitic currents and the resolution of the very thin liquid film.
  - Measurements with both liquids should overlap in the range $Ca \approx 0.1$ to investigate the influence of Re. Overall, Re should be roughly in the range 0.1 − 100 (relevance for micro-fluidics). It is $Re = Ca \cdot La$ where $La = \sigma \rho_L D_h / \mu_L^2$ is the Laplace number which is constant for a certain liquid and fixed D_h.
- Channel dimensions: The hydraulic diameter should be in the range from 1 to 5 mm. For smaller channels the measurement of the liquid film thickness may become to inaccurate while for larger channels the Reynolds number may become too large. After selection of suitable fluid pairings, the physical properties allow together with the above mentioned ranges for Ca and Re to estimate suitable values for D_h.

- Flow direction: In principal both upward and downward flow are possible. Upward flow may be more suitable since the bubble will rise with its tip stable on the axis of the channel. This may not be the case for downward flow where the driving pressure gradient and the buoyancy force act in opposite directions.
- Single Taylor bubble or Taylor flow: Both is possible, but requires different approaches in computations (For single bubbles simulations in a moving frame of reference with in- and outflow conditions is most suitable; for Taylor flow consideration of a single unit cell consisting of one bubble and one liquid slug and periodic boundary conditions may be more appropriate). Here, single bubbles may be more adequate since perfect Taylor flow with identical bubbles and liquid slug length may be difficult to realize.
- Measurement techniques. The main research topic of this project should be the adaptation and further development of measurement techniques that allow a high resolution of bubble shapes and of flow fields For example:
  - Bubble shape: The thickness of the liquid film can be measured e.g. with the laser focus displacement method [5] or with confocal laser scanning microscopy [6] or other available methods. In a square channel both the lateral and diagonal thickness of the liquid film should be measured. Highly desirable would be the development of a method which is based on fast tomography, since this would allow the measurement of the entire three-dimensional instantaneous bubble shape.
  - Liquid flow field: Measurements can be performed with PIV or µPIV. Alternatively it would be appropriate to perform LDA measurements in the liquid film and liquid slug. It is, however, very important to quantify the effect of the addition of tracer particles (e.g. on the coefficient of surface tension) in the experiments to allow for reliable recalculations of these experiments by numerical methods.

3 Suggestions for extension of the experiment in the second phase of the priority program

- Mass transfer from gas into liquid phase: The local instantaneous concentration field during the mass transfer of a component (e.g. oxygen) from a Taylor bubble into the liquid (e.g. water) can be measured by Laser-induced fluorescence (LIF).
- Thermal Marangoni effects: These can be generated in a defined manner by heating/cooling of a side wall of a square channel. Of benefit for investigation of thermal Marangoni effects in Taylor flow is the thin liquid film between the channel wall and the gas bubble which constitutes a very short diffusion path.
- Surfactants: Since Taylor flow is largely governed by surface tension forces the addition of even a minute amount of surfactant may have a profound effect. While surfactants can be injected by a piezoelectric principle it may be difficult to develop a measurement technique for quantifying the surfactant transport on the entire phase interface.
- Coalescence phenomena: These can be investigated by successive injection of two Taylor bubbles with slightly different volume. The smaller trailing bubble occupies a region with higher mean velocity and thus is faster than the leading bubble. This yields well defined conditions for contact/coalescence.

References

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