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Breif communication

Phase inversion in the mixing zone between a water flow and an oil flow through a pipe

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1. Introduction

The flow of two immiscible liquids often occurs as a dispersed flow, where one liquid is present in the other one in the form of drops. Water–oil dispersions can occur as oil drops in a water-continuous phase or as water drops in an oil-continuous phase. Phase inversion is the phenomenon by which the dispersed phase becomes the continuous one, and vice versa. The phase inversion phenomenon has been studied for many years (see, for instance Becher, 2001).

Recently we (see Piela et al., 2006, 2008) carried out continuous experiments and direct experiments to study phase inversion in a pipe flow. During the continuous experiments we started with the flow of one of the liquids and gradually injected the other liquid, while keeping the mixture velocity constant. During the direct experiments the two liquids are injected from the start simultaneously into the pipe with certain concentrations. Detailed pictures were taken of the phase inversion process and also the electrical conductivity of the mixture was measured to determine which liquid formed the continuous phase and which the dispersed phase. Although the concentration at inversion was significantly higher for continuous experiments than for direct experiments, the change in morphological structures during phase inversion was the same for the two types of experiments. At inversion the concentration of drops of the (originally) dispersed phase becomes so high, that they coalesce at certain places in the flow field and form relatively large, rather complex, morphological structures. With a further increase in concentration of the (originally) dispersed phase these morphological structures grow in size and start to form the new continuous phase in which again complex structures are present, but this time consisting of the (originally) continuous phase.

Recently we realized that there is still another type experiment possible during which phase inversion takes place: discontinuous experiments. In a discontinuous experiment a pure water phase is pumped through the pipe, and at a certain moment it is changed to a pure oil phase (or vice versa). Somewhere in the mixing zone between the two liquids phase inversion will occur similarly to, for instance, the direct experiments. The purpose of this brief communication is to report about the results of these experiments and to see whether the observed morphological structures are identical to the ones found in the continuous and direct experiments.

In Section 2 of this communication the experimental facility used for the experiment as well as the visualization method are described. Then results found during water-to-oil and oil-to-water discontinuous experiments are presented in Section 3. Finally, in Section 4 some conclusions are drawn.

2. Experimental set-up

A sketch of the pipe facility used for the experiment is shown in Fig. 1. An acrylic pipe with an inner pipe diameter of 16 mm was used. All the experiments were carried out at such a high mixture velocity, that a fully developed dispersed flow was present in the pipe. We realize that the results of these experiments are likely

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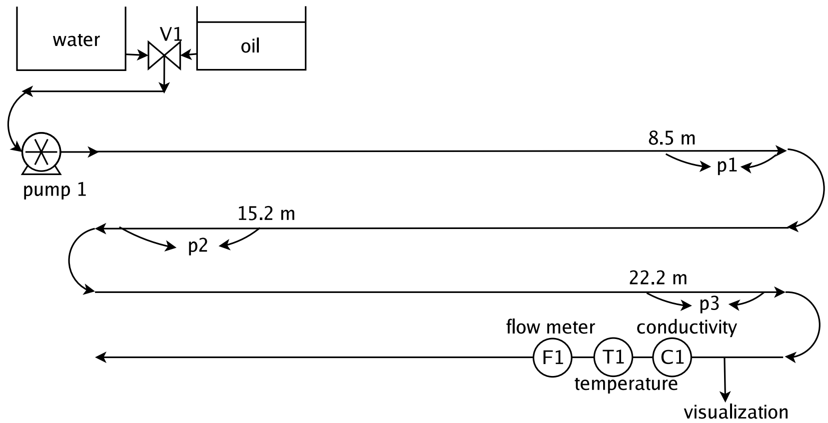

Fig. 1. Sketch of the experimental set-up for discontinuous experiments.

not representative for dispersed flow in a large diameter pipe, as wall effects have proved to be more significant for inversion behavior in small diameter pipes than in large diameter ones. (It was shown by Ioannou et al., 2005 that the wetting properties of the pipe wall can influence the concentration at which phase inversion occurs). Moreover, in a small diameter pipe what happens near the wall is quickly transported to the center of the pipe. Furthermore, in a large diameter pipe a higher mixture velocity is required for fully developed dispersed flow than in a small diameter one (see Brauner, 2001).

The two immiscible liquids were tap water and Shell Macron EDM 110 oil (density 794 kg/m^3, kinematic viscosity at 20° 3.9 mm^2/s and oil water interfacial tension 0.045 N/m). An experiment started by injecting one liquid (water or oil) by means of pump 1 (see Fig. 1) into the pipe. After several seconds the injection of the first liquid was stopped and the other liquid was injected by turning valve 1. Because pump 1 is a positive displacement pump, the second liquid was injected at nearly the same volume flow rate. Pump 1 was controlled by the feedback system from flow meter F1, which measured the density and mass flow rate (KROHNE OPTIMASS 7000, error <0.26%). Pressure drops were measured at different locations over a distance of 1 m. Differential pressure transducers (Validyne DP-15, error <3%) were used and the pressure signal was sampled at a rate of 2 kHz. Data were averaged over 2000 samples. The pressure drops were measured at three different positions: 8.5 m (530 d), 15.2 m (950 d) and 22.2 m (1390 d) from the inlet valve V1 (d is the pipe diameter). So the distance between the pressure drop measurement points p1 and p2 is 420 d and between p2 and p3 is 440 d. The pressure taps were located upstream of the bends. They were also rather close to the bends (see Fig. 1) to ensure a long development length for the flow before the measurements were taken. We found no significant influence of the pipe bends (downstream of the pressure taps) on the results.

Conductivity measurements (the signal was also sampled at a rate of 2 kHz) were made with a cell consisting of two (0.2 mm diameter) wire electrodes mounted in the pipe: one in the vertical direction and one in the horizontal direction. The distance between the electrodes in the center of the pipe was 2 mm. During the experiment we also monitored the temperature. The experiments were performed more than once and the repeatability of the experiments was good.

To make a detailed study of the dispersion morphology samples were taken from the flow by means of a 7 mm inner diameter sampling tube at a distance of 25.5 m downstream of the inlet valve V1 (see Fig. 1) and led through a visualization cell (two glass windows that were 1 mm apart). The visualization cell was illuminated from one side with a 500 W halogen lamp and a high speed camera took images at the other side. The camera was operated at a frame rate of 50 Hz. A sketch of the sampling technique is given in Fig. 2. To check whether this observation procedure had some influence on the dispersion morphology we performed experiments with various distances between the visualization cell and the pipe. We always achieved the same results. We also changed the distance between the glass walls from 1 to 5 mm and again the results were similar. Moreover in our earlier studies (see Piela et al., 2006, 2008) we compared the results with non-intrusive observations from the side of the pipe. The results were in agreement with those from the visualization cell.

3. Results

During the study of the mixing zone between the two liquids three types of morphological structures were observed (similarly to the continuous and direct experiments): drops, pockets and regions. A drop is the smallest part of the dispersed phase, usually smaller than 1 mm. A pocket is a larger unit of one of the two phases, that contains several drops of the other phase; it is usually of the order of a few millimeters up to 1 cm. Finally a region is a still larger part of one of the two phases in the flow field, that encloses several pockets and drops of the other phase and is of order of 1 cm or larger. At some conditions also multiple drops were observed, which are drops containing small droplets of the other (continuous) phase. A pocket is larger than a multiple drop and the surface tension is not strong enough to give a pocket a spherical shape, whereas a multiple drop is (nearly) spherical.

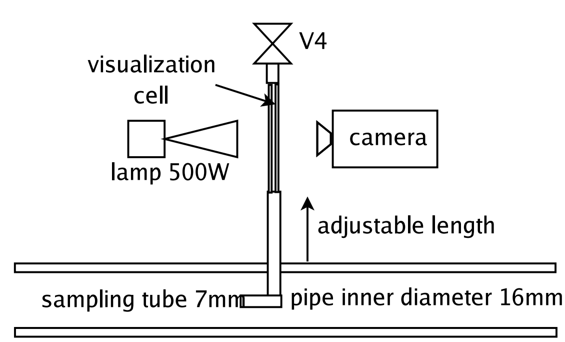

Fig. 2. Sketch of the visualization method.

3.1. Observations during experiments

We started with pumping, for instance, water at a constant velocity through the pipe and at a certain moment (by switching the manual valve) oil was pumped at the same superficial velocity. The valve is constructed in a such a way that a flow of pure water is followed by a flow of pure oil, or vice versa. Of course some disturbance is created by switching the valve. To study possible inlet effects on the mixing zone we repeated the experiments several times and at different velocities. The results were always the same. So the inlet effects are negligible. In the first part of the mixing zone the flow was water continuous (with oil drops) and in the second part the flow was oil continuous with water drops. Between these two parts there is a zone where both water-continuous regions and oil-continuous regions coexist next to each other. Some results for the morphological structures inside this mixing zone are given in Fig. 3. It shows some pictures taken as function of time at a certain position downstream of the entrance to the pipe. The top-left picture in Fig. 3 shows a continuous water phase with oil drops in the first part of the mixing zone. The center-left picture shows the morphology after 0.06 s (further downstream into the mixing zone, but still in its initial part) and a number of oil pockets has been formed. After 0.16 s (bottom-left picture) there are many oil pockets and (multiple) drops. After 0.38 s (top-right picture) oil-continuous regions occur with water drops and water pockets. The flow is almost completely oil-continuous after 0.5 s (center-right picture). Still some larger water regions exist. However, they break-up into smaller drops. After 0.86 s (bottom-left picture) the flow is oil-continuous.

Pictures taken during a similar experiment only with oil as the initial phase and water as the final one are shown in Fig. 4. Multiple drops (oil droplets inside water drops in a continuous phase of oil) can be observed at the start of the mixing zone (top-left picture). After 0.94 s (center-left picture) the concentration of water drops has increased and larger pockets of water have been formed. The concentration of these water pockets seems lower than the concentration of oil pockets at the same stage of the transition for the water-to-oil discontinuous experiment. After 4.9 s (bottom-left picture) and 5.64 s (top-right picture) the flow consists of both water-continuous regions and oil-continuous regions. At time 6.1 s (center-right picture) the flow is water-continuous with multiple oil drops. The existence time of these multiple oil drops (water droplets in oil drops in a continuous phase of water) is considerably shorter than the existence time of multiple water drops. Multiple oil drops break-up easily and the water droplets escape from their inside into the continuous water phase. After 8.2 s only pure oil drops in water remain.

3.2. Friction factor and conductivity

Before the phase inversion experiments single phase pressure drops were compared with Blasius friction factor values for the pressure drop and they compared well. Thereafter the two-phase experiments started. During phase transition an increase of the friction factor was observed. The friction factor is defined as $f = \frac{2\Delta P d}{\rho u^2 L}$, where ΔP is the pressure drop over a distance L, d the pipe diameter, ρ the density and u the average mixture velocity. The density ρ and mixture velocity u where measured by means of the flow meter F1. (Using the mixture velocity the results could be shifted from the location of the flow meter to the location of the pressure measurement points). Fig. 5 shows the friction factor and conductivity for a water-to-oil discontinuous experiment at a mixture velocity 2 m/s. As can be seen the friction factor is strongly increasing during the passage of the mixing zone. The difference between the friction factors at p1 and p2 suggests that the flow is definitively not fully developed. So even at p2 (15.2 m downstream of the entrance to the pipe) the flow is still developing. There is also still a noticeable difference between the friction factors at p2 and p3. So the flow appears to be developing all along the pipe.

The conductivity measurement shows that in the first part of the mixing zone (between 61 to 64 s) a water-continuous dispersion exists. With the passage of the mixing zone the concentration of oil drops increases, which causes a decrease in conductivity. Between 64 and 64.5 s inversion takes place. Both water-continuous regions and oil-continuous regions coexists. Finally (after 64.5 s) an oil-continuous dispersion is present. The concentration of water drops is decreasing and finally a pure oil flow is observed.

Results from an oil-to-water experiment are presented in Fig. 6. The mixture velocity is significantly larger than in the preceding

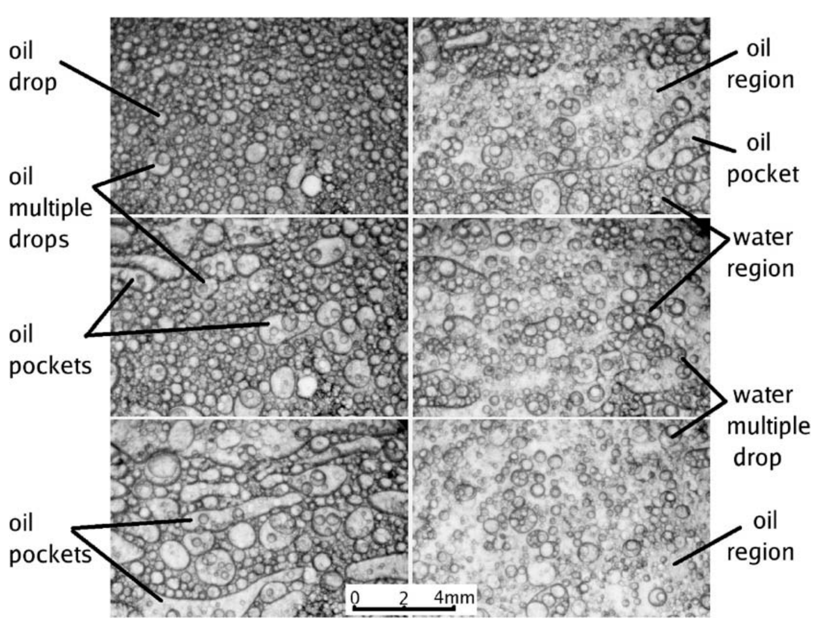

Fig. 3. Transition from a water-continuous flow to an oil-continuous flow during a discontinuous experiment. The flow velocity was kept constant at 1 m/s.

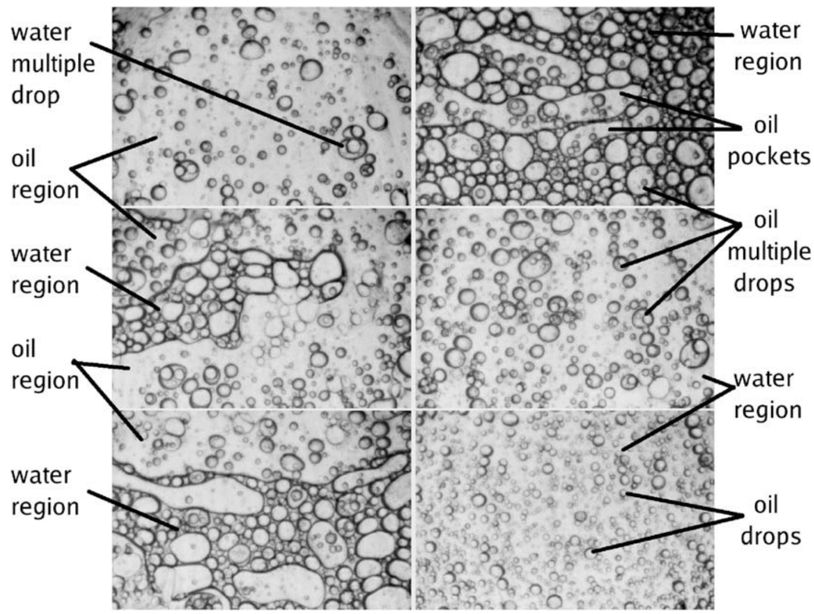

Fig. 4. Transition from an oil-continuous flow to a water-continuous flow during a discontinuous experiment. Flow velocity was kept constant at 1 m/s.

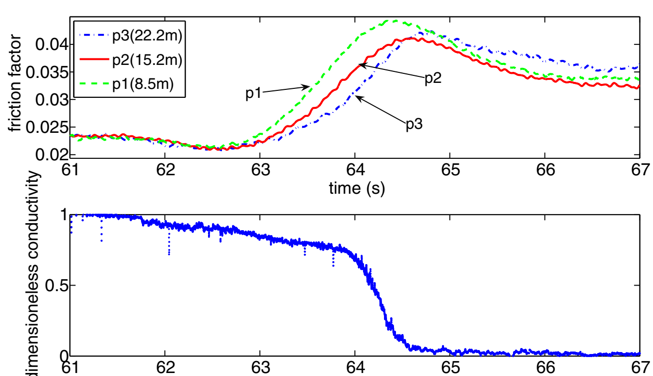

Fig. 5. Friction factor and dimensionless conductivity for a discontinuous water-to-oil experiment at a mixture velocity of 2 m/s. For each downstream location the time is shifted to the time at the inlet by using the mixture velocity. In this way it is possible to study the development in time of the mixing zone.

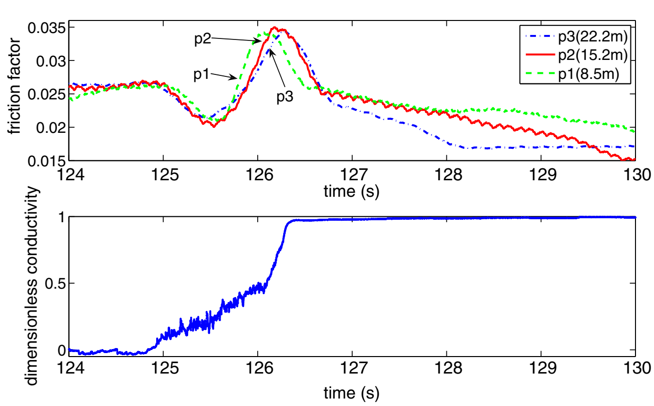

Fig. 6. Friction factor and dimensionless conductivity for a discontinuous oil-to-water experiment at a mixture velocity of 4 m/s. For each downstream location the time is shifted to the time at the inlet by using the mixture velocity. In this way it is possible to study the development in time of the mixing zone.

case, viz. 4 m/s. There is again a significant difference between the signals at p1, p2 and p3, although the difference is less pronounced than as shown in Fig. 5. So also in this case the flow is still developing. Between 125 and 126 s there is remarkable decrease in the friction factor (much more pronounced than in the preceding case). This is in agreement with our previous observations (Piela et al., 2006) as well as with observations made by Ioannou et al., 2005. In that part of the mixing zone oil is still the continuous phase, but the increase in conductivity implies that water-continuous pockets are already present. Between 126 and 126.3 s both water-continuous and oil-continuous regions coexist. Thereafter a water-continuous dispersion is present, which is finally followed by a pure water flow.

The width of the mixing zone is determined by the initial mixing due to the valve operation and by the subsequent mixing due to the turbulence in the pipe. However from the pressure measurements in Fig. 5 and certainly from Fig. 6 it can be seen that already after 8.5 m the width of the mixing zone is established. By repeating the experiments we confirmed that the width and the observed structures inside the mixing zone are independent of the exact details of the initial condition due to the valve operation.

In Fig. 7 the conductivity as measured during water-to-oil discontinuous experiments at 1, 2 and 4 m/s is given. This figure shows the surprising result, that the length of the mixing zone (found by multiplying the mixture velocity with the time duration of the mixing zone) is constant (about 6 m). (Although the part of

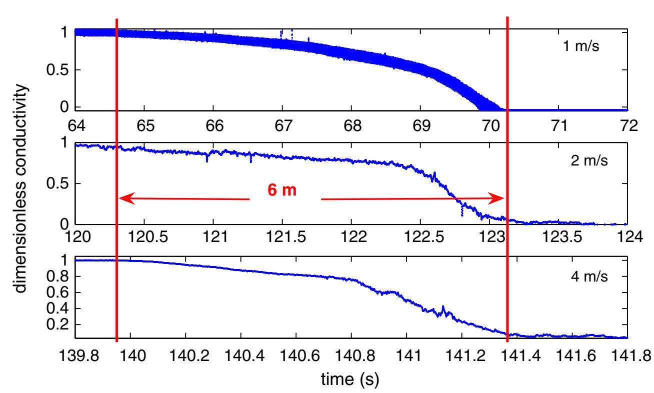

Fig. 7. Dimensionless conductivity for a discontinuous water-to-oil experiment at a mixture velocity of 1, 2 and 4 m/s. As can easily be calculated the length of the mixing zone is about 6 m for all cases.

the trace with a steep gradient shows about 1 m length for 2 m/s and 2.5 m length for 4 m/s.) The same length is found for oil-to-water discontinuous experiments. So, obviously, the length of the mixing zone seems independent of the location in the pipe, independent of the mixture velocity and of the type of experiment (water-to-oil or oil-to-water).

We are not certain about the explanation for this independence of the mixing length zone from (some of) the flow conditions, although we checked experimentally that this length is not influenced by the valve operation. We do not know, how general this result is and whether the mixing length is perhaps dependent on other flow conditions. The fact that the mixing length is independent of the mixture velocity indicates, that the time necessary for inversion is not constant and decreases with increasing velocity. This points out in the direction, that the length of the mixing zone is determined by the details of the mixing process of water and oil in this zone. With increasing velocity the (turbulent) mixing of (multiple) drops, pockets and regions will increase and likely cause a decrease of the time needed for the inversion process. It is clear, that this point needs further study.

4. Conclusion

The simple discontinuous experiments have given us much insight in the mixing and phase inversion process. The distinction between the different stages of the processes was easy. The observations made in the mixing zone of discontinuous experiments confirmed the existence of (multiple) drops, pockets and regions as also found during continuous and direct experiments. With the passage of the mixing zone the concentration of drops (of the last-injected liquid in the continuous first-injected liquid) becomes so high, that they coalesce at certain places in the flow field and form relatively large, rather complex, morphological structures. With a further increase in concentration of the last-injected liquid these morphological structures grow in size and start to form the new continuous phase in which again complex structures are present, but this time consisting of the first-injected liquid. During the passage of the mixing zone the local friction factor increases very considerably.

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