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# The effect of surfactants on upward air-water pipe flow at various inclinations

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## Abstract

In this work, we extend our previous efforts (A. T. van Nimwegen et al. 2014, IJMF, 71: 133-145 and A. T. van Nimwegen et al. 2014, IJMF, 71: 146-158) on the effect of surfactants on air-water flow in a vertical pipe by also considering pipe inclinations between 20 degrees (with respect to horizontal) and vertical. For air-water flow, independent of the inclination, there is a regular annular flow at large gas flow rates, and an irregular churn or slug flow at low gas flow rates. Closely related to the transition between regular and irregular flow, although not necessarily coinciding with it, there is a minimum in the pressure gradient as a function of the gas flow rate. In gas wells, surfactants are used to shift this minimum to lower gas flow rates, which allows a stable gas production up to lower reservoir pressures. In this work, we investigate how the pipe inclination affects air-water flow with surfactants and the shift in the minimum of the pressure gradient due to surfactants. Surfactants generate foam, which decreases the density and increases the thickness of the film at the pipe wall. For vertical flow, we previously established that surfactants increase the pressure gradient at high gas flow rates, decrease the pressure gradient at low gas flow rates, shift the minimum in the pressure gradient to lower gas flow rates, and shift the transition between regular and irregular flow to lower gas flow rates. The new results described in this paper show that for large gas flow rates, both the flow with and without surfactants is unaffected by the inclination. At low gas velocities, however, in inclined pipes the surfactants are much less effective at shifting the transition between irregular flow and regular flow and at shifting the minimum in the pressure gradient than in vertical pipes. The foam causes a regular film morphology at the top wall of the pipe, but is unable to make the morphology of the bottom liquid film regular. As a result, at low gas flow rates the relative decrease of the pressure gradient due to surfactants is smaller for smaller inclinations from horizontal. This larger relative

decrease for vertical flow compared to inclined flow is related to an increased foam formation and therefore a smaller mass density of the film in vertical flow.

*Keywords:*

annular flow, churn flow, foam, liquid loading, inclinations

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## 1. Introduction

A major problem in the production of natural gas is the *liquid loading* of gas wells. This problem occurs towards the end of the life of a well, when the reservoir pressure becomes low and the gas velocity in the well tubing is no longer sufficient to drag the liquids associated with the gas - water and gas condensate - upwards to the surface. This causes an accumulation of water at the bottom of the gas well, which can severely decrease, or even completely stop the production of gas (Lea et al., 2008).

One of the ways in which liquid loading can be postponed to lower gas flow rates, thereby extending the life of the well, is by injecting surfactants at the bottom of the gas well. Surfactants are molecules that have a polar and an apolar part, and therefore they preferentially adsorb at the gas-water interface. In this way surfactants allow the formation of a stable foam, which alters the nature of the flow in the well. As a result, the pressure gradient of the flow in the well is changed.

To show why the pressure gradient of the multiphase flow plays a key role in the phenomenon of liquid loading, we consider a gas well as a system with two components placed in series, as illustrated in figure 1. The first component is the flow from the reservoir to the bottom of the well tubing, also known as the bottom-hole location. The pressure at this location, known as the bottom-hole pressure, decreases with increasing gas flow rate. The Inflow Performance Relation (IPR) shows the relation between the bottom-hole pressure and the gas flow rate.

The second component of the gas well is the flow through the production tubing to the surface. This flow creates a pressure drop between the surface and the bottom-hole location. In single phase flow, this pressure drop would increase monotonically with increasing gas flow rate. However, because liquids are present in the well, at low gas flow rates the gas cannot drag the

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liquid upwards continuously, leading to a large pressure drop. As the surface pressure is usually fixed, the pressure drop in the production tubing determines the pressure at the bottom-hole location. This behaviour is illustrated by the Tubing Performance Curve (TPC), which relates the gas flow rate to the bottom-hole pressure. The TPC has a minimum: at gas flow rates above this minimum the frictional pressure drop is the dominant component of the total pressure drop, at gas flow rates below this minimum the hydrostatic component of the pressure drop is dominant.

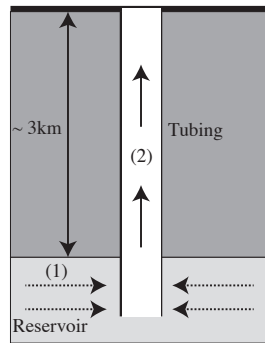


Figure 1: Schematic of a gas well consisting of two components in series: (1) flow from the reservoir to the bottom-hole location and (2) flow from the bottom-hole location through the production tubing to the surface.

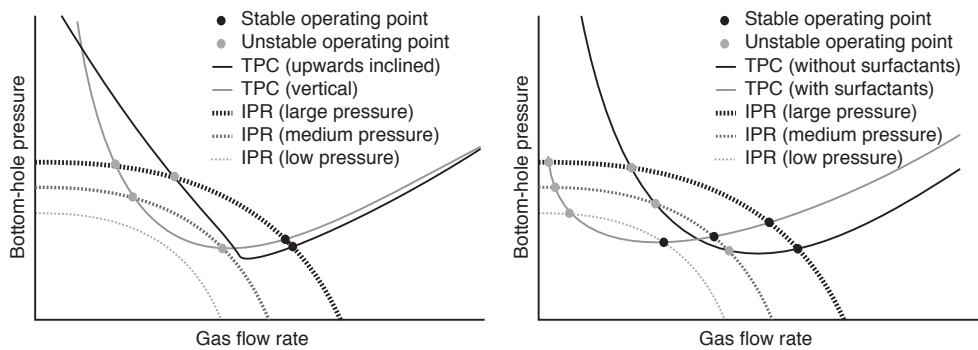


Figure 2: Schematic of the tubing performance curves and the inflow performance relations for gas-liquid flow in vertical and inclined pipes without surfactants (left graph) and for vertical flow with and without surfactants (right graph).

Of course, there can only be one value of the bottom-hole pressure, such that production of gas is only possible where the IPR and the TPC cross. Furthermore, the production is only stable when this crossing occurs at gas flow rates above the minimum in the TPC. These operating

points are illustrated on the left of figure 2, both for vertical flow and for inclined flow. The image shows that, as the reservoir pressure decreases, the IPR moves closer to the origin, until no stable operating points remain. At this point, the well becomes liquid loaded. The left graph in figure 2 also shows that the inclination has a significant effect on the TPC. Due to the thicker liquid film at the bottom of the pipe, it can be more difficult for the gas to drag the liquid upwards, which can lead to larger pressure gradients than for vertical flow.

The right graph in figure 2 illustrates the effect of surfactants on the TPC for vertical flow (van Nimwegen et al., 2014b). At large gas flow rates the foam that is created leads to an increase of the interfacial friction between the gas and the liquid, and therefore to an increase of the pressure drop. At low gas flow rates, the lower density of the film combined with the larger volume of the film allow the film to be carried upwards more easily by the gas, leading to a lower liquid holdup and a lower pressure drop. Note that the holdup of a phase is the volume occupied by this phase divided by the total volume of the pipe.

Much is known on gas-liquid flow without surfactants in inclined pipes, and we previously performed research on the effect of surfactants on air-water flow in vertical pipes (van Nimwegen et al., 2014a,b). However, to our knowledge, so far no systematic research has been performed on the effect of surfactants on gas-liquid flow in inclined pipes. In this work, we perform a systematic study of the effect of surfactants on air-water pipe flow, while changing the inclination between 20 degrees and 90 degrees from horizontal. The results give insight into the effect of the deviation of a gas well on the effectiveness of surfactants for the deliquification of the well. In our research, we make observations of the flow morphology and measure the pressure gradient and the holdup of foam and liquid, and relate the qualitative observations to the quantitative measurements. We investigate the effect of the surfactants on the minimum in the TPC, which gives an indication of the additional production that would be obtained in an actual gas well.

In the next section, we discuss air-water flow in inclined and vertical pipes. In section 3, we briefly cover the theory of surfactants and foam, and give an overview of earlier work on the effect of surfactants on air-water flow. Subsequently, in section 4, a description of the experimental setup is given, and in section 5 the results of the flow visualisation and the pressure gradient measurements are presented, both for inclined and vertical flow.

## 2. Vertical and inclined air-water flow

As discussed in the introduction, the minimum in the TPC, i.e. the pressure gradient as a function of the gas flow rate, determines liquid loading. The pressure gradient is closely related to the morphology of the flow. This can be easily observed from a balance of forces on the gas phase. We consider a regular, annular flow, as is found in normal production in gas wells, where the liquid is present in a liquid film at the pipe wall, and in droplets entrained in the gas core. Also, for the inclinations considered in our study (i.e. between 20 and 90 degrees from horizontal), we assume that the wall is fully liquid-wetted, implying that we do not consider friction between the gas and the wall. Note that for inclinations up to 20 degrees stratified flow can occur, and here this friction cannot be neglected (Barnea et al., 1985). The balance of forces for a section of length  $dx$  gives:

$$-\alpha_g \frac{\partial P}{\partial x} - \alpha_g \rho_g g \sin \beta - F_i = 0 \quad (1)$$

where  $\alpha_g$  is the gas holdup,  $\rho_g$  is the gas density,  $g$  is the gravitational acceleration,  $\beta$  is the inclination angle with respect to horizontal, and  $F_i$  is the interfacial friction per unit volume, which indicates the transfer of momentum between the two phases. Most of this transfer of momentum occurs at the interface between the gas and the liquid film at the wall, and only a small part is due to the entrainment of droplets (see Belt et al. (2009)). Assuming that the gas density is small, as is the case in our experiments at atmospheric conditions, we find that the pressure gradient is mostly determined by the interfacial friction between the phases. Therefore, we can write (using the expression of  $F_i$  by Issa (2010)):

$$-\frac{\partial P}{\partial x} \approx \frac{1}{\alpha_g} F_i = f_i \frac{4 \rho_g (u_g - u_i)^2}{D} \approx f_i \frac{4 \rho_g u_g^2}{D} \quad (2)$$

where  $u_g$  is the actual gas velocity in the pipe,  $u_i$  is the velocity of the gas-liquid interface and  $D$  is the pipe diameter. Note that in our experiments  $\rho_g$  and  $D$  are fixed,  $u_i$  is small compared to  $u_g$ , and  $u_g$  is to a large extent determined by the gas flow rate (as the liquid holdup is usually small). Therefore, the interfacial friction factor  $f_i$  mostly determines the pressure gradient, and is in itself determined by the flow morphology. Therefore, in this work, we study both the flow morphology and the pressure gradient, and we relate the two.

The morphology of gas-liquid flow is classified into several different flow patterns (Mandhane et al., 1974, Taitel and Dukler, 1976, Beggs et al., 1973, Weisman and Kang, 1981, Mukherjee

and Brill, 1985, Barnea, 1987). The minimum in the TPC, and therefore liquid loading, is related to the transition from annular flow at relatively large gas flow rates to an irregular churn or slug flow at lower gas flow rates. In annular flow, the morphology is relatively regular, and, therefore,  $f_i$  is relatively small. A relatively large gas flow rate is required to drag the liquid upwards, as the interfacial friction must balance the gravitational force acting on the film. When the gas flow rate is no longer large enough, the liquid starts to move downwards, leading to a thicker liquid film and consequently a more complex flow morphology and a larger  $f_i$ . At this large value of  $f_i$ , the gas velocity is again sufficient to drag the liquid upwards. The much more complex flow morphology, in which the liquid film moves upwards and downwards, marks the irregular flow regime (denoted churn flow in vertical pipes, and slug flow in upward flow at other inclinations). Note that, in this work, we quantify the flow rates in terms of superficial velocities, i.e. the gas flow rate divided by the cross-sectional area of the pipe. The actual gas velocity,  $u_g$ , is related to the superficial gas velocity  $u_{sg}$  through the gas holdup:  $\alpha_g = u_{sg}/u_g$ .

### 3. Surfactants and foam

Surfactants are molecules with a hydrophilic head and a hydrophobic tail, and therefore they preferentially adsorb at air-water interfaces. This decreases the equilibrium surface tension of these interfaces, usually by a factor 2-3 at the critical micelle concentration (cmc) (de Gennes et al., 2004). Below the cmc, the surfactants partly adsorb at the gas-liquid interface and partly dissolve in the bulk liquid. The surface tension decreases with increasing surfactant concentration. Above the cmc, no additional surfactants are adsorbed at the gas-liquid interface, but instead the additional surfactants form aggregates (micelles) in the bulk solution, such that the equilibrium surface tension no longer decreases. Above the cmc, the monomer concentration in the bulk liquid phase is also constant.

Apart from static effects, the surfactants also cause dynamic effects at the gas-liquid interface, since it takes time for surfactants to diffuse to and adsorb at the interface in order to reach an equilibrium between the concentration in the bulk solution and the surface concentration at the interface. This leads to two different phenomena. The first is the dynamic surface tension, which is the time-dependent development of the surface tension. When a new gas-liquid interface of an aqueous surfactant solution is created, initially the surface tension is equal to that of water (72.8 mN/s at atmospheric conditions at room temperature). In time, the adsorption of surfactants

at the interface leads to a decrease of the surface tension until the equilibrium surface tension is reached. It was shown that the dynamic surface tension is related to the formation of foam (Rosen et al., 1991), since the formation of foam requires the adsorption of surfactants at the interfaces of entrained gas bubbles. In earlier work, we characterised surfactants using the dynamic surface tension (van Nimwegen et al., 2013).

The second dynamic effect is the interfacial rheology, which can be characterised by e.g. the dilational parameters: the elastic modulus and the compression viscosity of the interfaces. These parameters play an important role in the stability of the foam, e.g. for drainage and film rupture (Langevin, 2000, Marmottant and Graner, 2007).

Foam can be seen as a shear thinning fluid with a yield stress. Its rheological properties, however, are dependent on the liquid content and on the bubble size of the foam; for instance, the yield stress decreases with increasing liquid content. Furthermore, both the liquid content and the bubble size of the foam change in time due to drainage and coarsening. There is not yet a complete rheological model for foam, addressing all these issues (Hutzler and Weaire, 2011). However, because foam is so ubiquitous, much research has been done on the fundamental physics of foams, which is reviewed in e.g. Kraynik (1988), Höhler and Cohen-Addad (2005) and Cohen-Addad et al. (2013). Foam can be considered highly viscous, even though the liquid forming the foam is not. At low shear stress, below the yield stress, the effective foam viscosity is infinite. At larger shear stresses, the foam is shear thinning (Kraynik, 1988). Many measurements show that the viscosity of foam is much larger than that of the water it contains, see e.g. Herzhaft (1999) and Calvert (1990).

In previous work (van Nimwegen et al., 2014a,b), we have studied the effect of surfactants on air-water flow in a 50 mm diameter vertical pipe at ambient conditions. We found that the entrainment of air into the liquid phase leads to the formation of foam, and more foam is formed as the air-water interface becomes more irregular, i.e. at larger  $f_i$  (and therefore at larger pressure gradient for air-water flow). In annular flow, the foam forms on the crests of waves on the liquid film, which increases  $f_i$ , leading to an increased pressure gradient. The foam shifts the transition between annular flow and churn flow to lower gas flow rates. This means that for a range of low gas flow rates where the flow without surfactants is irregular (churn flow or even hydrodynamic slug flow), in the presence of surfactants there is an annular flow with an almost stagnant foam film at the wall, and foam waves move upwards superposed on this film. Because the liquid con-



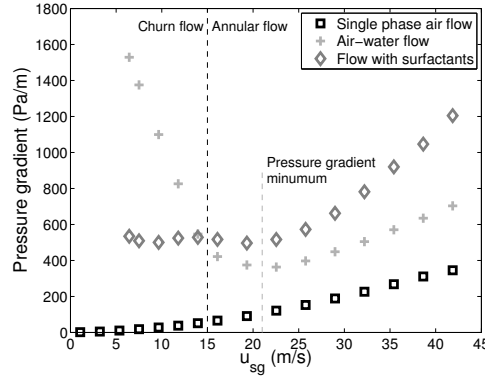


Figure 3: Pressure gradient as a function of  $u_{sg}$  for single phase air flow, for air-water flow (without surfactants), and for flow with surfactants in a 50 mm pipe at  $u_{sl} = 10$  mm/s.

tinuously moves upwards, this leads to a significant decrease of the hydrostatic pressure gradient and therefore to a decrease of the total pressure gradient at low gas velocities. A curve of the pressure gradient as a function of the superficial gas velocity for flow with surfactants, showing the lower pressure gradient at low gas flow rates, is presented in figure 3. It is compared to the curves for single phase air flow and air-water flow without surfactants. For each  $u_{sg}$ , there is an optimum surfactant concentration for pressure gradient reduction compared to flow without surfactants, which increases as the gas flow rate decreases. Below this optimum concentration, the flow reversal of the liquid film is not prevented, and the hydrostatic pressure gradient ( $\alpha_l \rho_l g$ ) is still large. Above this concentration, the large amount of foam causes a large  $f_i$ , and therefore a large frictional pressure gradient (equal to  $F_l$ , the frictional force of the liquid on the wall per unit volume of the pipe). Effectively, the surfactants cause a larger shift of the minimum in the pressure gradient to lower gas flow rates as the concentration is increased. Note that the surfactant is significantly more effective at low liquid flow rates than at high liquid flow rates. Above about  $u_{sl} = 20$  mm/s, a stagnant foam film no longer appears as it is too often disturbed by upward moving waves and the transition from annular flow to churn flow occurs at larger gas flow rates than for lower  $u_{sl}$ . The new results obtained in the current work for inclined flow will be compared with our previous results for vertical flow.

Other authors have also studied the influence of surfactants on air-water flow, including Christiansen (2006) who used a Champion Foamatron VDF-127 commercial surfactant product, Duangprasert et al. (2008) who used Sodium Dodecyl Sulphate as a surfactant and Saleh and

Al-Jamae'y (1997) who do not specify the surfactant used in the experiments. A more detailed overview of their work can be found in van Nimwegen et al. (2014a). We especially refer to the work by Rozenblit et al. (2006) (who used an Alkyl (8-16) Glucoside surfactant) and Sawai et al. (2004) (who used an n-hexadecyltrimethyl ammonium chloride mixed with a counter-ion sodium salicylate surfactant), who obtained similar results as ourselves for vertical flow. We also compared three different surfactants (van Nimwegen, 2015), i.e. the commercial product Trifoam 820 Block, Sodium Dodecyl Sulphate, and Cocamidopropyl betaine, and we obtained similar results for the three surfactants. This indicates that the results presented in this work are valid for a wide range of water soluble surfactants.

#### 4. Experimental setup

The setup used in the experiments consists of a 50 mm inner diameter perspex pipe connected to a frame, which can be inclined between horizontal and vertical. The same setup has previously been used in the work by Belt et al. (2009) and by van 't Westende et al. (2007) and in our earlier work van Nimwegen et al. (2014a). A schematic of the setup is presented in figure 4. Below, we will give a description of the setup, focussing on the different components presented in the schematic.

The air is introduced at the bottom of the setup, at flow rates between 0 and 5000 l/min ( $u_{sg} = 0 - 46$  m/s at room temperature and atmospheric pressure) using an M+W D6383 gas flow controller with an accuracy of 2% of the measured value. At the top of the setup, the air is vented into the atmosphere. One meter downstream of the air inlet, water is introduced through an annulus, at flow rates from 0 – 20 l/min. The liquid flow is regulated through a valve (Badger RC 200 1/4"), which is connected to two turbine flowmeters (Equflow PFA) through a PID controller. The turbine flow meters have a range of 0.2-2 l/min ( $u_{sl} = 1.7 - 17$  mm/s) and 2-20 l/min ( $u_{sl} = 17 - 170$  mm/s). The accuracy of the liquid control is 2% of the measured value.

The water is either taken from the tap (open-loop system), or from a tank containing a surfactant solution (closed-loop system). The surfactant solution is replaced twice a day to avoid surfactant degradation. We consider the surfactant degradation and the related measurement reproducibility in section 5.2.1.

The pressure is measured 6 m, 8 m and 10 m downstream of the water injection using UNIK

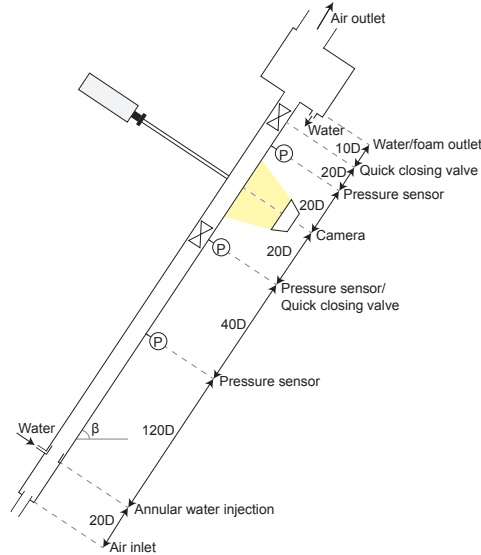


Figure 4: Schematic of the setup where the positions of the pressure sensors, the holdup valves and the camera are indicated. All distances are given in terms of the pipe diameter  $D = 50$  mm.

5000 pressure sensors by General Electric, with premium accuracy, a range of 70 mbar gauge, and a frequency response of about 1 kHz. We checked the factory calibration of the pressure sensors, and found that the output from the pressure sensors is within 1% full-scale of the expected value. The pressure gradient at the two intervals (between 6 and 8 and between 8 and 10 metres from the water injection), determined from these measurements, is used to evaluate the flow development: for vertical flow in van Nimwegen et al. (2014b) and for inclined flow in section 5.2.2.

Holdup measurements are performed using two quick-closing ball valves placed 8 and 11 metres downstream of the water injection. From these measurements, the holdup of foam and free water before the collapse of foam and the holdup of water after the collapse of the foam can be determined. In a holdup measurement, we first allow the flow to develop for 10 minutes. Subsequently, we close both ball valves simultaneously. Using a measuring tape attached to the outside of the pipe the height of the foam and free water in the pipe between the valves is measured. The combined holdup of foam and free water is determined by dividing the measured height of foam and water after closing the valves by the total length of the pipe between the two valves. Because the valves themselves are not transparent, we cannot detect the amount of free

water (i.e. water not in the foam) and the amount of foam separately if the water holdup before foam collapse is less than 3.3 % for vertical flow, and less than 2.8 % for 60 degrees inclined flow. In none of the measurements performed in this work the amount of free water exceeds this lower limit for the holdup measurements. Subsequently, we allow the water to drain from the foam. We found that most of the water has drained from the foam after 30 minutes, at which point we measure the water holdup, from which the hydrostatic pressure gradient is determined. Note that total collapse of the foam can take several more hours, depending on the surfactant concentration. Assuming that all water is incorporated into the foam (i.e. that there is no free water after closing the valves, which is a reasonable assumption at larger surfactant concentrations), the original water content of the foam can be determined. For inclined flow, the measuring tape is placed at the bottom wall, and we use simple trigonometry to obtain the holdups.

About 9 metres downstream of the water injection, a high-speed camera (Olympus ISpeed 2; 1000 fps; 800x600px) is mounted, the orientation of the camera is shown in figure 4. Images are obtained using two different techniques: (1) the outside visualisation, in which the camera is mounted about one metre away from the pipe, and images of the outside of the pipe are made (showing the film at the top wall in inclined flow), and (2) the inside visualisation, developed by Kalter (2010) and Khosla (2012), in which the camera makes images of the liquid film at the far (bottom) wall, through an insert piercing the near wall. In inclined flow, images of the liquid film at the bottom wall are made using the inside visualisation. A schematic of the inside visualisation is presented in figure 5.

The surfactant used in the experiments is Trifoam 820 Block (Oilchem GmbH, Dessau-Roßlau, Germany). It is a proprietary product, and also contains non-surfactant components, such as an anti-freezing agent. The surfactant concentrations used in this work are given in mg/l (milligram per litre); it is always the concentration of the entire product, and not just of the surfactant components. The surfactant was characterised using the static and the dynamic surface tension; the result can be found in van Nimwegen et al. (2014a).

## 5. Results

In this section, the results of the flow visualisation (in section 5.1), the pressure gradient measurements (in section 5.2), and the holdup measurements (in section 5.3) are presented. Unless indicated otherwise, all results were obtained at a superficial liquid velocity of 10 mm/s, and with

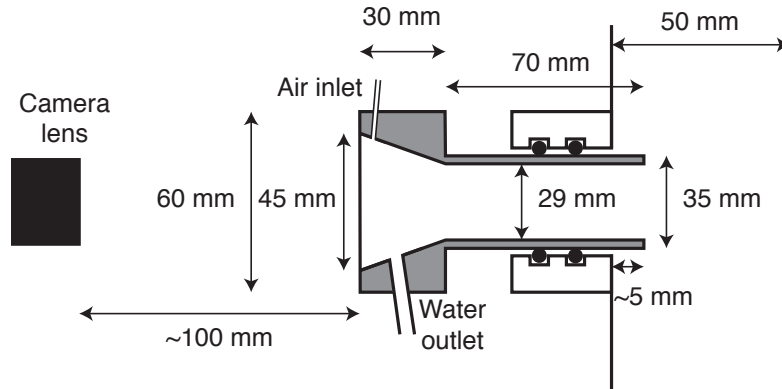


Figure 5: Schematic of the inside visualisation that shows the insert. In the experiments, a lamp is placed behind the pipe, such that the liquid film is backlit. Air is blown into the insert (through the air inlet) in order to prevent liquid from entering the insert and to remove droplets from the window.

a surfactant concentration of 1000 mg/l.

### 5.1. Visualisation

In this subsection, first the results of the outside visualisation are presented, and, subsequently, the results of the inside visualisation are discussed.

#### 5.1.1. Outside visualisation

Figure 6 summarises results of the outside visualisation, showing, side by side, snapshots of the flow with and without surfactants in the annular and irregular flow regimes for air-water flow, at three different inclinations. For each inclination, a movie is available in the supplemental material (movies 1, 2 and 3 for inclinations of 20, 60, and 90 degrees, respectively), showing the four flow conditions presented in the figure. At  $u_{sg} = 45.1$  m/s, shown in the top row of the figure, the annular air-water flow is not much affected by the inclination. The small ripple waves appear similar in each of the snapshots. However, due to the inclination the circumferential distribution of the roll waves changes: in vertical flow they span the entire pipe circumference, while at an inclination of 20 degrees, they extend only across the thicker bottom film. Therefore, for flow visualisation from the outside for a 20 degree inclination, the roll waves appear blurry, as they are only present on top of the bottom liquid film, and here they are observed through the top liquid film.

For annular flow with surfactants, the morphology is only little affected by the inclination. There appears to be somewhat more foam formed in an inclined pipe than in a completely vertical pipe. This might be due to the thicker liquid film at the bottom part of the wall for inclined flow. This is analogous to vertical flow where a large  $u_{sl}$ , and therefore a thicker liquid film, also leads to increased foam formation.

For vertical air-water flow at  $u_{sg} = 10.7$  m/s, parts of the liquid film move downwards. Some larger waves still move upwards, leading to an irregular behaviour of the flow. Infrequently, a flooding wave passes, causing a lot of liquid to move upwards simultaneously. For inclined flow at the same superficial gas velocity, the liquid film at the bottom wall moves downwards much faster and more consistently than for vertical flow. The shear stress that is exerted by the gas on the liquid is no longer sufficient to drag the thicker bottom liquid film upwards. Also, the flooding waves become more frequent, and they become coherent over the entire length of the pipe, which was not the case for vertical flow, where the flooding waves can disperse after some distance. Unlike for vertical flow, there is no upward transport of liquid through the liquid film; the flooding waves carry all liquid upwards, such that it can be considered a slug flow. After a flooding wave or liquid slug, the liquid film at the bottom wall moves downwards again.

At  $u_{sg} = 10.7$  m/s, for vertical flow with surfactants, the churn flow is replaced by a regular annular flow with an almost stagnant foam film at the wall, with waves of foam moving upwards on top of this film; these waves provide the upward liquid transport. As the inclination decreases, there is less liquid transport through the top film, leading to a more motionless foam film at the top wall, with less waves moving upwards; at an inclination of 20 degrees, holes are formed in the foam film. At this lowest inclination, the film at the top wall only forms through the deposition of foam by the flooding waves.

Overall, at high  $u_{sg}$ , above the transition between annular flow and irregular flow, the flow is little affected by the inclination. At low superficial gas velocities, the foam forms a foam film at the top wall, suppressing the downwards motion of the liquid film. At lower inclinations, this film becomes more immobile, transporting less liquid upwards. However, in inclined pipes at low superficial gas velocities virtually all of the net liquid transport is through the film at the bottom wall of the pipe. Therefore, we turn to the inside visualisation to take a closer look at the effect of surfactants on the bottom liquid film.

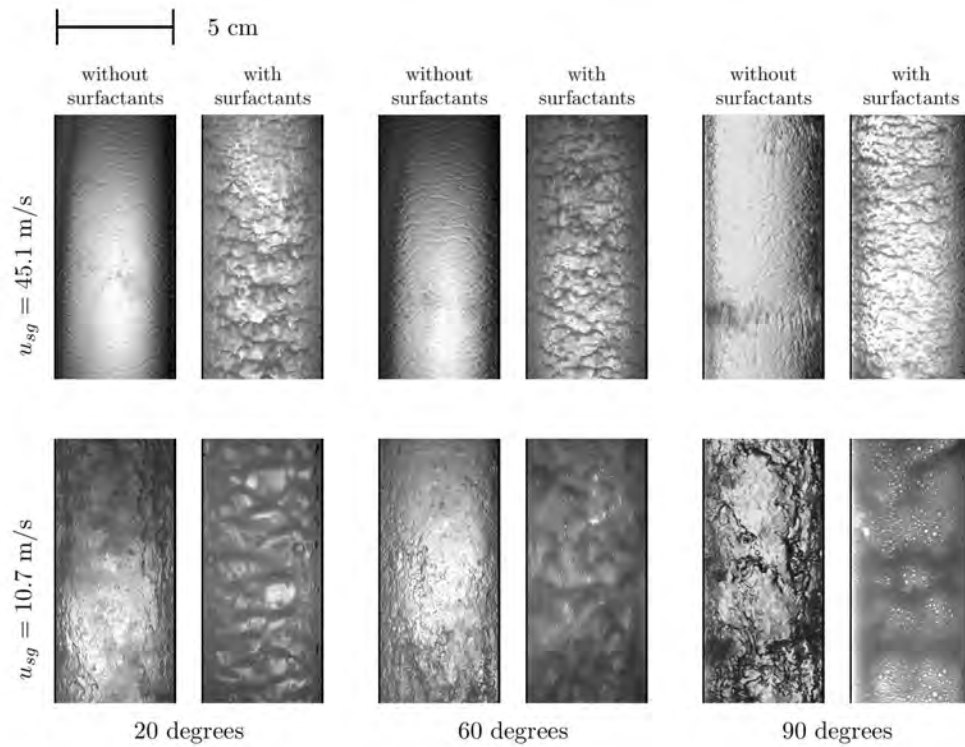


Figure 6: Outside flow visualisation for flow without and with surfactants, for three different inclinations, in both the annular flow regime and the irregular flow regime. The superficial liquid velocity is 10 mm/s. The images show the liquid film at the top wall of the pipe for inclined flow. At  $u_{sg} = 45.1$  m/s, the flow is always annular, at  $u_{sg} = 10.7$  m/s the flow is irregular, except for vertical flow with surfactants. The flow behaviour can be better observed in movies 1-3 in the supplemental material.

### 5.1.2. Inside visualisation

In figure 7 (and in movie 4 of the supplemental material) results of the inside visualisation for air-water flow without surfactants are presented, again for vertical flow and for inclinations of 20 and 60 degrees. For annular flow at  $u_{sg} = 45.1$  m/s, a roll wave is shown for each of the inclinations. The images show the ligaments and droplets that are part of the complex morphology of the roll waves. Topological changes at the air-water interface, that result from the formation of these droplets and ligaments, lead to the formation of foam when surfactants are added to the liquid. The roll waves grow as the inclination decreases; at low inclinations the bottom liquid film is thicker, allowing the formation of larger waves. The roll waves, however, extend only

across the liquid film at the bottom wall.

In the churn flow regime, at  $u_{sg} = 10.7$  m/s, for vertical flow an increase in the number of droplets and ligament can be observed compared to annular flow. This more irregular topography leads to a larger  $f_i$ , such that the gas, now moving at a lower velocity, is able to drag the thicker liquid film upwards. In inclined flow the number of ligaments increases substantially compared to vertical flow; there is a much more chaotic morphology at the bottom liquid film than at the top liquid film. This more complex morphology is primarily present in the flooding waves, that cause the upward transport of liquid. Between the flooding waves, the flow morphology is more regular. In a flooding wave,  $f_i$  is very large, such that the air can drag the water upwards. In between the flooding waves, the morphology is more regular,  $f_i$  is low, and the liquid film moves downwards. Behind flooding waves many bubbles are visible, indicating large entrainment of gas into the liquid phase.

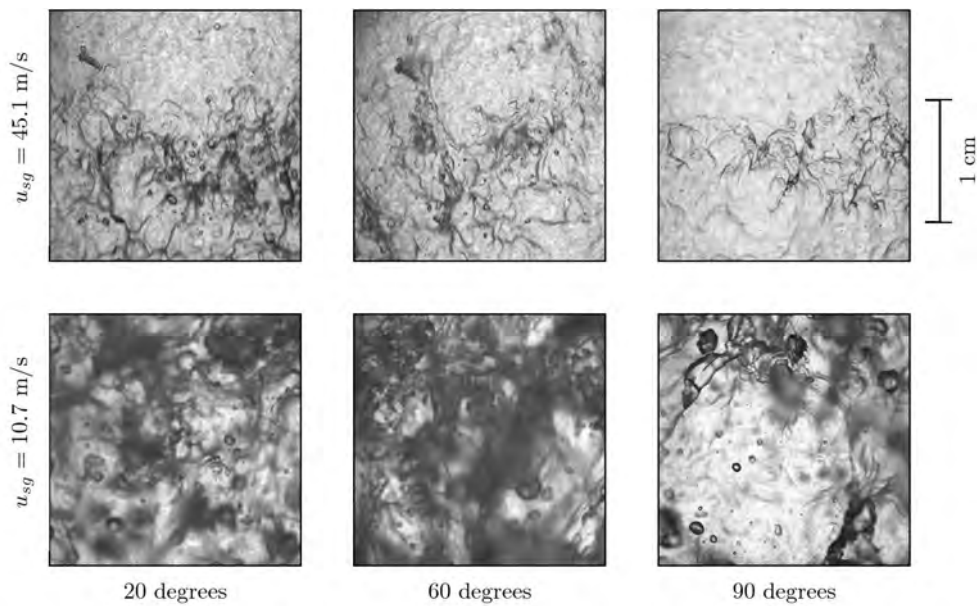


Figure 7: Inside flow visualisation for flow without surfactants, again at three inclinations and in both the annular flow regime (at  $u_{sg} = 45.1$  m/s) and the irregular flow regime (at  $u_{sg} = 10.7$  m/s). The dynamics of the flow can be observed in movie 4 in the supplemental material.  $u_{sl} = 10$  mm/s.

Figure 8 (and movie 5 in the supplemental material) show the results of the inside visualisation for flow with surfactants. At  $u_{sg} = 45.1$  m/s, the flow is largely unaffected by the inclination.



At each inclination there is an annular flow, but the roll waves and ripples of the air-water flow are replaced by foam waves of various sizes. The morphologies of the bottom liquid film and the top liquid film are very similar.

At the reduced gas flow rate of  $u_{sg} = 10.7$  m/s, the effect of the inclination on the flow is much larger. In a vertical pipe the flow with surfactants is regular, with the foam forming an almost stagnant film at the wall. In an inclined pipe the flow morphology becomes much more irregular, with larger waves and ligaments forming on the bottom film; the foam behaves much more liquid-like. The size of the foam bubbles is much smaller, and the way the foam moves indicates that there may be a significant amount of water that is not incorporated into the foam. The fact that a lot of the foam displayed in the image is out of focus means that the foam film is much thicker than for vertical flow, as the depth of field of the camera is not sufficient to capture all of the structures on the liquid film.

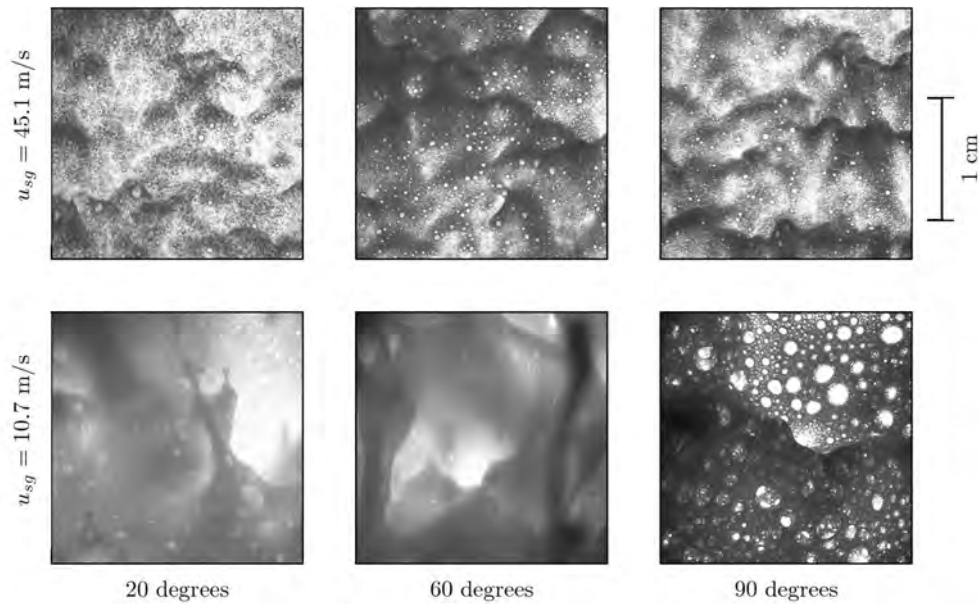


Figure 8: Inside flow visualisation for flow with surfactants, again at three inclinations and at two superficial gas velocities. At  $u_{sg} = 45.1$  m/s there is an annular flow for all inclinations. At  $u_{sg} = 10.7$  m/s the flow is irregular at inclinations of 20 degrees and 60 degrees, and the flow is annular at an inclination of 90 degrees. The dynamics of the flow can be observed in movie 5 of the supplemental material.  $u_{sl} = 10$  mm/s.

Overall, in case of thin liquid films the surfactants make the morphology at low gas flow rates

(in the irregular flow regime for air-water flow) much more regular. These thin liquid films are found at the top wall in inclined air-water flow. However, the thicker bottom film in inclined air-water flow, which is much more irregular than the film in vertical flow, does not become regular due to the surfactants. As a result, the surfactants shift the transition between annular flow and irregular (churn or slug) flow much more for vertical pipes than for inclined pipes. This is illustrated in figure 9, which shows this transition as a function of the inclination for both flow with and without surfactants.

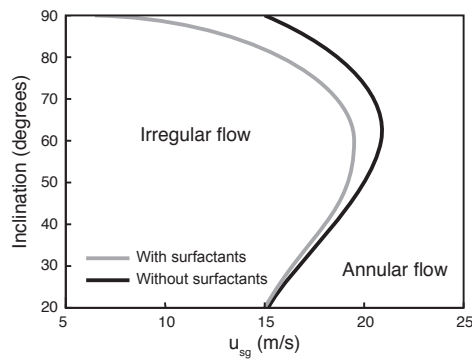


Figure 9: Schematic showing the transition between irregular flow and annular flow at the different inclinations, both for flow without and with surfactants (for a surfactant concentration of 1000 mg/l).

## 5.2. Pressure gradient

In this section, the results of measurements of the pressure gradient in vertical and inclined flow are presented. First, we consider the measurement reproducibility and the flow development for inclined flow. Next, we present results at a surfactant concentration of 1000 mg/l and  $u_{sl} = 10$  mm/s. Subsequently, other liquid flow rates and other surfactant concentrations are considered.

### 5.2.1. Reproducibility and surfactant degradation

During the measurements the surfactant degrades, such that the surfactant solution in the tank should be replaced regularly. In this work, we measure curves of the pressure gradient versus the superficial gas velocity. In these measurements, we fix the superficial liquid velocity and start the measurement at the largest superficial gas velocity. We subsequently decrease  $u_{sg}$  in steps. The entire measurement of one of these curves takes between 90 and 120 minutes. A fresh surfactant solution is made before each of the measurements, but the solution is not replaced

during the measurements. To investigate whether the surfactant deteriorates significantly during a measurement, we performed three measurements: two using the procedure outlined above, and one in which we replaced the surfactant solution halfway through the measurement. The results are presented in figure 10. We found that the results from the three measurements are very similar, indicating that the reproducibility of the measurements is good, and that the surfactants do not degrade significantly during the measurements.

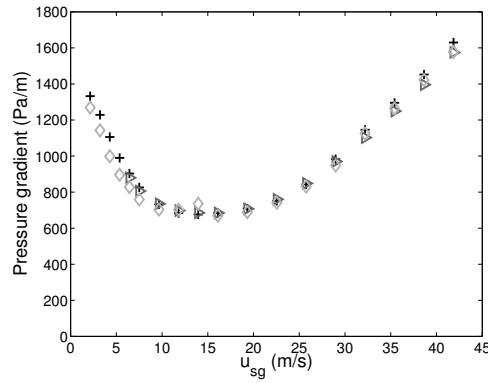


Figure 10: The average pressure gradient as a function of the superficial gas velocity for vertical flow at  $u_{sl} = 20$  m/s. The three symbols indicate three different measurements, performed on different days. The diamonds indicate a measurement in which the surfactant solution was replaced halfway through the measurement. For the other two curves (crosses and triangles), the surfactant solution was not replaced during the measurement. The surfactant concentration is 1000 mg/l.

### 5.2.2. Flow development

In earlier work (van Nimwegen et al., 2014a), we have shown the development of flow without and with surfactants for vertical flow. In this section, we consider the effect of the inclination on the flow development. Figure 11 shows the pressure gradient between 6 and 8 and between 8 and 10 metres from the water injection, for flow with and without surfactants, at inclinations of 20, 60 and 90 degrees.

Vertical flow without surfactants is fully developed 6 metres, or 120 diameters, downstream of the water injection, which is consistent with results from Wolf et al. (2001). For inclined flow, the results for large gas flow rates are similar. At low gas flow rates, the results from the two measurement sections differ, because, due to the large pressure gradient fluctuations, the pressure 6 m from the water injection is sometimes outside the range of the pressure sensor, leading to an underestimation of the pressure gradient in the bottom section. Therefore, for flow without

surfactants, we always present the results for the measurement section between 8 and 10 metres downstream of the water injection.

For large superficial gas velocities at all presented inclinations, the development length for flow with surfactants is longer than for flow without surfactants. This is clear from the measured pressure gradient in the two sections, which is not equal; more foam is still being formed 6 metres downstream of the water injection, leading to an increase of the pressure gradient from the first to the second measurement interval.

At low gas flow rates, where the surfactants are effective in reducing the pressure gradient, the measured pressure gradient for the two measurement sections is about equal; we conclude that the flow is developed 6 metres downstream of the water injection. There is one exception: at an inclination of 20 degrees the pressure gradient between 6 and 8 metres is significantly larger than between 8 and 10 metres. At these conditions there is a slug flow, with a liquid film moving downwards rapidly between subsequent slugs. However, once the water and the foam reach the top of the setup, they will not flow back downwards any more. Therefore, near the end of the setup, there is on average much less liquid in the pipe, leading to a lower pressure gradient. This effect occurs over a longer distance from the end of the setup at lower inclinations. Therefore, for flow with surfactants, we always present results for the segment between 8 and 10 meters downstream of the water injection, except for inclinations of 20 and 45 degrees and  $u_{sg} < 12$  m/s, where results from the segment between 6 and 8 metres downstream of the water injection are presented.

### 5.2.3. Measurements at 1000 mg/l and $u_{sl} = 10$ mm/s

In this section, results of measurements at fixed concentration (1000 mg/l) and at fixed liquid flow rate ( $u_{sl} = 10$  mm/s) are given, for inclinations of 20, 45, 60, 70, 80 and 90 degrees. On the left of figure 12, the pressure gradient in air-water flow is presented, as a function of  $u_{sg}$  and the pipe inclination. The figure shows that for large gas flow rates, the pressure gradient is little affected by the inclination. This is in line with the results of the flow visualisation, that show that the morphology is almost independent the inclination. At low gas flow rates, the effect of the inclination is much more significant. At an inclination of 60 degrees, the pressure gradient is larger than for vertical flow, as the thicker bottom liquid film requires a larger interfacial friction to be moved upwards. When the inclination is decreased below 60 degrees the pressure gradient decreases again, because the effective gravitational acceleration  $g \sin \theta$  decreases. To better show

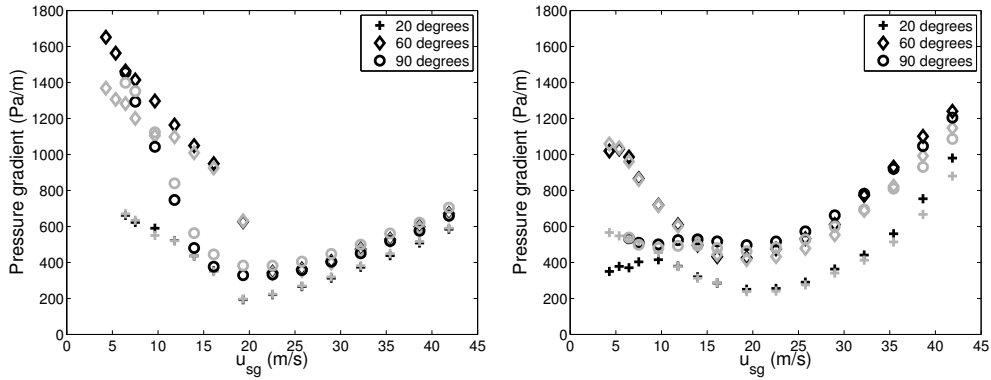


Figure 11: The pressure gradient between 8 m and 10 m (black symbols) and between 6 m and 8 m (grey symbols) downstream of the water injection, for flow without (left) and with (right) surfactants, indicating the development of the flow. The superficial liquid velocity is 10 mm/s, and the surfactant concentration is 1000 mg/l.

the effect of the inclination on the pressure gradient, we show the percentual difference between the pressure gradient for the different inclinations and the pressure gradient in vertical flow on the right of figure 12. For vertical flow, this deviation is 0% by definition. The image shows that at  $u_{sg} \approx 17$  m/s, the pressure gradient is most affected by the inclination, with the largest increase of the pressure gradient occurring at an inclination of 60 degrees. At lower gas velocities ( $u_{sg} < 10$  m/s), the largest deviation occurs at a 70 degree inclination, probably due to the larger value of  $g \sin(\beta)$ .

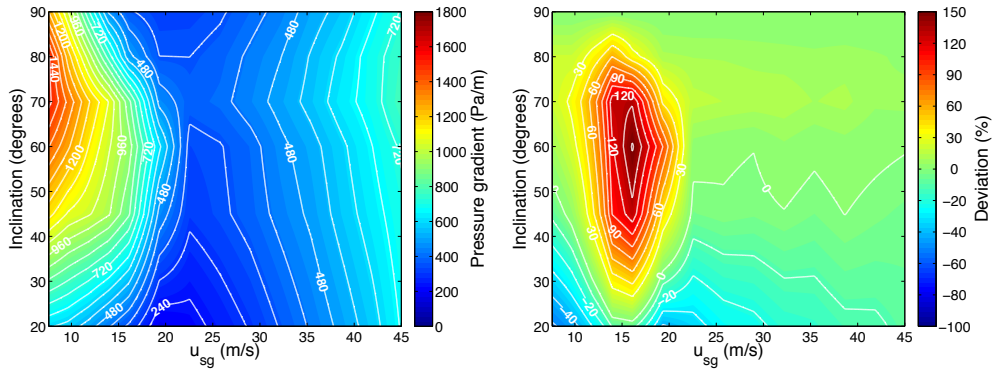


Figure 12: The average pressure gradient as a function of the inclination and the superficial gas velocity for flow without surfactants at a superficial liquid velocity of 10 mm/s (left graph), and a comparison of the average pressure gradient for inclined flow with the average pressure gradient for vertical flow, for the same flow conditions (right graph).

Figure 13 shows that in flow with surfactants in the annular flow regime, the pressure gradient is much higher than for air-water flow, but remains unaffected by the inclination. At low gas flow rates the surfactants reduce the pressure gradient significantly for all inclinations, but this reduction is larger for larger inclinations.

From the flow visualisation, we observe that the interfacial morphology of the flow with surfactants is significantly more irregular at inclinations of 20 and 60 degrees, compared to vertical flow. This is consistent with the significantly larger pressure gradient for flow at an inclination of 60 degrees compared to vertical flow. For flow without surfactants, the pressure gradient at  $u_{sg} = 10$  m/s is largest at 70 degrees, and is lower for inclinations of 60 degrees and 45 degrees. For flow with surfactants, the pressure gradient at  $u_{sg} = 10$  m/s is approximately constant for inclinations between 45 and 70 degrees. This is a consequence of the fact that surfactants relatively decrease the pressure gradient less as the inclination is decreased: surfactants are less able to make the thicker and more irregular bottom liquid film regular at these smaller inclinations.

Note that for flow without surfactants, the pressure gradient is most affected by the inclination at  $u_{sg} \approx 17$  m/s, which is near the transition between regular flow and irregular flow. However, for flow with surfactants, the comparison of the pressure gradient for inclined flow with the pressure gradient for vertical flow, shown on the right of figure 13, shows that the pressure gradient is most affected by the inclination at lower superficial gas velocities ( $u_{sg} \lesssim 10$  m/s). This indicates that the surfactants move the transition between annular and irregular flow, and the corresponding increase in  $f_i$ , to lower gas flow rates, even at inclinations below 90 degrees. This is also confirmed by the location of the minimum of the pressure gradient: for vertical flow with surfactants, the minimum is a plateau and the pressure gradient only increases with decreasing  $u_{sg}$  for  $u_{sg} < 7$  m/s, while the pressure gradient increases for  $u_{sg} < 15$  m/s in flow without surfactants. For inclined flow, this shift in the minimum is much smaller, e.g. from  $u_{sg} \approx 22$  m/s to  $u_{sg} \approx 18$  m/s for an inclination of 60 degrees. This is made more clear in section 5.2.5.

Figure 14 shows that the root-mean-square fluctuations of the pressure gradient in air-water flow at large gas flow rates are unaffected by the inclination. At low gas flow rates, in the churn flow regime, the fluctuations of the pressure gradient are very much affected by the inclination; at all lower inclinations, they are much larger than for vertical flow. The relatively small flooding waves in the churn flow regime in vertical flow are replaced by much larger slugs in the irregular

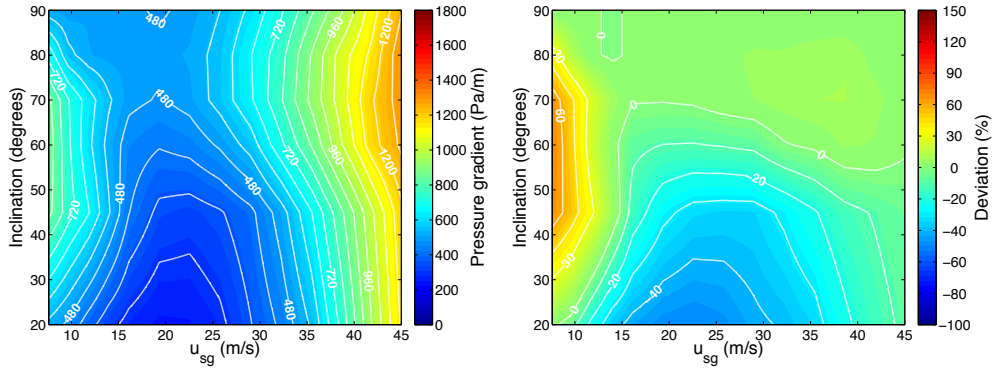


Figure 13: The average pressure gradient as a function of the inclination and the superficial gas velocity for flow with 1000 mg/l of surfactants at a superficial liquid velocity of 10 mm/s (left graph), and a comparison of the average pressure gradient for inclined flow with the average pressure gradient for vertical flow, for the same flow conditions (right graph).

flow regime in inclined pipes. On the right of the figure, again a percentual comparison with vertical flow is presented, showing an increase in the fluctuations of the pressure gradient by up to a factor 6 at an inclination of 45 degrees.

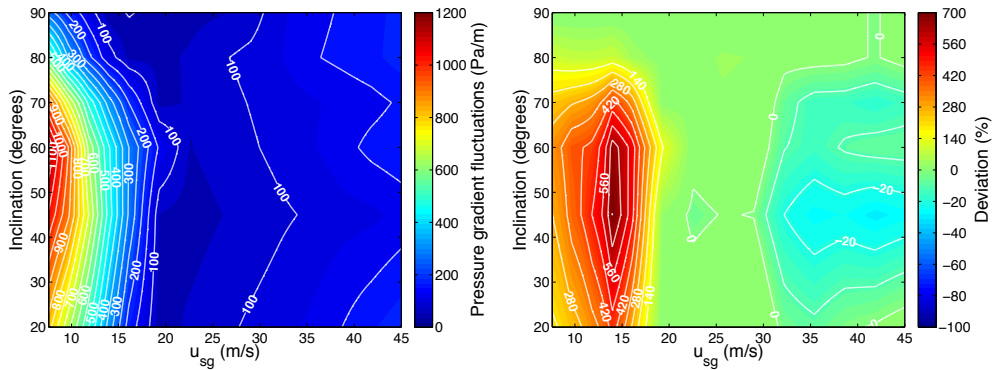


Figure 14: The fluctuations of the pressure gradient as a function of  $u_{sg}$  and the inclination at  $u_{sl} = 10$  mm/s for flow without surfactants (left graph), and a comparison of the fluctuations of the pressure gradient for inclined flow with the fluctuations of the pressure gradient for vertical flow, for the same flow conditions (right graph).

As shown in figure 15, in flow with surfactants at high  $u_{sg}$  the fluctuations of the pressure gradient are not affected by the inclination. At low  $u_{sg}$ , the fluctuations of the pressure gradient are much smaller than for air-water flow, but they are much larger for inclined flow than for vertical flow. This is shown in the percentual comparison on the right of figure 15; at an inclination of 45

degrees, the fluctuations are up to 7 times larger than for vertical flow. The visualisation showed that at  $u_{sg} = 10.7$  m/s, for a vertical pipe, there was still a regular annular flow; in inclined flow, this was no longer the case and fluctuations of the pressure gradient grow correspondingly. The increase in the fluctuations of the pressure gradient due to the inclination occurs at lower gas flow rates for flow with surfactants than for flow without surfactants.

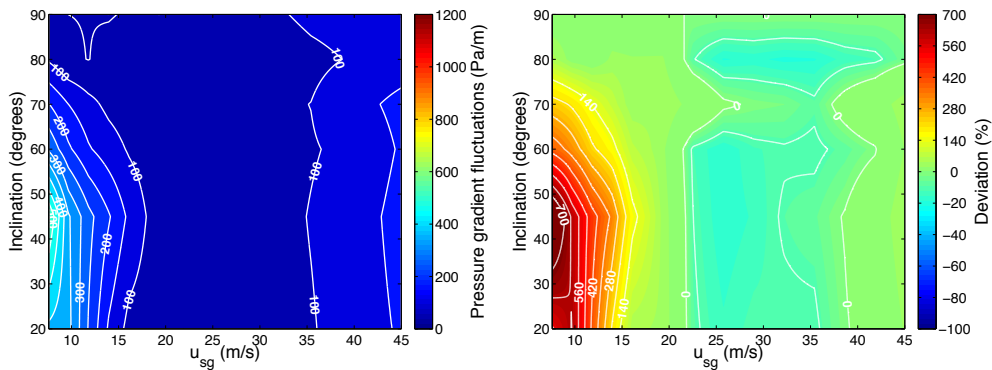


Figure 15: The fluctuations of the pressure gradient as a function of  $u_{sg}$  and the inclination at  $u_{sl} = 10$  mm/s for flow with 1000 mg/l of surfactants (left graph), and a comparison of the fluctuations of the pressure gradient for inclined flow with the fluctuations of the pressure gradient for vertical flow, for the same flow conditions (right graph).

To quantify the change in pressure gradient caused by the surfactant, a percentual comparison of the flow with and without surfactants as a function of  $u_{sg}$  and the inclination is presented on the left of figure 16. It shows that at large gas flow rates, the surfactants always increase the average pressure gradient, by up to 80%. At low gas velocities, the surfactants decrease the pressure gradient, and they do so more effectively as the inclination approaches vertical. The black line corresponds to an equal pressure gradient for the flow with and without surfactants. It roughly corresponds to the transition between annular flow and irregular flow for flow without surfactants. This equal pressure gradient, like the transition, is found at larger gas flow rates in inclined pipes than in vertical pipes.

Overall, in regular, annular flow, the foam created due to the addition of surfactants increases  $f_i$ , and therefore increases the pressure gradient. At low  $u_{sg}$ , the lower mass density of the foam allows it to be carried by the gas more easily, and the transition to irregular flow occurs at lower  $u_{sg}$ .

On the right of figure 16 the effect of the surfactants on the fluctuations of the pressure



gradient is shown. For almost all gas flow rates and inclinations the surfactant decreases the fluctuations of the pressure gradient. The surfactants are more effective at doing so in the irregular flow regime. Within this regime, the surfactants are more effective at larger inclinations. Only at  $u_{sg}$  just above the transition between regular flow and irregular flow, where the pressure gradient fluctuations are lowest for both flow with and without surfactants, the surfactants are unable to decrease the fluctuations of the pressure gradient. In air-water flow without surfactants at this  $u_{sg}$ , there are few roll waves (Belt et al., 2009), while the flow is still regular; there are not many irregularities in the flow morphology for the surfactants to suppress.

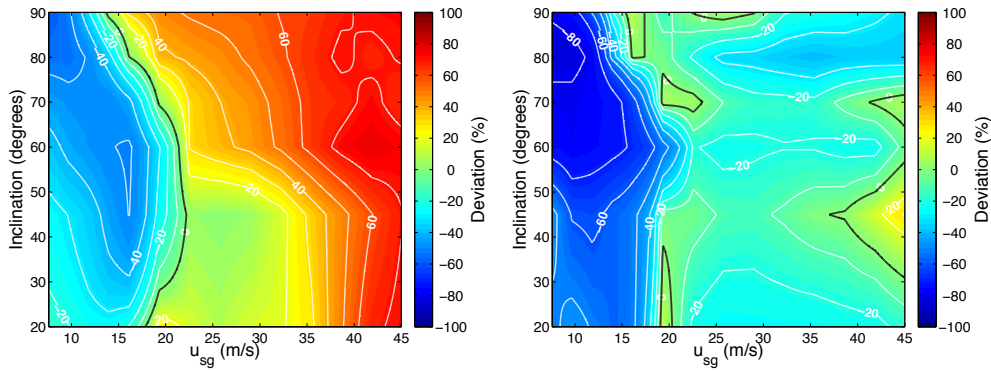


Figure 16: Comparison of the average pressure gradient for the flow with 1000 mg/l of surfactants with the average pressure gradient for the flow without surfactants (left graph) and a comparison of fluctuations of the pressure gradient for the flow with 1000 mg/l of surfactants with the fluctuations of the pressure gradient for the flow without surfactants (right graph);  $u_{sl} = 10$  mm/s.

In this section, we considered the relation between the flow morphology and the pressure gradient. To illustrate this further, in figure 17 we show five snapshots of both annular flow and irregular churn flow without surfactants in a vertical pipe taken exactly one second apart. Note that for churn flow the morphology is much more complex than for annular flow, but also that the morphology of irregular flow varies much more in time. The time signals of the pressure gradient for annular and churn flow are also shown in the figure, over a period of 4 seconds (but a different period than in which the snapshots were created). The time signal illustrates that the more complex flow morphology leads to a larger pressure gradient and that the larger changes in the flow morphology in time lead to larger pressure gradient fluctuations.

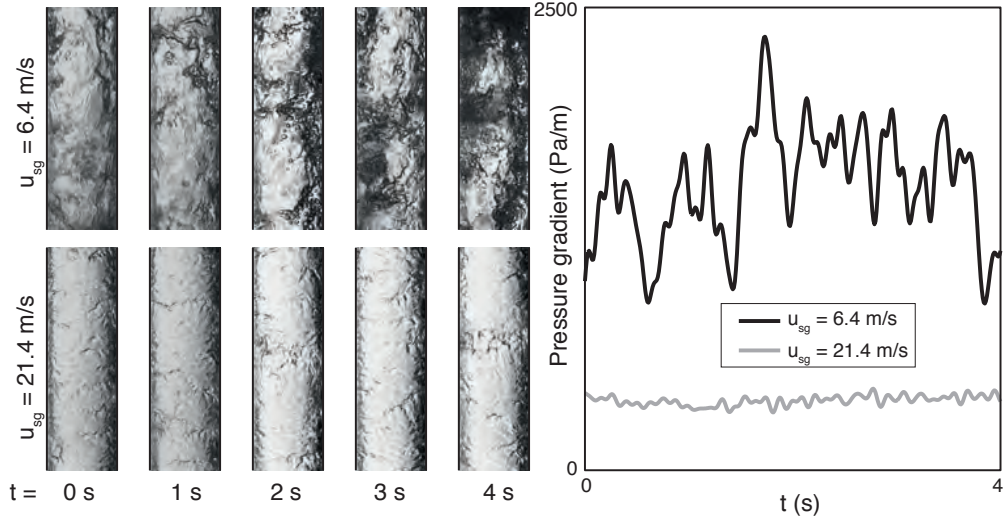


Figure 17: Snapshots of the flow for churn flow (top row) and annular flow (bottom row) taken one second apart, and the pressure gradient as a function of time for a 4 second period for both churn flow and annular flow. All data is for vertical pipes and flow without surfactants at  $u_{sl} = 10$  mm/s.

#### 5.2.4. Effect of liquid flow rate on the pressure gradient

In the previous results, only a single liquid flow rate was considered. At inclinations of 60 degrees and 90 degrees, we also performed measurements at a higher and at a lower liquid flow rate. The results for air-water flow are presented in figure 18. In vertical flow (right graph), the  $u_{sg}$  corresponding to the minimum in the pressure gradient is independent of the liquid flow-rate. At  $u_{sg}$  above this minimum, in the annular flow regime, the pressure gradient strongly depends on the liquid flow rate. In the irregular flow regime, at  $u_{sg}$  below this minimum, the pressure gradient becomes less dependent on the liquid flow rate as the superficial gas velocity decreases; the pipe fills up to the same liquid holdup regardless of the liquid flow rate, and the hydrostatic pressure gradient is the dominant contribution to the total pressure gradient.

At an inclination of 60 degrees, the minimum in the pressure gradient decreases with decreasing  $u_{sl}$ . However, the other observations made for vertical flow still hold; a characteristic of irregular flow is that the pressure gradient becomes independent of the liquid flow rate. For inclined flow, especially at low  $u_{sl}$ , the transition from annular flow to irregular flow is much less gradual than for vertical flow.

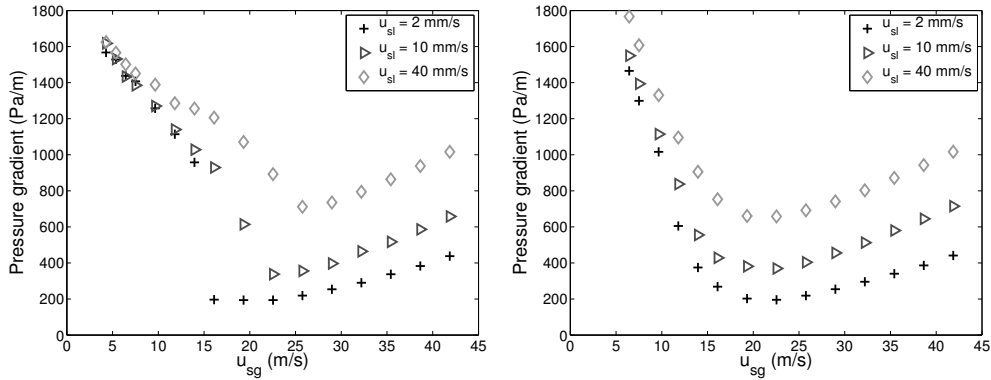


Figure 18: The average pressure gradient of flow without surfactants as a function of the superficial gas velocity for three liquid flow rates for an inclination of 60 degrees (left graph) and for vertical flow (right graph).

In figure 19 the pressure gradient for vertical flow and for 60 degrees inclined flow with surfactants is presented at different  $u_{sl}$ . For vertical flow (right graph), there is one main difference with the flow without surfactants: at low  $u_{sg}$ , there is a large difference between the pressure gradients at the three considered liquid flow rates. At  $u_{sl} = 2$  mm/s and at  $u_{sl} = 10$  mm/s, the pressure gradient is still at its minimum value at the lowest superficial gas velocities considered here. The flow is still regular, and for regular flows, the pressure gradient is much more strongly dependent on the liquid flow rate than for irregular flow. At  $u_{sl} = 40$  mm/s, the pressure gradient starts increasing at the lowest gas velocities considered, indicating that there is a transition to a more irregular flow; the surfactants are less effective at higher liquid flow rates. Note that both a smaller inclination and a larger superficial liquid velocity lead to a thicker liquid film and a smaller effectiveness of the surfactants: this indicates that, in general, surfactants are less effective for thicker liquid films.

On the left of figure 19, the effect of the liquid flow rate on the pressure gradient is shown for an inclination of 60 degrees. At low  $u_{sg}$  we observed from the visualisation that the flow morphology is much more irregular at an inclination of 60 degrees than for vertical flow. This leads to an increase in the pressure gradient at low  $u_{sg}$ , regardless of the liquid flow rate. Like for the irregular air-water flow, the pressure gradient is less affected by the liquid flow rate, although the surfactant is still somewhat more effective at lower  $u_{sl}$ .

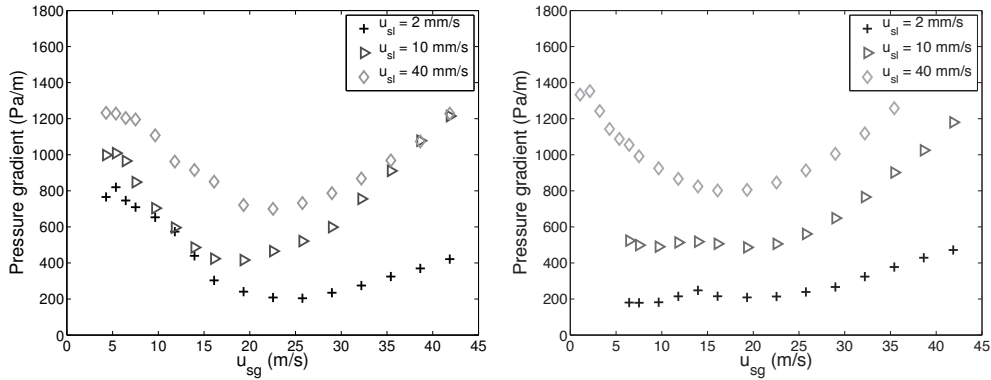


Figure 19: The average pressure gradient of flow with 1000 mg/l of surfactants as a function of the superficial gas velocity for three liquid flow rates for an inclination of 60 degrees (left graph) and for vertical flow (right graph).

### 5.2.5. Effect of surfactant concentration on the pressure gradient

In all previous results, a surfactant concentration of 1000 mg/l was considered. To investigate the effect of the surfactant concentration on the flow, we have performed measurements at three additional concentrations (500, 2000 and 3000 mg/l) at an inclination of 60 degrees and for vertical flow.

In the right graph of figure 20, the pressure gradient for vertical flow at the four considered concentrations is compared to the pressure gradient for air-water flow. In the annular flow regime, at large  $u_{sg}$ , the pressure gradient increases with increasing surfactant concentration, as the increased amount of foam leads to a larger  $f_i$ . The minimum in the pressure gradient occurs at lower  $u_{sg}$  as the surfactant concentration increases, indicating that the optimum surfactant concentration to reduce the pressure gradient increases with decreasing  $u_{sg}$ . The minimum in the curve of the pressure gradient for 3000 mg/l corresponds to the slug flow regime.

On the left of figure 20, the curves of the pressure gradient for different concentrations are shown at an inclination of 60 degrees. Again, for annular flow the behaviour is independent of the inclination. For low gas flow rates, like in vertical flow, the minimum in the curve of the pressure gradient shifts to lower superficial gas velocity as the surfactant concentration is increased. However, the minimum in the curve is shifted less than for vertical flow, and the corresponding value of the pressure gradient is larger, confirming our observation that the surfactant is less effective for inclined pipes.

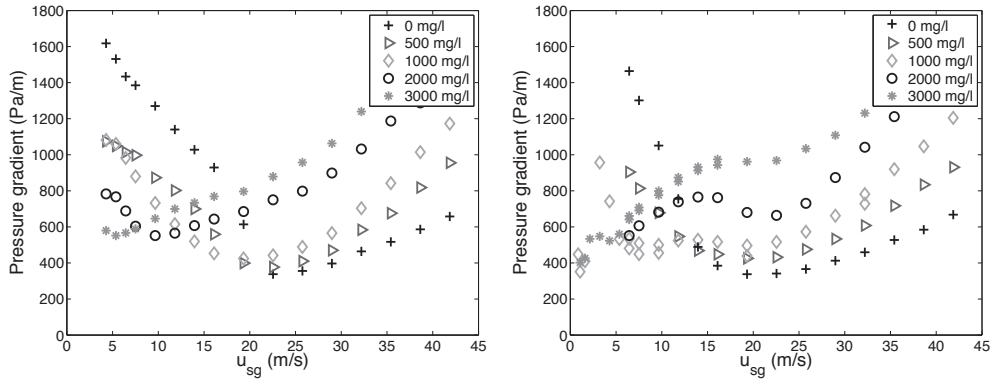


Figure 20: The average pressure gradient as a function of the superficial gas velocity for flow at different surfactant concentrations and for flow without surfactants, for an inclination of 60 degrees (left graph) and for vertical flow (right graph).

### 5.3. Holdup measurements

In this section the results from the holdup measurements are presented. In figure 21, the frictional and hydrostatic pressure gradient are presented for flow with and without surfactants in a vertical pipe; concentrations of 1000 mg/l and 3000 mg/l are considered. For flow with surfactants, the film has a lower density and a larger volume than for flow without surfactants, such that it is dragged upwards faster by the air, leading to a larger frictional pressure gradient. Simultaneously, the faster upward movement of the liquid decreases the hydrostatic pressure gradient, especially at low  $u_{sg}$ , where the surfactants cause a change from irregular churn flow to annular flow. Therefore, the total pressure gradient increases for high  $u_{sg}$  and decreases for low  $u_{sg}$ .

At a surfactant concentration of 3000 mg/l, at  $u_{sg} = 1.1$  m/s, the hydrostatic pressure gradient is significantly larger than the total pressure gradient. At this gas flow rate, there is a slug flow, where the foam film moves downwards between the slugs, causing a negative frictional pressure gradient.

Figure 22 shows the frictional and hydrostatic pressure gradient for flow without and with surfactants (1000 mg/l) in a vertical pipe, for  $u_{sl} = 50$  mm/s. At this larger liquid flow rate, the surfactant no longer causes a significant increase in the frictional pressure gradient; the average velocity gradient of the film at the wall is not increased. At lower gas flow rates the foam does not cause as large an increase of the average liquid velocity compared to lower liquid flow rates,

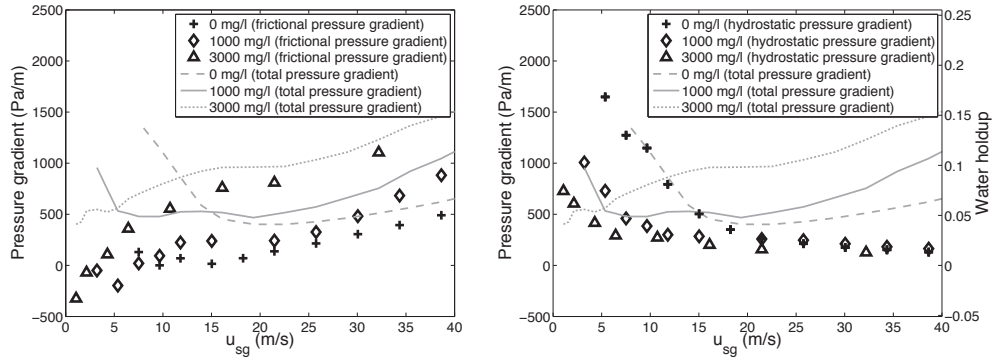


Figure 21: The frictional (left graph) and the hydrostatic (right graph) pressure gradient for vertical flow, both without and with surfactants, for  $u_{sl} = 10$  mm/s, represented by symbols in the graphs. For comparison, the total average pressure gradient is shown, represented by the lines in the graphs. The water holdup indicates the fraction of the pipe filled with water after collapse of the foam.

leading to a smaller decrease in the hydrostatic pressure gradient. Overall, the surfactants are less effective at large liquid flow rates. This is consistent with the less regular flow morphology at these larger liquid flow rates (van Nimwegen et al., 2014a).

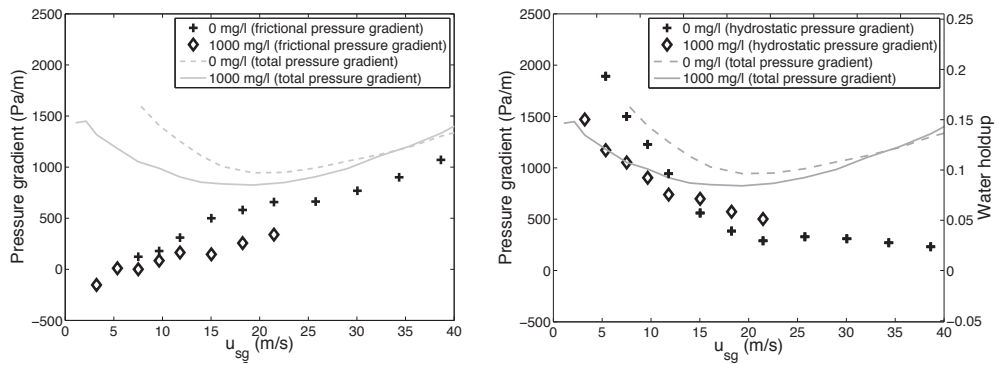


Figure 22: The frictional (left graph) and the hydrostatic (right graph) pressure gradient for vertical flow, both without and with surfactants, for  $u_{sl} = 50$  mm/s, represented by symbols in the graphs. For comparison, the total average pressure gradient is shown, represented by the lines in the graphs. The water holdup indicates the fraction of the pipe filled with water after collapse of the foam.

In figure 23, the frictional and the hydrostatic pressure gradient are given for measurements

at an inclination of 60 degrees for  $u_{sl} = 10$  mm/s at surfactant concentrations of 0 mg/l, 1000 mg/l, and 3000 mg/l. Like for vertical flow, at large  $u_{sg}$  the foam merely causes an increased frictional pressure gradient. At low gas flow rates, the surfactant decreases the hydrostatic pressure gradient. Unlike for vertical flow, however, at a concentration of 1000 mg/l the frictional pressure gradient already goes to zero at  $u_{sg} \approx 15$  m/s, while for vertical flow this occurs at  $u_{sg} \approx 7$  m/s. This confirms that the flow reversal, marking the transition to irregular flow, occurs at larger gas flow rates for inclined flow. At a concentration of 3000 mg/l the transition to irregular flow, where the frictional pressure gradient goes to zero, is postponed to  $u_{sg} \approx 5$  m/s. This is also a significantly larger superficial gas velocity than for vertical flow, where the transition from annular to slug flow occurs at  $u_{sg} \approx 1.5$  m/s.

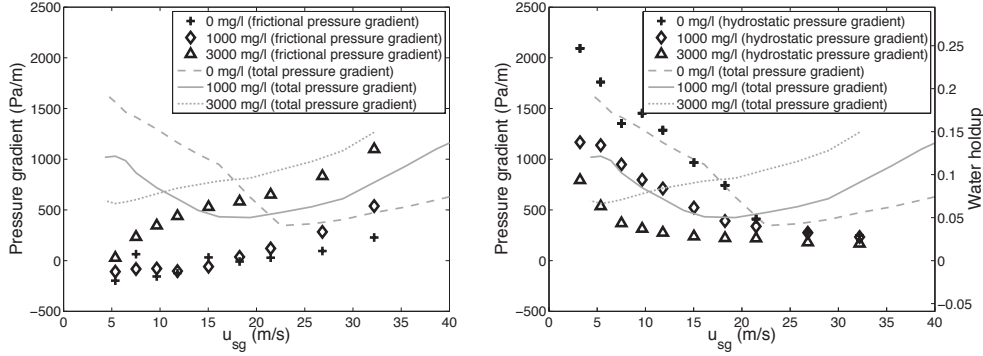


Figure 23: The frictional (left graph) and the hydrostatic (right graph) pressure gradient for flow at an inclination of 60 degrees, both without and with surfactants, for  $u_{sl} = 10$  mm/s, represented by symbols in the graphs. For comparison, the total average pressure gradient is shown, represented by the lines in the graphs. The water holdup indicates the fraction of the pipe filled with water after collapse of the foam.

For inclined flow at  $u_{sl} = 50$  mm/s, as is shown in figure 24, the frictional pressure gradient, shown in the left graph, is not significantly affected by the surfactant (compared to the measurement accuracy) for  $u_{sg} < 21$  m/s, indicating that the surfactant is unable to shift the transition between churn flow and annular flow. This shows that the surfactant is even less effective at both a larger liquid flow rate *and* a smaller inclination. The surfactant does decrease the hydrostatic pressure gradient somewhat in the churn flow regime. The liquid does move upwards faster due to the surfactants, but it is transported through the slugs filling the pipe cross-section, and not through the film at the wall.

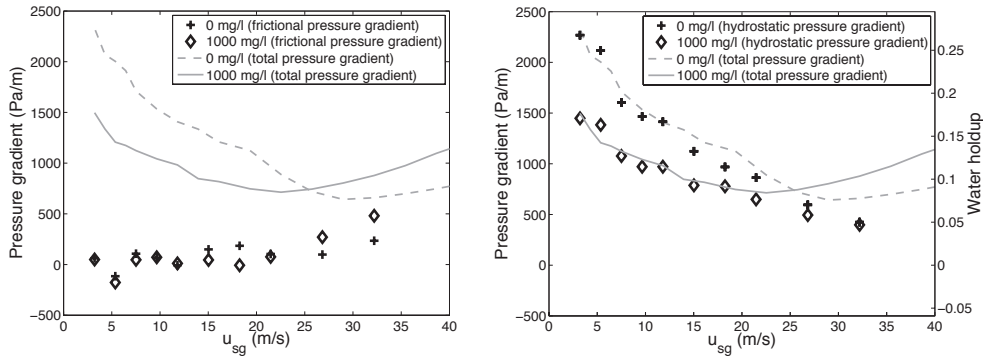


Figure 24: The frictional (left graph) and the hydrostatic (right graph) pressure gradient for flow at an inclination of 60 degrees, both without and with surfactants, for  $u_{sl} = 50$  mm/s, represented by symbols in the graphs. For comparison, the total average pressure gradient is shown, represented by the lines in the graphs. The water holdup indicates the fraction of the pipe filled with water after collapse of the foam.

In figure 25 we show the holdup of foam and free water before collapse of the foam, and the holdup of water after collapse of the foam for a surfactant concentration of 1000 mg/l, both for a vertical pipe and for a pipe at an inclination of 60 degrees from horizontal. From this data we can calculate the ratio between the holdup of free water and foam before collapse and the holdup of water after collapse. The ratio indicates the reduction of the density of the film at the wall, and, assuming all liquid is incorporated into the foam, this ratio is equivalent to the inverse of the water content of the foam. The ratio is shown in figure 26. For vertical flow, especially at the largest liquid flow rate, the ratio is independent of the gas flow rate. On average, the ratio decreases with increasing liquid flow rate, and therefore the density of the film at the wall increases with increasing liquid flow rate; the surfactant is most effective for lower liquid flow rates, when it is able to effectuate the largest reduction in the density of the film.

At an inclination of 60 degrees, the ratio between the holdup of free water and foam before collapse and the holdup of water after collapse decreases with increasing gas flow rate. However, it is usually lower than for vertical flow, and it is independent of the liquid flow rate. This indicates a larger liquid content of the foam for inclined flow, which explains the more liquid-like behaviour of the foam observed in the visualisation; a larger foam liquid content leads to a lower yield stress and to a lower viscosity of the foam. Because the reduction of the mass density of the foam compared to water is also smaller, all fluid properties are less affected by



the surfactant for inclined flow. The smaller reduction of the density of the film at the wall for inclined flow explains why the surfactants are less effective at lower inclinations. The reduced foam formation is possibly due to (i) the relatively regular morphology of the liquid film between the subsequent slugs and (ii) the relatively small interfacial surface area per unit volume of the thicker bottom liquid film.

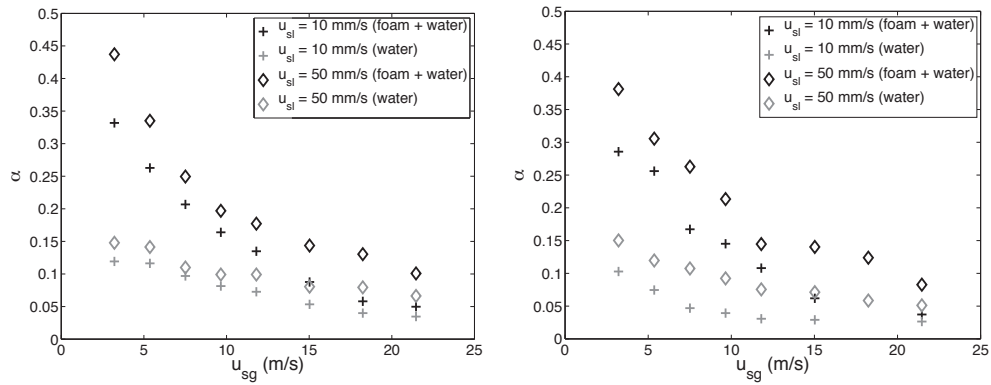


Figure 25: The combined holdup of foam and water before foam collapse (indicated as foam + water in the legend) and the water holdup after foam collapse (indicated as water in the legend) for two different liquid flow rates at a surfactant concentration of 1000 mg/l, for inclined flow (left graph) and for vertical flow (right graph).

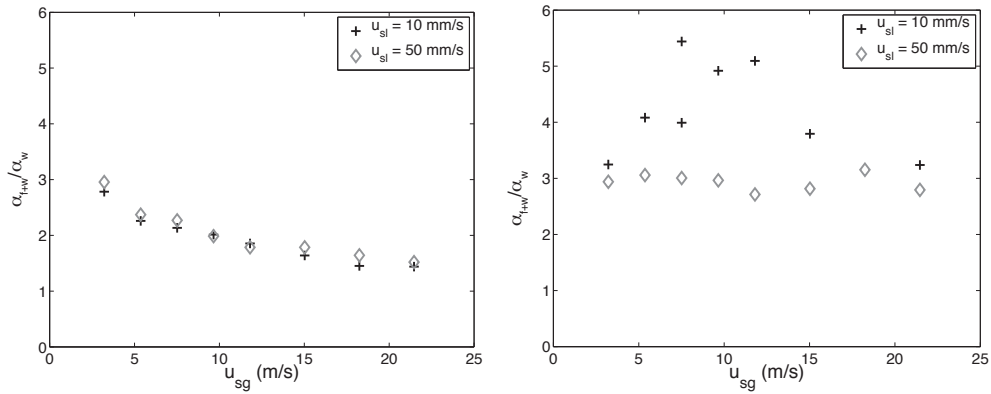


Figure 26: Graphs showing the ratio of the volume of foam and water before foam collapse ( $\alpha_{f+w}$ ) and the volume of water after foam collapse ( $\alpha_w$ ) for 60 degrees inclined flow (left graph) and for vertical flow (right graph) at a surfactant concentration of 1000 mg/l, at two liquid flow rates.

## 6. Conclusions

In gas wells, surfactants are frequently applied to increase the total production from the reservoir, by preventing liquid accumulation at the bottom of the well. These surfactants change the gas-liquid flow inside the well, thereby decreasing the minimum gas flow rate required to lift the liquids to the surface. At this minimum gas flow rate, the pressure gradient, as a function of gas flow rate, is minimum. However, the effect of the surfactant on the flow is not yet well understood. In previous research, we have investigated the influence of surfactants on air-water flow in vertical pipes (van Nimwegen et al., 2014a,b). In the current paper, we expand our work by including results from inclined upward pipe flow, at inclinations between 20 degrees (from the horizontal) and vertical.

The addition of surfactants to the air-water flow causes the water to foam. The foam has a lower mass density and a larger viscosity than water. At large gas flow rates, in the annular flow regime, the foam increases the volume of the liquid film and forms foam waves on the liquid film, thereby increasing the interfacial friction and the pressure gradient; this result is unaffected by the inclination.

At low gas flow rates, in vertical flow, particularly at lower liquid flow-rates, the surfactant makes the morphology of the liquid film more regular, by forming an almost static foam film at the wall. This leads to a decrease of the velocity of the transition between annular flow and churn flow, and to a significant decrease of both the average pressure gradient and the fluctuations of the pressure gradient. The surfactants are less effective at larger liquid flow rates, where the mass density of the foam is larger and the change in the properties of the liquid is smaller, leading to a smaller downward shift of the superficial gas velocity at the transition from annular flow to churn flow.

In inclined air-water flow, the liquid film at the bottom wall is thicker than at the top wall, leading to a much more irregular morphology of the bottom film compared to vertical flow. The surfactants are easily able to make the already relatively regular morphology of the film at the top wall completely regular, but are unable to form a stable foam film at the bottom wall, where the morphology of the bottom film thus remains irregular. The foam at the bottom wall has a much more liquid-like behaviour than in vertical flow. This is due to the larger liquid content of the foam in inclined flow, which leads to a smaller yield stress, and to a smaller effective viscosity above the yield stress. In this respect, the flow at the bottom wall for inclined flow is,

even at lower liquid flow rates, comparable to the flow in vertical pipes at large liquid flow rates. Increasing the liquid flow rate in vertical pipes increases the film thickness and decreasing the inclination from vertical leads to a thicker film at the bottom wall; it appears that surfactants are less effective at reducing the pressure gradient for thicker films.

Overall, surfactants increase the average pressure gradient at large gas flow rates and decrease the average pressure gradient at small gas flow rates. They are more effective in decreasing the average pressure gradient at larger inclinations and at lower liquid flow rates. Therefore, the surfactants shift the minimum in the pressure gradient more for larger inclinations and lower liquid flow rates. In actual gas wells, the shift of the minimum determines the additional production that can be obtained.

The surfactants always decrease the fluctuations of the pressure gradient by making the flow morphology more uniform, except at gas flow rates just above the transition from annular flow to irregular flow, where the fluctuations of the pressure gradient of the air-water flow are already so low that the foam cannot reduce them further.

The results of the current work are summarised in figure 27. This work has increased our understanding of the effect of surfactants on inclined air-water flow and is relevant for the prevention of liquid loading in inclined pipes. The results will be used as subsidies for the development of a model for gas-liquid flow with surfactants.

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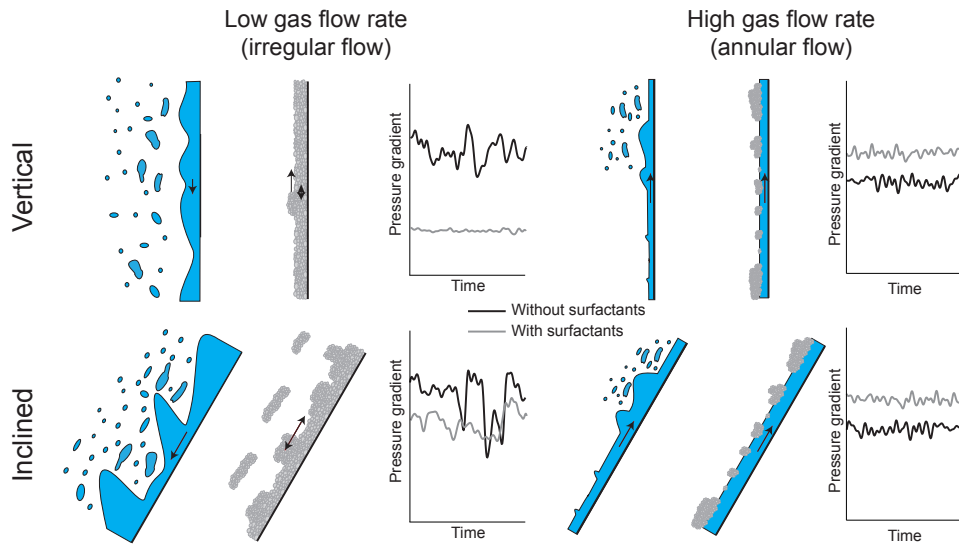


Figure 27: Schematic showing the results of the visualisation of the flow morphology and of measurements of the pressure gradient, for both vertical and inclined flow, at large and small gas flow rates. For each of these four flow conditions, on the left a sketch of the flow morphology of air-water flow without surfactants is presented, subsequently a sketch of the morphology of the flow with surfactants is given, and on the right, a qualitative graph of the pressure gradient is shown. In this graph, the black curve indicates the flow without surfactants, and the grey curve indicates the flow with surfactants. Four points are illustrated in the figure: (1) for annular flow at large gas flow rates the flow is independent of the inclination, (2) in annular flow the addition of surfactants leads to an increase of the pressure gradient, (3) for irregular air-water flow at low gas flow rates the film at the wall is thicker and the flow morphology is more irregular for inclined flow than for vertical flow, and (4) at low gas flow rates surfactants are more able to make the flow morphology regular and to decrease the pressure gradient for vertical flow than for inclined flow.

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