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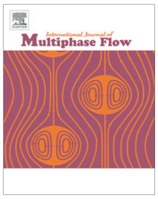

The effect of surfactants on air–water annular and churn flow in vertical pipes. Part 1: Morphology of the air–water interface

A.T. van Nimwegen [a], L.M. Portela [a,*], R.A.W.M. Henkes [b,c]

[a] *Department of Chemical Engineering, Delft University of Technology, Julianalaan 136, Delft, The Netherlands*
[b] *Department of Process & Energy, Delft University of Technology, Mekelweg 2, Delft, The Netherlands*
[c] *Shell Projects & Technology, Grasweg 6, Amsterdam, The Netherlands*

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ABSTRACT

In this work, the influence of surfactants on air–water flow was studied by performing experiments in a 12 metre long, 50 mm inner diameter, vertical pipe at ambient conditions. High-speed visualisation of the flow shows that the morphology of the air–water interface determines the formation of foam. The foam subsequently alters the flow morphology significantly. In annular flow, the foam suppresses the roll waves, and a foamy crest is formed on the ripple waves. In the churn flow regime, the flooding waves and the downwards motion of the liquid film are suppressed by the foam. The foam is transported in foam waves moving upwards superposed on an almost stagnant foam substrate at the pipe wall. Foam thus effectively reduces the superficial gas velocity at which the transition from annular to churn flow occurs. These experiments make more clear how surfactants can postpone liquid loading in vertical pipes, such as in gas wells.

1. Introduction

Surfactants are molecules with a hydrophilic head group and a hydrophobic tail and are used in a wide range of applications. For example, surfactants are used to create emulsions, as wetting agents, and to create foam (see e.g. Farn, 2006). This latter function is of particular interest to the gas industry, as it is known from experience that it allows for a longer, stable production from a gas well.

In gas wells, both gas and liquid (water and/or gas condensate) are produced. This leads to a multiphase flow inside the well tubing that connects the reservoir with the surface. At the preferred operating conditions, at high gas velocities, the gas is able to drag along the liquid to the surface and the flow pattern in the well is annular dispersed. As the reservoir pressure declines, the gas flow rate decreases until the gas is no longer able to bring the liquid to the surface. Consequently, the liquid will start to accumulate at the bottom of the well. The additional liquid creates a hydrostatic pressure on the gas reservoir, severely limiting, or even prohibiting, gas production. This is called *liquid loading* and it is closely related to the changes of the flow pattern inside the gas well (see e.g. Lea et al., 2003).

From field experience in the gas industry, it is known that the injection of surfactants at the bottom of the well postpones liquid loading, allowing additional gas production over some additional years (Lea et al., 2003), before closure of the well. However, the knowledge and understanding of the effect of surfactants on the gas–liquid pipe-flow is still poor.

There exists a long history of observation and visualisation of two-phase flow in pipes. For instance, visualisation was used to classify flow patterns for vertical flow, as summarised by Taitel et al. (1980). The goal of this work is to gain qualitative understanding of the influence of surfactants on upward air–water flow in a vertical pipe at ambient conditions using flow visualisation. More specifically, images from a high speed camera were used to characterise the changes in flow pattern morphology due to surfactants.

In the remainder of the paper, first the flow patterns in air–water flow are discussed in more detail. Next, a section is devoted to the behaviour of surfactants in aqueous solutions and the foam that is created from these solutions; previous work relevant for the current research is presented. After the description of the experimental setup, the results of flow visualisation are discussed, showing the changes in flow pattern due to surfactants.

2. Flow patterns in upward vertical air–water flow

Depending on the superficial liquid velocity, u_{sl}, and on the superficial gas velocity, u_{sg}, different flow patterns occur in vertical

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* Corresponding author. Tel.: +31 152782842.
E-mail addresses: a.t.vannimwegen@tudelft.nl (A.T. van Nimwegen), l.portela@tudelft.nl (L.M. Portela), r.a.w.m.henkes@tudelft.nl (R.A.W.M. Henkes).

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pipes. On the left of Fig. 1, the flow pattern map for air–water flow in a 5 cm inner diameter vertical pipe at ambient conditions is shown, based on the work by Taitel et al. (1980). In the present work, superficial gas velocities between 6.4 m/s and 45 m/s are considered, while the superficial liquid velocity is varied between 2 mm/s and 40 mm/s. This operational region is indicated by the rectangle in Fig. 1 and corresponds to the annular and churn flow regimes, which are shown in schematic drawings on the left of Fig. 1.

At high gas velocities, co-current annular flow is obtained. In this flow pattern, the liquid is contained in a thin film at the wall and in droplets entrained in the gas core, and both the liquid film and the droplets continuously move upwards. On the interface between the liquid film and the gas core three types of waves can be distinguished: ripple waves, roll waves and ephemeral waves. Ripple waves are capillary waves, with a small amplitude compared to the wavelength (Asali and Hanratty, 1993). Roll waves are much larger and stretch along the entire pipe circumference, remaining coherent while travelling large distances in the axial direction (Belt et al., 2010). Roll waves occur only above a certain critical u_{sl}. At even larger superficial liquid velocities, ephemeral waves are present. These are still much larger than the ripple waves, but do not span the entire pipe circumference (Wolf et al., 1996).

When the superficial gas velocity is reduced in the annular flow regime, the roll waves grow in size, causing the formation of large ligaments. At even lower u_{sg}, the interfacial friction is no longer sufficient to move the liquid upward continuously. This onset of flow reversal of the film marks the transition from co-current annular flow to churn flow. In our setup, this transition occurs at $u_{sg} \approx 15$ m/s. At velocities just below this transition, the flow is also known as churn-annular flow, as most of the liquid is still contained in the film at the pipe wall. Especially at lower superficial gas velocities, the churn flow regime is characterised by flooding waves. These large aerated waves are responsible for the upward liquid transport in churn flow and cause large entrainment. Between these large waves a liquid film is present at the wall, moving upwards closely behind the flooding wave, next reversing, and eventually entraining in the next flooding wave (Hewitt and Jayanti, 1993).

There exist several correlations in the literature predicting the transition between co-current annular flow and churn flow for vertical pipes. For small pipes ($D \leqslant 0.05$ m for water and air at ambient conditions), these correlations are based on the Froude number:

$$\mathrm{Fr} = \frac{\rho_g^{1/2} u_{sg}}{\left(gD\left(\rho_l - \rho_g\right)\right)^{1/2}} \quad (1)$$

where ρ_g and ρ_l are the gas and liquid densities, u_{sg} is the superficial gas velocity, D is the pipe diameter and g is the gravitational acceleration. Film reversal occurs when $\mathrm{Fr} \approx 1$ (Wallis, 1969). In pipes with a larger diameter ($D \geqslant 0.15$ m), the Kutateladze number can be used to determine the onset of film reversal.

$$\mathrm{Ku} = \frac{\rho_g^{1/2} u_{sg}}{\left(g\sigma\left(\rho_l - \rho_g\right)\right)^{1/4}} \quad (2)$$

In this equation σ is the static surface tension. The onset of film reversal is predicted at $\mathrm{Ku} \approx 3.2$. Richter created a correlation merging these two expressions (Richter, 1981).

The Turner criterion (Turner et al., 1969), with or without small modifications (Veeken et al., 2010), is often used in the gas industry and predicts liquid loading by calculating the velocity at which the largest droplets in the flow start to move downwards. It is remarkable that this criterion is equivalent to the Kutatelatze criterion, based on analysis of the liquid film. However, the Turner criterion does over-predict the size of the largest droplets in the gas core significantly (van 't Westende et al., 2007). Recent results obtained by Khosla (2012), however, show that large droplets, such as predicted by the Turner criterion, exist close to the air–water interface. These results indicate that the interplay between (i) the morphology and the dynamics of the liquid film interface and (ii) the entrainment and deposition of droplets close to the interface are key to predicting the transition from annular flow to churn flow. In the next section, the effect of surfactants on air–water flow, and how this relates to the correlations given above, will be discussed.

3. Surfactant solutions and foaming

3.1. Surfactant solution

Introducing surfactants to the air–water flow has three effects. First, the static surface tension between air and water is decreased, usually by a factor 2–3 (de Gennes et al., 2004). Note, however, that the two correlations (Eqs. (1) and (2)) for the transition between

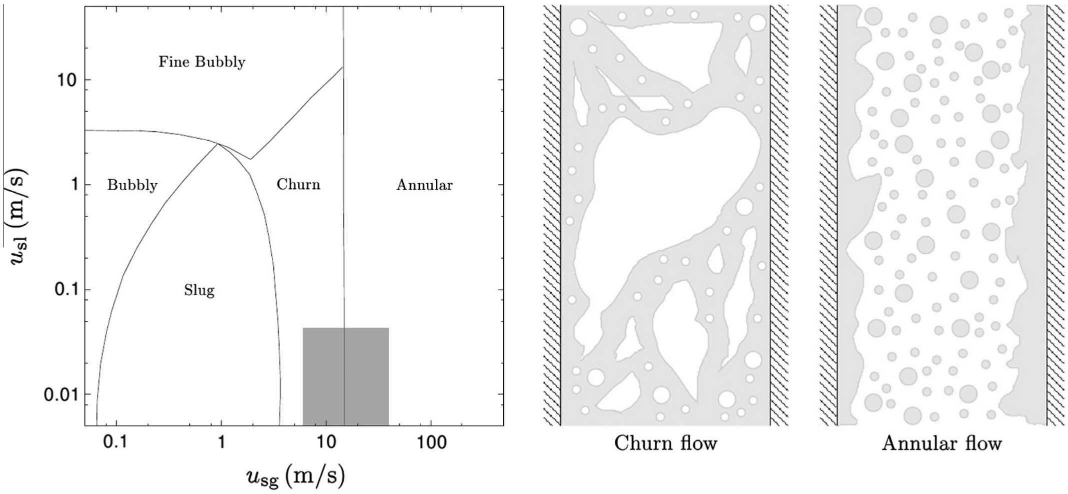

Fig. 1. Flow pattern map for air–water flow in a 5 cm inner diameter pipe at atmospheric pressure (left), where the grey rectangle indicates the range of gas and liquid superficial velocities considered in this work. On the right, schematic drawings of the flow patterns in air–water flow within the operating range are given (van 't Westende, 2007).

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