Counter-current gas-liquid flow in vertical narrow channels. Film characteristics and flooding phenomena

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Abstract: Flooding experiments have been carried out in a vertical rectangular channel with 10 mm gap between its parallel plates, using smooth inlet and outlet conditions, with air and two liquids (i.e. water and water/butanol solution). The critical gas velocity, $U_G$, at the onset of flooding tends to decrease with increasing liquid feed rate, as expected. There is a $Re_L$ range (~150-250), for both liquids, where the critical velocity is weakly dependent on the liquid Reynolds number, and the incipient flooding mechanism involves wave growth and instability including breakage of wave crests. At $Re_L>250$ a stronger dependence of $U_G$ on $Re_L$ is observed, attributed to a different flooding mechanism, i.e. "bridging" of growing waves due to the relatively narrow gap. Concerning fluid properties, differences are observed (compared to water) in the flooding velocities with the lower interfacial tension butanol solution. Experimental data on liquid film characteristics with counter-current gas flow have also been obtained to facilitate data interpretation. Film thickness power spectra provide evidence that by increasing air flow the wave structure is significantly affected; e.g. the dominant wave frequency is drastically reduced.

Keywords: Gas-liquid flow, counter-current, narrow vertical channel, flooding, film characteristics.

Introduction

In counter-current gas-liquid flow, the onset of flooding is identified by the critical gas rate at which partial liquid flow reversal is observed. The phenomenon of flooding is of considerable technological importance being a limiting factor in the operation of various types of two-phase equipment including the common reflux condensers. The purpose of this work is to study flooding in a vertical uniform rectangular channel with relatively small gap. Such a channel is considered to simulate in a simplified manner, a single flow “element” of a compact condenser.

The amount of work on counter-current flow in vertical rectangular channels is limited, particularly for a narrow gap between the plates (Bankoff et al., 1986). Biage (1989) conducted flooding tests in a vertical channel with porous liquid inlet and outlet sections and a relative large channel gap (25mm). Osakabe & Kawasaki (1989) carried out “top flooding” experiments in thin rectangular passages (i.e. 10x100, 5x100 and 2x100mm) motivated by problems in the nuclear industry. Larson et al. (1994) reported experiments with similar liquid feeding conditions, in very narrow rectangular channels of 1.1 and 2.2mm gap. Zapke & Kroeger (2000) studied the effect on flooding of the duct geometry (with duct height and width 50 to 150mm and 10 to 20mm, respectively) and of fluid properties, using water, methanol, propanol and several gas phases. They concluded that the flooding gas velocity, $U_G$, is strongly dependent on the duct height, the phase densities and duct inclination; furthermore $U_G$ tends to decrease with increasing liquid viscosity, which seems to have a stronger effect than the surface tension. Vlachos et al. (2001) reported flooding data obtained in a vertical rectangular channel with 5 and 10mm gap between its main flat parallel plates.

Experimental set-up and procedure

An experimental facility was specifically built to study counter-current gas-liquid flow and flooding (Figure 1). Two-phase flow is developed in a 70cm high and 12cm wide rectangular channel made of Plexiglas. The spacing between the two parallel plates is 10mm. The air entrance section is constructed with special care to achieve well-developed conditions before air contacts the falling liquid film. Liquid phase is introduced at the top and removed from the bottom via porous sections (covering the entire active channel width), embedded flash with the main flat surfaces. The length of the test section, measured between the bottom edge of the inlet porous wall and the top edge of the outlet porous section, is 38cm. A small amount of gas flows out together with the liquid film, removed in the lower porous wall section, which is measured by a rotame-
Table 1. Properties of liquids used in the experiments.

<table>
<thead>
<tr>
<th></th>
<th>Water</th>
<th>2.5% Butanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu), kg m(^{-1}) s(^{-1})</td>
<td>0.00102</td>
<td>0.00098</td>
</tr>
<tr>
<td>(\rho), kg m(^{-3})</td>
<td>1000</td>
<td>992</td>
</tr>
<tr>
<td>(\sigma), kg s(^{-2})</td>
<td>0.075</td>
<td>0.040</td>
</tr>
<tr>
<td>Contact Angle, deg</td>
<td>50 (25)*</td>
<td>30 (10)*</td>
</tr>
</tbody>
</table>

*on treated surface

channel with the gas flowing at a relatively low rate. Then, the required liquid flow rate was fixed and the liquid flowed steadily down to the outlet porous wall section where it exited the channel. Next, the gas flow rate was progressively increased stepwise until the onset of flooding. The latter is defined as the condition where at least part of the liquid flow is reversed in direction and carried above the liquid entrance section. Visual studies were made using a Redlake MotionScope PCI® high-speed camera, either slightly above the liquid exit or below the liquid entrance section. Film thickness was also measured, using the “parallel-wire conductance” technique, in order to determine the liquid film characteristics.

Results

Visual Observations - Critical Flooding Velocities

From visual observations and high-speed camera recordings, the following liquid mechanisms are identified at the onset of flooding. At low \(Re_L\) (<250), the mechanism involves roughly 2-D “isolated” waves, covering part of the liquid film surface in the lateral direction, that tend to grow and be swept up the channel due to drag and pressure forces exerted by the gas flow. Furthermore, liquid droplets torn off the surface waves are entrained by the gas upflow. At higher \(Re_L\) (>250) some waves on the liquid film surface tend to become unstable with their amplitude rapidly increasing till they partially block the gap (“local bridging”). The liquid of these waves is then forced by the gas to move upwards.

The observed critical flooding velocities \(U_{CG}\) for the two different liquids used are plotted in Figure 2. Here \(Re_L\) is defined as \(4\Gamma_L/\mu_L\), where \(\Gamma_L\) is the liquid mass flow rate per unit length of channel circumference and \(\mu_L\) is the liquid viscosity. The data show that at relatively low liquid flow rates, there is a significant decrease of the critical air velocity, \(U_{CG}\), with \(Re_L\). By further increasing the liquid flow rate in the range \(Re_L \sim 150-250\) the flooding velocity appears to be weakly dependent on the liquid Reynolds number. This behavior may be attributed to the structure of the free falling liquid film under the action of gravity. The different mechanism (“bridging”) observed for incipient flooding at high \(Re_L\) seems to be reflected in the changing slope of the data at \(Re_L \sim 250\). The rather strong influence of the fluid properties on critical flooding velocity is evident in Figure 2. With the butanol solution flooding occurs at lower air velocities compared to water, mainly because of its lower surface tension.

As is well-known, at small \(Re_L\) numbers the liquid film is very thin and laminar. The pictures in Figure 3 is an example of liquid film development at \(Re_L=109\) (near the liquid entrance) for butanol solution, at small to rather high gas flow rates \((Q_G=2.58-10.31\text{ l/s})\), but still below critical conditions. The film appears to be initially smooth and undis-
Downstream nearly two-dimensional disturbances develop first, evolving into a three-dimensional, small-amplitude wave structure. These waves are characterized by (somewhat faster moving) pebble-like wave fronts, clearly identified in the picture. This behavior is very similar to that previously observed in free falling films in this Laboratory (Vlachos et al., 2001) and elsewhere (e.g. Pearson et al., 1977, Chang et al., 1994). By increasing the gas flow rate, the wave disturbance on the film surface moves upstream covering the entire plate surface up to the liquid entry.

Film Thickness Characteristics

Water and a water/butanol solution (2.5%) were also used for measurements of film characteristics near the bottom of the channel (36cm from liquid entrance), as incipient flooding was mainly observed close to the liquid exit. Experiments were conducted without and with counter-current air flow. In Figure 4 the mean film thickness for the butanol solution case, during counter-current flow is plotted as a dimensionless film thickness ratio, by dividing with the mean thickness for falling film (without air). It is evident that increasing gas rate results in increasing mean thickness as flooding is approached. This increase is rather small at low U_G, but as the gas rate approaches the critical value for flooding, the mean thickness increases sharply. This trend was also observed by Zabaras (1985). Another feature of the liquid film worth examining is the value of the maximum film thickness at incipient flooding. This value is estimated as the average of the ten largest values of film thickness observed in a 80sec (with a sampling rate of 125Hz) recording which corresponds to flooding and it can be seen for various Re_L, as an insert in Figure 4. It is important to note that the maximum film thickness for Re_L<250 is significantly lower compared to the length of the wire probe employed (~2.7mm), whereas for Re_L>250 it is very close to this length. Therefore, the true mean film thickness at flooding point for Re_L>250, may be larger than one can measure with the present probes.

The sharp increase of the RMS values of film thickness at flooding, shown in Figure 5 provides additional evidence of the change of the wave structure. Comparing Figures 4 and 5, it appears that by increasing the gas rate above critical conditions, the mean and RMS values tend to decrease due
to the decreasing downflow rate at the location of the channel were characteristics of liquid film are examined (bottom edge).

Typical power spectral density (PSD) of the liquid film thickness fluctuations at the bottom edge of the channel are presented in Figures 6 and 7, for the case of the butanol solution and for two different values of Reynolds number. A very pronounced maximum, at frequencies between 7 and 10Hz is observed for the free falling film, for both Reynolds numbers and it can be related to the periodic passage of the waves covering the liquid surface. This dominant frequency tends to increase with increasing ReL, as expected. It is interesting that for both liquids there is a region of ReL (150-250), where critical flooding velocity is weakly dependent on liquid flow rate. Concerning fluid properties, significant differences are observed (compared to water) in the flooding velocities with the lower interfacial tension butanol solution.

Under conditions approaching flooding, drastic changes seem to occur in liquid film flow. Interpretation of instantaneous film thickness measurements shows that a sharp increase of the mean film thickness and of RMS values take place near the onset of flooding; furthermore, a significant reduction of the dominant wave frequency is observed.

Concluding Remarks

The observations suggest that the dominant mechanism of flooding at the smaller values of Reynolds numbers examined, involves growth and flow reversal of nearly 2-D isolated waves covering part of the liquid film surface in the lateral direction, with liquid droplets torn off the wave surfaces entrained by the gas. At higher ReL (>250), local bridging of surface waves is the dominant mechanism. The gap size appears to influence the characteristic ReL at which “bridging” occurs first.

The critical gas velocities at the onset of flooding in general tend to decrease with increasing liquid rate, as expected. It is interesting that for both liquids there is a region of ReL (150-250), where critical flooding velocity is weakly dependent on liquid flow rate. Concerning fluid properties, significant differences are observed (compared to water) in the flooding velocities with the lower interfacial tension butanol solution.

References


