AIChE WILEY InterScience DISCOVER SOMETHING GREAT

Effect of Gas Density on Countercurrent Flow Limitation in Wetted Wall Column

J. R. F. G. Carvalho and J. M. C. P. Costa
Departamento de Engenharia Química, Faculdade de Engenharia da Universidade do Porto, 4200-465 Porto, Portugal

DOI 10.1002/aic.10981
Published online September 5, 2006 in Wiley InterScience (www.interscience.wiley.com).

Countercurrent wetted wall flow limitation was studied in a 20.6 mm i.d. cylindrical column, with water as the liquid. The gas was either air at up to 0.8 MPa, or argon at up to 1.3 MPa, thus covering a range of gas densities (1.6–21.3 kg/m^3) of great practical interest for which very few data are available. The film Reynolds number varied in the range 515–3090. The velocity of gas for which signs of flooding instability first became apparent was typically 5 to 25% below the velocity at which liquid carryover started and this may be a result of the particular design adopted for fluid inlet to and outlet from the test section. Over the range of gas densities tested, the limiting gas velocity decreased with pressure from between 2.5 and 5.0 m/s to between 0.4 and 0.8 m/s, very approximately following the law: (gas density) $\times$ (limiting gas velocity)^2 = constant. The data collected were used to test the correlation of Wallis, which gave remarkably good prediction of the limiting gas velocities, and a correlation of Alekseev and coworkers modified by McQuillan and Whalley in 1985, which gave poor predictions, particularly with regard to the effect of changes in liquid flow rate. The results of the present work are shown to be useful in interpreting recent data on the effect of gas density on the slug/churn flow transition in cocurrent vertical gas–liquid flow. *AIChE J*, 52: 3375–3382, 2006
Keywords: flooding, wetted wall, flow limitation, high pressure, two phase flow

Introduction

Countercurrent wetted wall flow in vertical columns (or tubes) is found in a wide variety of equipment in the power and process industries, such as in falling film chemical reactors, vertical tube condensers, and film separators.

For any given rate of film flow down the wall of a tube, there is a limiting gas flow rate above which orderly film flow is disrupted; the upflowing gas starts to interact strongly with the descending liquid; large waves grow occasionally on the interface and move up along the column, eventually bridging across the gas core or/and tearing in small drops. This occurrence is generally described as flooding[1] or countercurrent flow limitation,[2] and it is important to study the parameters that govern it. Much effort has been devoted to improving the understanding of flooding in tubes and narrow channels, in connection with the performance of nuclear reactor safety systems, given that flooding may limit the penetration of emergency coolant into a hot reactor core during a loss of coolant accident.[3] Flooding is also an important issue in other applications, however, where countercurrent flow of gas and liquid take place through very different geometries, such as in packed towers or plate columns.[4]

In a typical experiment on flooding in a vertical tube, liquid is supplied at a steady flow rate to the inner wall of the tube, uniformly around the perimeter of some upper section, and allowed to fall, initially with little or no gas counter flow. The upflow of gas is then gradually increased, until the flooding point is reached. Some authors[5,6] take the flooding point to correspond to the inception of strong disturbances in the flowing liquid film, usually accompanied by a sudden increase in the pressure gradient along the column; other authors[7,8] take it to coincide with the beginning of liquid carryover above the

This article is dedicated to Prof. John F. Davidson, F.R.S., on the occasion of his 80th birthday.

Correspondence concerning this article should be addressed to J. Carvalho at jrguedes@fe.up.pt.

liquid feed point. With certain experimental arrangements, the difference between the two criteria may be of no practical consequence because according to Dukler and coworkers,[8] who studied flooding in a 51 mm inner diameter (i.d.) column, the gas velocity above which there is liquid carryover coincides quite precisely with that for which there is a steep increase in pressure gradient along the column. In the experiments described in the present work the two criteria will be seen to lead to somewhat different values of flooding velocity, possibly as a result of the particular design adopted for removing gas from the test section and admitting liquid to it.

Over the years, a considerable body of data has been collected on flooding in vertical columns, the vast majority being for air–water at near ambient conditions.[9] The data are frequently reported in plots of U_{flooding} vs. Re, where U_{flooding} represents the superficial velocity of the gas at the flooding point and Re is the Reynolds number (defined below) for the film of liquid flowing down the column wall. Studies have been performed on the dependency of flooding velocity on column diameter, length of the test section, and detailed design of gas and liquid entrance to and exit from the test column.[10] A significant number of studies have been reported on the effect of liquid properties on flooding. Clift et al.[11] were early to study the dependency of flooding velocity on liquid viscosity and various other groups[5,6] considered also the effect of surface tension.

Very few studies have been published on the effect of gas density on flooding. In one extensive review[9] of experimental data on flooding, published in 1985, one reference[12] is to be found to work at high pressure, that is, at up to 7.0 MPa, with steam–water, in tubes with diameters of 74 and 95 mm. The velocity of steam required for no water penetration in the tubes, from the upper water tank, was found to decrease from near 2.6 to about 1.6 m/s, as the operating pressure increased from 3.0 to 7.0 MPa. In 1992 a study was published[13] of flooding in countercurrent flow of saturated liquid and vapor CCl_2F_2 in rectangular channels, at 0.67, 1.0, and 1.3 MPa; these three pressures resulted from operating the system at temperatures of 26, 41.5, and 52.5°C. It was found that flooding velocities decrease dramatically with the increase in pressure, at each of the liquid flow rates tested, and a flooding velocity of only 0.7 m/s was measured for the highest operating pressure. More recently,[14] in a study on the effect of gas density (and viscosity) on flooding, air, argon, helium, and hydrogen were used, in counter flow with water and other liquids, in a 30 mm i.d. column, operated at atmospheric pressure. It was concluded that flooding velocity did not depend on gas viscosity and was inversely proportional to the square root of gas density.

In the present work we undertook to study the effect of gas density on flooding in a systematic way, keeping all other variables unchanged. The range of variables selected was largely determined by the need to obtain data that might be compared with the results of a recent study[15] on the slug/churn flow transition, in gas–liquid upflow in vertical tubes.

Experimental

Measurements of flooding velocity were made in a 20.6 mm i.d. transparent acrylic tube with a 5 mm thick wall, rated to withstand a pressure of 5.0 MPa (with a safety factor of 6). The total length of the tube was 2.46 m, but the length of the test section, between gas entrance and exit nozzles, was 1.77 m, as indicated in the diagram of the experimental setup in Figure 1. Details of the column inlet and outlet sections are given in Figure 2. The inlet nozzle for the gas was 10.0 mm i.d. and 12.0 mm outer diameter (o.d.) and the exit nozzle was 8.0 mm i.d. and 10.0 mm o.d.; the axes of both nozzles were carefully aligned with that of the acrylic tube, so that the film of water could flow unhindered, past the nozzles. The design adopted is different from any of the 12 configurations reviewed by Bankoff and Lee,[16] in that it provides for gas injection and gas extraction near the axis of the test column, through only a reduced fraction of the cross section. The gas enters the column as a jet that spreads out to reach the downflowing film of liquid and it leaves the test section through the "mouth" of the upper nozzle, which will also be the outlet port for any liquid that is entrained by the gas. Part of the curiosity of the present work was to see whether this results in significantly different values of the limiting gas velocities.

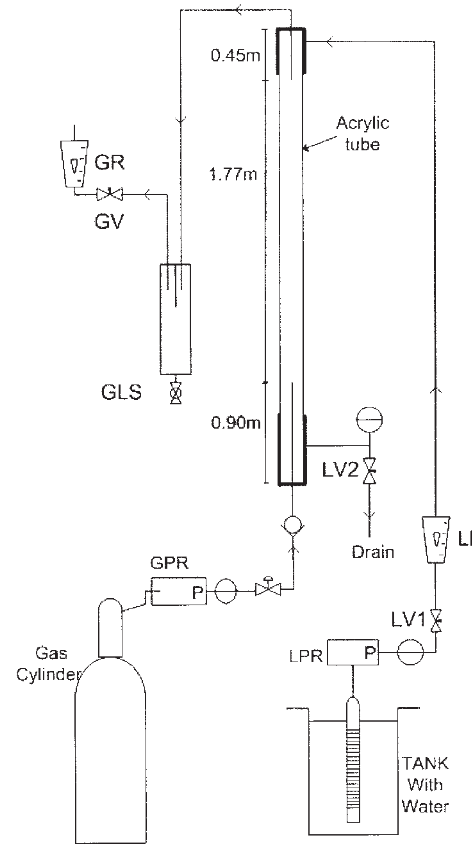

Figure 1. Experimental setup (not to scale).

The gas used in the experiments was either air from an oil-free compressor (delivered at up to 0.85 MPa) or argon from a pressurized cylinder (at 20 MPa, when full). A pressure regulator (GPR) was used to set the gas pressure at the value intended in the test column and the gas flow rate was adjusted by means of a flow control valve (GV); the gas flow rate was measured in a calibrated flow meter (GR) open to the atmosphere, at the end of the line (the flow meter used was either a rotameter or an orifice meter, depending on the range of flow rates being measured). In the experiments with argon, the gas

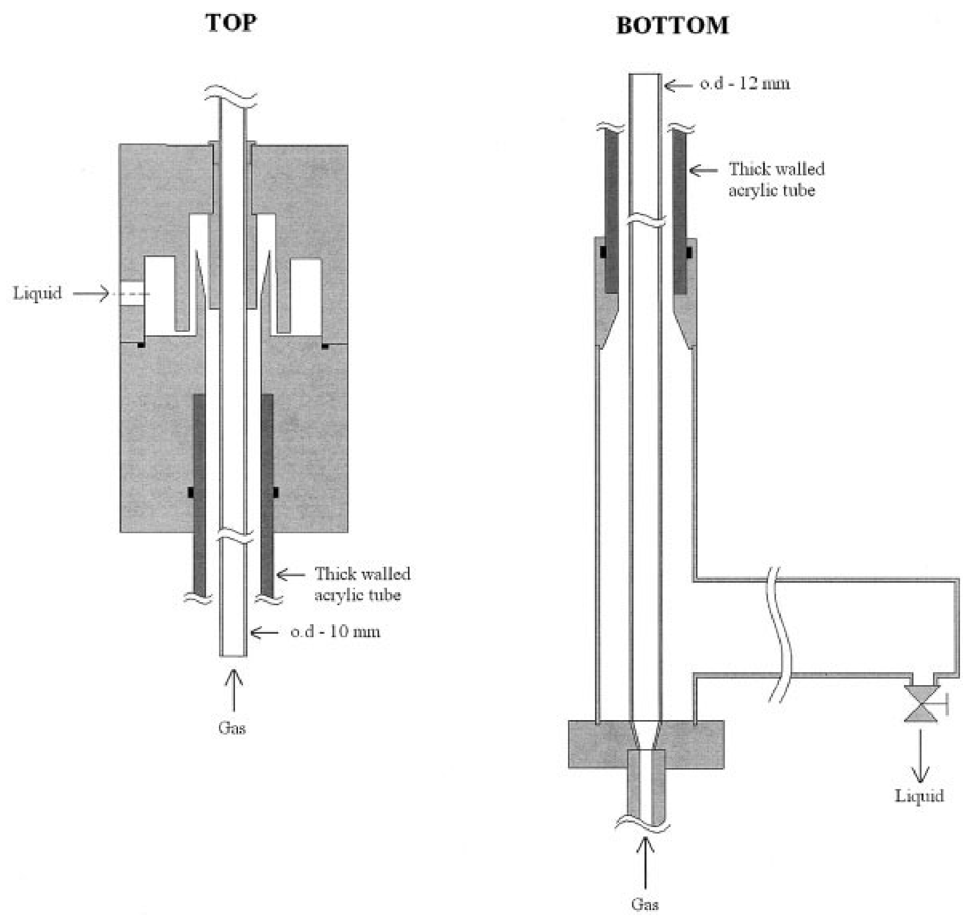

Figure 2. Details of top and bottom sections of test column.

was forced along a 10 m copper coil submerged in stirred water at near ambient temperature, so as to warm it back up, after it had cooled significantly as a result of the considerable expansion at the pressure regulator.

The water fed to the test column was stored in a tank where a submersible multistage centrifugal pump was installed. The water delivered by the pump went through a pressure regulator (LPR) to set its pressure some 0.4 to 0.5 MPa above the value in the test column, whereas the flow rate was adjusted by means of a valve (LV1) that led to a rotameter (LR).

In continuous operation, during an experimental run, the liquid accumulated by gravity at the bottom of the test column, from where it was directed to the drains, through flow control valve LV2. This valve had to be "continually" adjusted, to always keep the level of the free surface of the liquid (collected at the bottom of the column), some 0.15–0.25 m below the "mouth" of the gas injection nozzle; in this way, a "liquid seal" was created that prevented the gas from exiting the column at the bottom.

Each run started with valves LV1 and LV2 fully closed and valve GV only slightly open, to allow a little gas flow through the column, while the operating pressure was being set, through manipulation of GPR. Valve LV1 was then gradually opened, until the required flow rate of water (measured in LR) was reached; shortly afterward, the water that flowed along the column wall started to accumulate at the bottom of the test column and valve LV2 was opened, to set the level of the free surface at the required distance below the mouth of the gas inlet nozzle. Valve GV was then opened gradually, to increase the gas flow rate, until the first signs of flooding instability started to show. The most obvious sign was the formation of "coherent" horizontal ripples, each one spanning all around the perimeter of the column, as if it were a horizontal "ring of water" that moved down fairly quickly for some distance, before disappearing again. These "rings" seemed to form at random, at a considerable distance above the gas injection nozzle (up to some 0.5 to 0.8 m) and they appear to correspond to waves of comparatively large amplitude. These same waves disappeared spontaneously in the lower 0.10–0.30 m of the test section, above the gas injection nozzle, probably because the force exerted by the gas on the liquid decreases significantly below that level. Fears that the jet of gas entering the test section might originate some localized disruption of film flow were soon dissipated by visual observation.

We denote by U_{fl} the superficial velocity of gas for which this "flooding instability" was first detected, for each flow rate of liquid. As the flow rate of gas was gradually increased, these "ring-like" waves of liquid started to form at a gradually greater distance from the injection nozzle and to move down slower; and it did not take a very significant increase in gas flow rate before many of them slowed to a near (dynamic) rest, to subsequently move up the test column, swiftly, for some distance, before either vanishing or reaching the gas exit nozzle.

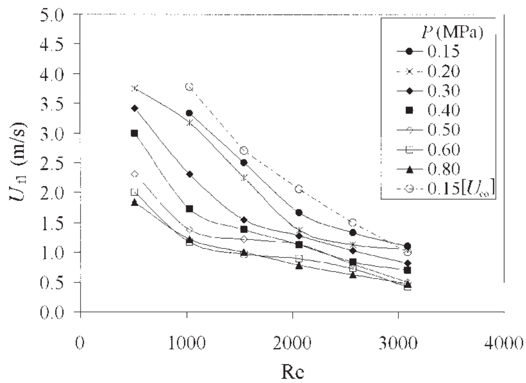

Figure 3. Values of U_{fl} (and one set of values of U_{co}) for air–water.

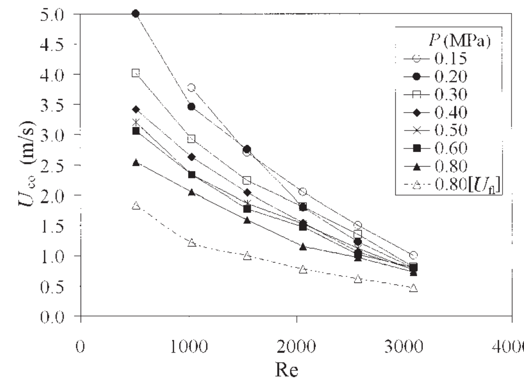

Figure 4. Values of U_{co} (and one set of values of U_{fl}) for air–water.

A reasonable explanation is that this happened when the waves in the film grew and bridge across the gas core, to form some kind of "water membranes," which "locked" the gas beneath them; this would lead to their being propelled up the column, by the gas, before either rupturing or being pushed into the mouth of the outlet nozzle. When this happened, liquid carryover into the transparent gas–liquid separator (GLS) started and we denote by U_{co} the corresponding superficial gas velocity. With the two or three lower flow rates of liquid used in the experiments (see below) it was easy to maintain the test column in a condition of flooding instability, with no carryover, for a long time. For any gas density, the values of U_{fl} and U_{co} became closer as the flow rate of water was increased. A "blind" repetition of several runs showed that the values of U_{co} are reproducible, typically within $\pm 5\%$, whereas repeated values of U_{fl} may vary within $\pm 15\%$; this lower reproducibility is not surprising considering that the detection of the first signs of flooding instability is somewhat dependent on the observer and on lighting (partly, natural).

Experiments were performed with air at 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.8 MPa and with argon at 0.3, 0.4, 0.6, 0.7, 0.9, 1.1, and 1.3 MPa, thus covering a significant range of gas densities (1.6–21.3 kg/m^3). Six values of water flow rate (Q) were used, corresponding to values of the Reynolds number ($\mathrm{Re} = 4Q/\pi D \nu$) of 515, 1030, 1545, 2060, 2575, and 3090, where D is the inside diameter of the test column and ν is the kinematic viscosity of water at the operating temperature (taken to be 20°C in all runs). For reasons of economy, not all the values of Re indicated above were covered in the experiments with argon; each gas cylinder lasted only a few runs and the data reported below were considered to be sufficient.

Results and Discussion

Altogether, nearly 100 new data points were obtained, not counting those obtained in runs repeated at random, to test for reproducibility. Series of measurements were made for each pressure, covering the intended range of liquid flow rates. The values of U_{fl} and U_{co} shown in Figures 3 and 4 correspond to actual values in individual series with air–water, and not to average values from separate (repeated) series. In this way the reader gets a feel for the magnitude of the (random) inaccuracy of individual measurements—the trend lines for different pressures would not cross (and they would be even smoother) if average values had been taken.

It will be seen that, overall, at any given pressure, both U_{fl} and U_{co} decrease with an increase in Re and at any given Re, both U_{fl} and U_{co} decrease with an increase in pressure, in agreement with earlier findings.[13,14] The higher reproducibility of the U_{co} values results in correspondingly smoother trend lines in the plot of Figure 4, as might be expected (the series of points at 0.20 MPa is the exception and it could have been easily "smoothed out" by representing average point values from repeated measurements). The points for $P = 0.8$ MPa in Figure 3 were also plotted in Figure 4 and those for 0.15 MPa in Figure 4 were also plotted in Figure 3, to help compare the relative magnitudes of U_{fl} and U_{co}; the former are typically between 35 and 0% below the latter (going from low to high Re) and this is not much considering the particular design of the gas outlet.

In the case of argon, only the values of U_{co} are shown in Figure 5 because few measurements were made of U_{fl}, only those needed to confirm that the overall trend was the same as for air. The values of U_{co} obtained with air at 0.40 and 0.80 MPa are also plotted in Figure 5 because the corresponding densities (of air) are virtually the same as those of argon at 0.30 and 0.60 MPa, respectively. It may be seen that, within experimental scatter, the trend lines for argon and air are nearly coincident when the densities of both gases are the same; the particular nature of the gas is of no relevance, as expected.

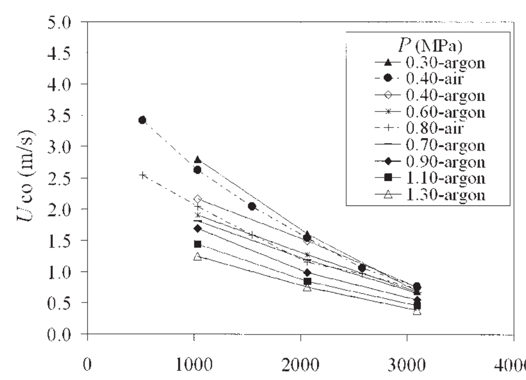

Figure 5. Values of U_{co} for argon–water and comparison with air–water.

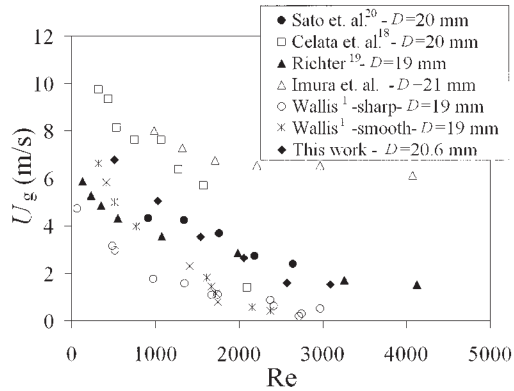

Figure 6. Comparison of data on flooding from different authors.

In the past, several authors studied flooding in countercurrent flow of air and water in columns with a diameter close to that used in the present work. It may be interesting to compare our data with theirs, especially considering that in the present work, the design of the gas inlet to and outlet from the test section is somewhat unconventional. In the comparison it is important to keep in mind that the data previously available are for atmospheric pressure, whereas the rig used in the present work could be operated down to only 0.15 MPa, the lowest pressure that would still drive the liquid out of the column, at the required flow rate; we therefore had to extrapolate the data obtained in the present work down to 0.10 MPa, to plot it in Figure 6. It is encouraging to see that our data are in excellent agreement with those reported by two other authors[19,20] and that they do not deviate significantly from what would be the line representing the average flooding velocities, for all data in Figure 6.

The data obtained in the present work are useful in testing available correlations for the prediction of flooding velocities, particularly with regard to the effect of gas density. Indeed, a large number of data points on flooding are now available, all for the same liquid in the same tube (with unchanged inlet and outlet arrangements) and spanning a wide range of gas densities.

The most popular correlation for the prediction of flooding velocities is that of Wallis,[1] but from a statistical analysis of a very large data bank it was concluded[9] that the most accurate predictions of flooding velocity are given by a modified version of the correlation of Alekseev et al.[17] According to Wallis,[1] the relation

$$(U_g^*)^{1/2} + (U_l^*)^{1/2} = C \tag{1}$$

is expected to be observed at the inception of flooding, where C is a constant with a value close to 1.0, when the fluids enter the test section smoothly; if fluid admission to the test section is not smooth, the value of C is expected to be lower (down to about 0.8). The dimensionless variables U_l^* and U_g^* are defined by

$$U_l^* = U_l \rho^{1/2} \{gD(\rho - \rho_g)\}^{-1/2} \tag{2}$$

$$U_g^* = U_g \rho_g^{1/2} \{gD(\rho - \rho_g)\}^{-1/2} \tag{3}$$

where U_l is the superficial velocity of the liquid, ρ is its density, and g is the acceleration arising from gravity.

The correlation of Alekseev et al., modified by McQuillan and Whalley,[9] reads

$$K_g = 0.286\ \mathrm{Bo}^{0.26}\ \mathrm{Fr}^{-0.22}\left(1 + \frac{\mu}{\mu_w}\right)^{-0.18} \tag{4}$$

with

$$K_g = (U_g \rho_g^{1/2})/[g\sigma(\rho - \rho_g)]^{1/4} \tag{5}$$

$$\mathrm{Bo} = D^2 g(\rho - \rho_g)/\sigma \tag{6}$$

$$\mathrm{Fr} = (Q/\pi D)[g(\rho - \rho_g)^3/\sigma^3]^{1/4} \tag{7}$$

and $\mu/\mu_w = 1$, if the liquid is water at 20°C. It may be seen that for $(\rho - \rho_g) \cong \rho$ (as in our experiments), both correlations predict a dependency between gas velocity and gas density of the form $\rho_g U_g^2$ = constant, at the flooding point, if all other variables are unchanged. To test this prediction, the data obtained in the present work were organized in plots of $\rho_g U_{\mathrm{co}}^2$ vs. ρ_g, for each value of Re, as shown in Figure 7. It may be seen that, contrary to the prediction of the correlations mentioned above, the criterion $\rho_g U_{\mathrm{co}}^2$ = constant is not exactly observed over the entire range of values of ρ_g, for each value of Re; instead, the value of $\rho_g U_{\mathrm{co}}^2$ is seen to increase gradually with ρ_g, for values of this parameter of up to about 8 kg/m^3, and then level off, or even decrease a little. It may nevertheless be said that the overall relative variation in $\rho_g U_{\mathrm{co}}^2$ (for each value of Re) is not very pronounced, especially if attention is restricted to the range $\rho_g > 4$ kg/m^3.

The next step was to test the correlations with regard to variations in the velocity of the liquid. In Figure 8, the correlation of Wallis[1] is tested in a plot of $[\sqrt{U_g^*} + \sqrt{U_l^*}]^2$ vs. ρ_g. The square of the expression on the left-hand side of Eq. 1 was used, so that the parameter being plotted is of the order of magnitude of U_g, rather than $\sqrt{U_g}$; this will be important in comparing with the plot for the other correlation. The plot in Figure 8 shows that the correlation of Wallis is approximately observed, with the possible exception of the points for the two higher values of Re. (As pointed out by one reviewer of the present article, this is in line with the finding of O'Brien et al.[21] that the correlation of Wallis becomes increasingly inaccurate as Re is increased, above about 2000.) The value $C = 0.99$ ($=\sqrt{0.98}$) may be seen to fit the data reasonably well, for ρ_g greater than about 6 kg/m^3, but for the lower densities tested, $C \approx 0.9$ ($=\sqrt{0.81}$) would give a better fit. These values of C are higher than the expected minimum ($C = 0.8$) for disturbed entrance of the fluids, possibly because the values of U_{co}, used to mark the flooding point in the calculations above, are significantly higher than the corresponding values of U_{fl}.

The modified[9] correlation of Alekseev et al. is tested in the plot of Figure 9 and from Eq. 4, the parameter $K_g \mathrm{Fr}^{0.22}$ would be predicted to have the same value for all the experiments reported in the present work. This is seen not to be the case and the conclusion is that the correlation accounts poorly for the

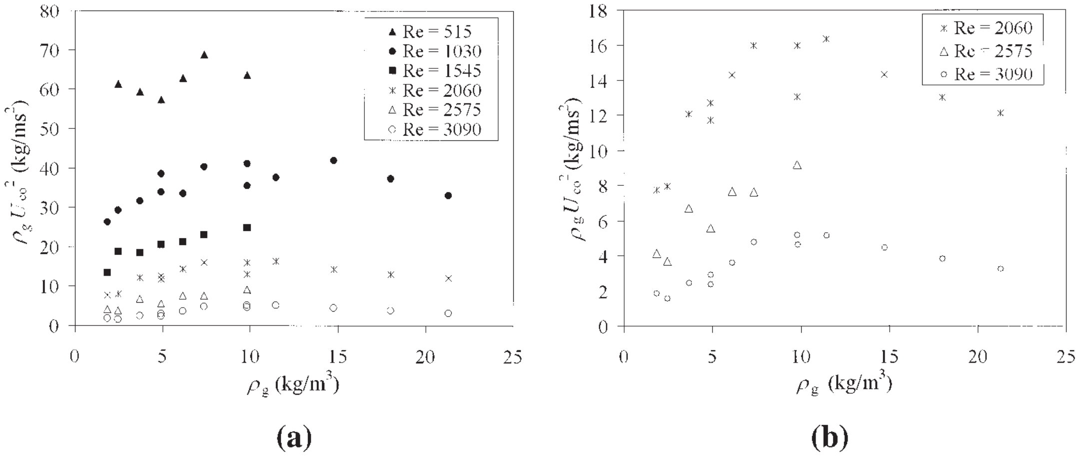

Figure 7. (a) Dependency of $\rho_g U_g^2$ on ρ_g; data for all values of Re. (b) Dependency of $\rho_g U_g^2$ on ρ_g; data for high Re on expanded scale.

effect of liquid flow rate on flooding, in the range of variables studied.

The data obtained in the present work are also useful in the interpretation of some recent results[15] on the slug/churn flow transition in gas–liquid up flow in a vertical tube. Nicklin and Davidson[22] were early to suggest that orderly cocurrent gas–liquid slug flow is bound to break down when the velocity of the gas slugs exceeds that corresponding to flooding of the film of liquid flowing down around them. In recent experiments,[15] the movement of very long slugs of argon, flowing cocurrently with water along a 19.8 mm i.d. vertical tube, was followed at pressures up to 1.3 MPa. At each operating pressure, the superficial velocity of the liquid was increased until slug instability was detected. The results were reported in terms of the superficial velocity of the liquid, U_L (observed below and above the individual slugs), for which slug instability first became apparent. To each value of U_L there corresponds a value of slug velocity and therefore of U_g and Re (calculated by well-known formulae[15]) and they are reproduced in Table 1.

It will be seen that the values of Re for film flow around the slugs, in those experiments, were always between 3073 and 3735, which is near enough the value Re = 3090 observed for one of the liquid flow rates studied in the present work. It would therefore be expected that the values of U_g, obtained from the work with slugs, fall close to the velocities of flooding (taken as U_{co}) for the corresponding pressures in the present work. Figure 10 represents the values of U_g and U_{co} from Table 1 and it will be seen that, with the exception of the points at 0.40 MPa, they are not far apart, at each pressure level and that they become very close as the operating pressure is increased. The slight discrepancy is not surprising in view of the fact that the formation of a falling film alongside a slug is likely to correspond to conditions of smooth admission of the liquid to the section where flooding will be taking place (that is, along the main portion of the long slug). It may therefore be concluded that the values of flooding velocity measured in the present work give support, in quantitative terms, to the idea that the slug/churn flow transition is associated with the occurrence of flooding in the rising slugs.

Conclusions

Measurements of flooding velocities in a 20.6 mm i.d. column are reported, for the previously (nearly) unexploited range of pressures of 0.14–1.3 MPa, covering a range of gas densities of 1.6–21.3 kg/m^3. The inception of flooding instability was detected to occur at gas velocities some 0–35% (depending on the film Reynolds number) below those for which there was carryover of liquid in the exiting gas stream; this may be partly

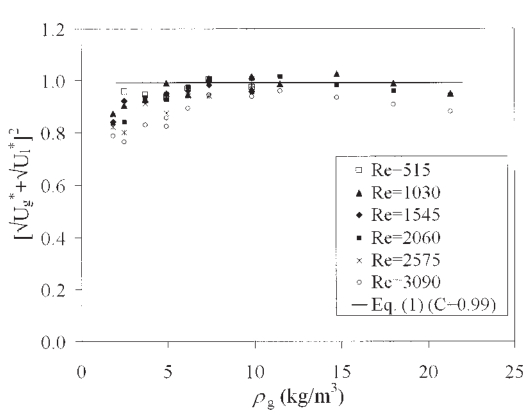

Figure 8. Test of correlation of Wallis.[1]

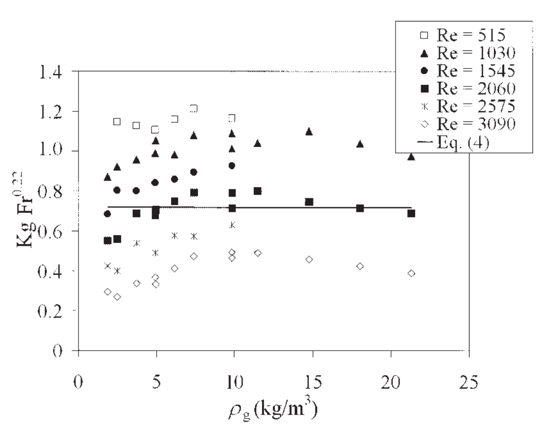

Figure 9. Test of modified[9] correlation of Alekseev et al.

Table 1. Comparison between Data for Slug/Churn Flow Transition and Data for Flooding*

P (MPa) (argon 293 K)	ρ_g (kg/m^3)	This Work U_{co} (m/s) (Re = 3090)	Work on Slug/Churn Flow Transition**				
			U_L (m/s)	u_s (m/s)	δ (mm)	U_g (m/s)	Re (Film)
0.4	6.6	0.76	1.23	1.62	0.71	1.52	3735
0.6	9.9	0.69	0.80–0.72	1.10–1.0	0.69–0.68	1.04–0.95	3473–3420
0.9	14.9	0.55	0.56–0.50	0.80–0.70	0.68	0.77–0.70	3306–3260
1.1	18.2	0.46	0.39–0.35	0.62–0.57	0.66	0.58–0.54	3170–3136
1.3	21.5	0.39	0.28	0.48	0.65	0.46	3073

*Both sets of data are for argon–water at ambient temperature.
**From Carvalho.[15]

associated with the design adopted for gas removal from the test section.

The velocity of flooding (taken as the velocity at which carryover first occurs) was found to be strongly dependent on gas density, but not on the particular nature of the gas used (argon and air were used in the present work). The velocity of flooding was found to be a decreasing function of the gas density, described with good approximation by the relation (gas density) × (flooding velocity)^2 = constant, other variables remaining unchanged; this is in close agreement with previous findings.[13,14]

The fact that so many new data were obtained over a hitherto (nearly) unexploited range of gas densities afforded an important test of available correlations on flooding. The dependency of flooding velocity both on gas density and liquid flow rate was found to be very much that predicted by the correlation of Wallis,[1] whereas the modified[9] correlation of Alekseev et al. was shown to predict very poorly the effect of changes of liquid flow rate on flooding.

The values of flooding velocity measured in the present work were also compared with the values of gas velocity for which slug instability was found to be initiated, in a recent study[15] on the slug/churn flow transition; the comparison lends support to the idea that, in vertical gas–liquid flow, the slug/churn flow transition is closely associated with the occurrence of flooding in the rising slugs.

Acknowledgments

This work was supported by project grant POCTI/EQU/40910/2001, from FCT (Fundação para a Ciência e a Tecnologia). The authors are grateful to L. C. Matos, N.M.F. Garrido, and J.P.F. Lopes for assistance in the course of the experimental work.

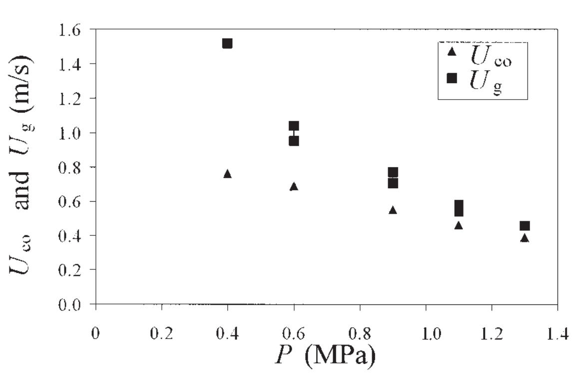

Figure 10. Comparison of velocity of flooding with velocity of gas at the slug/churn flow transition (argon–water at ambient temperature).

Notation

Bo = dimensionless group defined by Eq. 6
C = constant in Eq. 1
D = internal diameter of tube
Fr = dimensionless group defined by Eq. 7
g = acceleration arising from gravity
K_g = dimensionless group defined by Eq. 5
L = length of test section
P = pressure of operation
Q = volumetric flow rate of liquid
Re = Reynolds number for film flow
u_s = velocity of slug
U_{co} = superficial gas velocity at the inception of carryover
U_{fl} = superficial gas velocity at the inception of flooding instability
U_g = superficial velocity of gas
U_g^* = dimensionless superficial velocity of gas, defined by Eq. 3
U_l = superficial velocity of liquid
U_l^* = dimensionless superficial velocity of liquid, defined by Eq. 2
U_L = average velocity of liquid between slugs

Greek letters

δ = thickness of liquid film
μ = viscosity of liquid
μ_w = viscosity of water at 20°C
ν = kinematic viscosity of liquid
ρ = density of liquid
ρ_g = density of gas
σ = surface tension of liquid

Literature Cited

1. Wallis GB. Flooding velocities for air and water in vertical tubes. United Kingdom Atomic Energy Authority (UKAEA), Report No AEEW-R123. Harwell, UK: UKAEA; 1961;1-17.
2. Sudo Y. Mechanism and effects of predominant parameters regarding limitation of falling water in vertical counter current two-phase flow. *Int J Heat Transfer.* 1996;118:715-724.
3. Lee SC, Bankhoff SG. Parametric effects on the onset of flooding in flat-plate geometries. *Int J Heat and Mass Transfer.* 1984;27:1691-1700.
4. Perry RH, Green DW. *Perry's Chemical Engineers' Handbook*. 7th Edition. New York: McGraw Hill; 1997:14-26 and 14-41.
5. Imura H, Kusuda H, Funatsu S. Flooding velocity in a counter-current annular two-phase flow. *Chem Eng Sci.* 1977;32:79-87.
6. Chung KS, Liu CP, Tien CL. Flooding in two-phase counter-current flow. Experimental investigation. *Phys Chem Hydrodyn.* 1980;1:209-220.
7. Hewitt GF, Wallis GB. Flooding and associated phenomena in falling film flow in a vertical tube. Proceedings of the Multiphase Flow Symposium Winter Annual Meeting of ASME, Philadelphia, PA; 1963:62-74.
8. Dukler AE, Smith L, Chopra A. Flooding and upward film flow in tubes—I: Experimental studies. *Int J Multiphase Flow.* 1984;10:585-597.
9. McQuillan KW, Whalley PB. A comparison between flooding correlations and experimental flooding data for gas–liquid flow in vertical circular tubes. *Chem Eng Sci.* 1985;40:1425-1440.

10. Hewitt GF. Countercurrent two-phase flow. Proceedings of the 4th International Topical Meeting on Nuclear Reactor Thermal Hydraulics, NURETH-4. 1989;2:1129-1144.
11. Clift R, Pritchard CL, Nedderman RM. The effect of viscosity on the flooding conditions in wetted wall columns. *Chem Eng Sci.* 1966;21: 87-95.
12. Augello L, Martini R. Flooding experiments in tubular geometry with steam–water up to 70 bar. Proceedings of the European Two-phase Flow Group Meeting, Paper A23, Paris, France, June; 1982.
13. Stephan M, Mayinger F. Experimental and analytical study of counter current flow limitation in vertical gas/liquid flows. *Chem Eng Technol.* 1992;15:51-62.
14. Zapke A, Kröger DG. The influence of fluid properties and inlet geometry on flooding in vertical and inclined tubes. *Int J Multiphase Flow.* 1996;22:461-472.
15. Carvalho JRFG. Experimental study of the slug/churn flow transition in a single Taylor bubble. *Chem Eng Sci.* 2006;61:3632-3642.
16. Bankoff SG, Lee SC. A critical review of the flooding literature. In Hewitt GF, Delhaye JM, Zubber N, eds. *Multiphase Science and Technology*. Volume 2. Washington, DC: Hemisphere; 1986:95-180.
17. Alekseev VP, Poberezkin AE, Gerasimov PV. Determination of flooding rates in regular packings. *Heat Transfer Soviet Res.* 1972;4:159-163.
18. Celata G, Cumo M, Setaro T. A data set of flooding in circular tubes. *Exp Therm Fluid Sci.* 1992;5:437-447.
19. Richter H. Flooding in tubes and annuli. *Int J Multiphase Flow.* 1981;7:647-658.
20. Sato S, Katayama J, Takahashi H. Flooding in gas–liquid counter current two-phase flow in parallel vertical pipes. *JSME Int J.* 1997; 30:409-414.
21. O'Brien SA, Such DK, Mills AF. The effect of liquid flow rate on flooding in vertical annular countercurrent two-phase flow. *Int J Multiphase Flow.* 1986;12:699-704.
22. Nicklin DJ, Davidson JF. The onset of instability in two-phase slug flow. Proceedings of the Institute of Mechanical Engineers Symposium on Two-Phase Flow, Paper 4, London, UK, February; 1962:29-34.

Manuscript received Mar. 16, 2006, and revision received July 28, 2006.