Drag reduction in two-phase annular flow of air and water in an inclined pipeline

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Abstract

Measurements of drag reduction for air and water flowing in an inclined 0.0127 m diameter pipe were conducted. The fluids had an annular configuration. The injection of drag reducing polymers (DRP) solution produced drag reductions as high as 71% with a concentration of 100 ppm in the pipeline. A maximum drag reduction that is accompanied (in most cases) by a change to a stratified or annular stratified pattern. The drag reduction is sensitive to the gas and liquid superficial velocities and the pipe inclination. Maximum drag reduction was achieved in the case of pipe inclination of 1.28^{o} at the lowest superficial gas velocity and the highest superficial liquid velocity.
Keywords: inclined pipeline, annular gas-liquid flow, drag reducing polymers, injection method.

1 Introduction

The injection of small amounts of high molecular weight long-chain polymers into a single-phase liquid flow can cause large decreases in the frictional resistance at the wall; this interesting finding was first published by (Toms, [1]).

Two-phase gas liquid flow in pipes is regularly encountered and is of great commercial importance in the natural gas and petroleum industries. This paper presents results of experiments in which drag-reducing polymers were added to the flow of water and air in an inclined pipe, with a diameter of 0.0127 m. The gas velocity was large enough that an annular flow existed. This pattern commonly occurs in natural gas/ condensate pipelines. It is characterized by a situation in which a part of the liquid flows along the wall as a liquid layer and part as drops entrained in the gas in the core of the pipe.

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At low gas and liquid rates the liquid flows along the wall in a stratified manner. At high enough superficial gas velocity, U_{SG}, drop mixing and deposition is such that the film on the side walls becomes thick enough for groups of large amplitude irregular waves to form intermittently. These disturbances are sites for atomization and the fluid in them has characteristics similar to turbulence. They greatly enhance the ability of liquid to climb up the wall in opposition to the gravitational force and called disturbance waves (Lin and Hanratty, [2]).

A similar previous study of the effect of drag-reducing polymers on annular gas-liquid flow was carried out by Sylvester and Brill [3] for air-water in a horizontal pipe with a diameter of 1.27 cm and a length of 6.1 m. A polymer solution with 100 ppm of polyethlene oxide, contained in a holding tank, was pumped to a tee where it was mixed with the gas. The data are plotted as pressure gradient versus liquid flow rate for superficial gas velocities 86 m/s and 111 m/s. The percent change in the pressure gradient from what was observed in the absence of polymer varied from zero to about 37. No explanation for these changes was given.

Sylvester et al. [4] studied the effect of liquid flow rate and gas flow rate on drag reduction in horizontal natural gas-hexane pipe flow in three different diameter (1, 2 and 3 inch). Drag reduction of 34% was obtained. It was found that drag reduction increased with decreasing gas rate.

Al-Sarkhi and Hanratty [5] found that the injection of a concentrated drag reducing polymers into an air-water in a 9.53 cm pipe changed an annular pattern to a stratified by destroying the disturbance waves in the liquid film. Drag reduction of 48% was realized. In a following study in a 2.54 cm pipe, Al-Sarkhi and Hanratty [6] observed similar results and obtained drag reduction as high as 63%.

Soleimani et al. [7] studied experimentally the effect of drag reducing polymers on pseudo-slugs-interfacial drag and transition to slug flow. They revealed that the transition to slug flow is delayed by drag reducing polymers and the pressure drop can increase or decrease when polymers are added.

Al-Sarkhi and Soleimani [8] conducted a series of experiments to investigate the effect of drag reducing polymer on two-phase flow pattern in a horizontal 2.54cm pipe. The characteristics of two phase flow with and without drag reducing polymers were described. It is noted that the interfacial shear stress decreases sharply by adding polymers and flow pattern map is changed.

Studies of the effect of the drag-reducing polymer on frictional losses have been made by Rosechart et al. [9] and by Otten and Fayed [10] for bubbly and plug flows. Kang et al. [11] studied the influence of an additive (which is not identified) on three-phase flow (oil, water and carbon dioxide). They found a drag-reduction of 35 percent at the two highest superficial gas velocities that were studied, U_{SG} =13, 14 m/s. A review of work on this area by Manfield et al. [12] concludes that understanding of the influence of drag-reducing polymers on multiphase flows is not satisfactory.

The present study used technology developed by Al-Sarkhi and Hanratty [5] for injecting the polymers directly in the liquid film in the pipeline. It differs from all of the studies listed above in that a concentrated polymer solution was injected at the wall without using a pump. The concentration in the pipeline was controlled by varying the flowrate of the injected polymer concentrated solution. Gas and liquid superficial velocities of 19-38 m/s and 0.04-0.1 m/s were used.

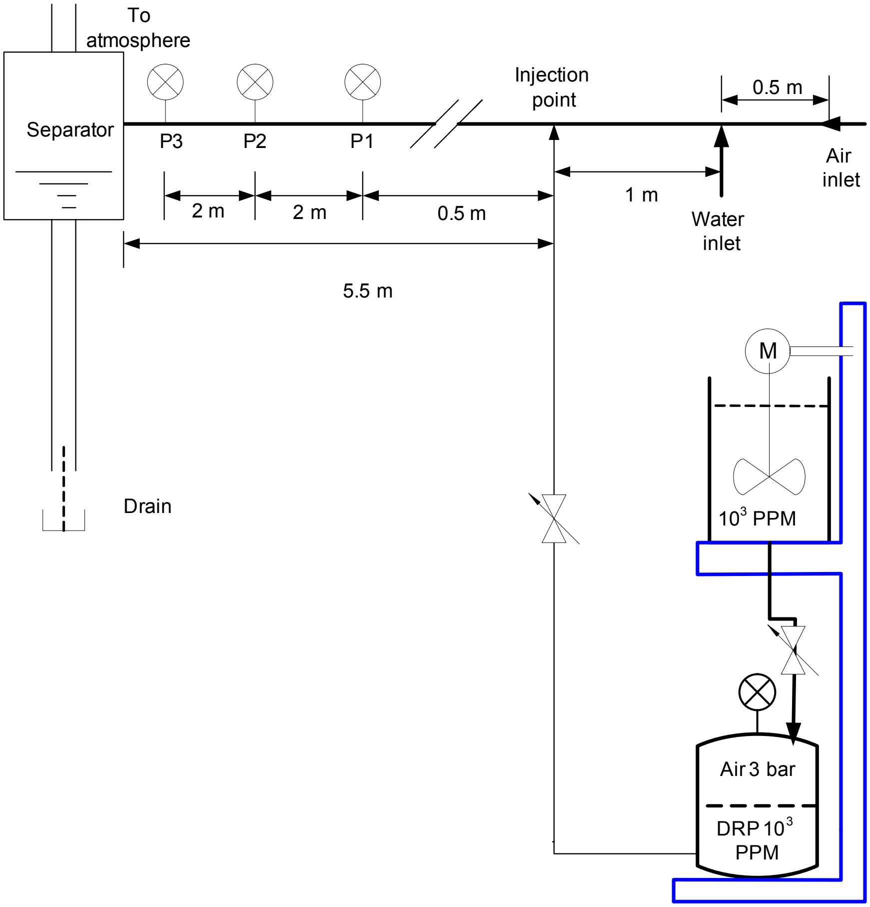

Figure 1: Experimental setup.

2 Experimental setup

The 0.0127 m pipeline used in this study has a length of 7 m. The pipe sections were constructed from Plexiglas to allow visual observations. The air and water were combined in a tee-section at the entry. The water flowed along the run of the tee. The air discharged to the atmosphere so the pressure was slightly above the atmospheric. A detailed description of the loop is shown in fig. 1.

The master polymer solution was prepared the day before an experiment was performed. MAGNAFLOC 110L is a high molecular weight anionic polyacrylamide flocculant as a liquid dispersion grade (produced by Ciba) was mixed gently with water in a 150-liter tank with a concentration of 1000 ppm (weight basis). The master solution was transferred by gravity to a smaller tank, which was pressurized with air at 3 bar (see fig. 1). The flow rate out of the tank was measured by a rotameter. These methods for transferring the concentrated polymer solution were used in order to avoid the degradation that would have occurred if a pump were used.

The polymer solution was injected into the flow loop by introducing of the master solution into the liquid through a hole with a diameter of 2 mm that was located at the bottom of the pipe, 1.0 m downstream of the tee where the air and water were mixed. This method involved injection at a location where the annular pattern was developed, i. e., 1.0 m from the mixing tee. In this way the polymer was rapidly mixed with liquid flowing along the wall. A polymer concentration of 100 ppm was used. A U-tube manometer was used to measure the pressure drop over a 2 m length of pipeline. The first pressure tap was located 0.5 m from the downstream injection point.

3 Results

3.1 Visual observations

Visual observations of the air-water flow revealed a turbulent liquid film with intermittent disturbance waves around the whole pipe circumference. These were longer and more intense at the bottom, as would be expected, since the average height of the film is distributed asymmetrically (Williams at al., [13]).

Detail explanation of the effect of the addition of polymer to the flow on the flow pattern is listed in Table 1. The air and water without DRP has an annular configuration with liquid film wetting the whole pipe circumference and the presence of a large-scale disturbance wave. The forth, fifth and sixth column represent the flow of air and water with 100 ppm of polymer added to the liquid for horizontal, and 1.28^{o} and 2.4^{o} of pipe inclination. The flow pattern at lowest gas and liquid superficial velocities (U_{SG} =19, 24 m/s and U_{SL}=0.04, 0.05 and 0.07 m/s) shows a stratified flow with a relatively smooth surface and a negligible amount of entrained drops in the gas phase. These results can be interpreted by noting that the polymers damped the disturbance waves. This, in turns, reduces the rate of atomization and the ability of liquid to spread upward along the wall. A secondary effect is a damping of the waves on the stratified flow that finally results.

At the lowest superficial gas velocities (19 and 24 m/s) and highest superficial liquid U_{SL} (U_{SL} =0.1). Considering the horizontal case; the flow pattern with 100 ppm of polymer injected to the liquid film, the new flow pattern characterized by a thin liquid film at the top of the pipe and a thick film at the lower half of the pipe with no disturbance waves shown in the pipe. This flow configuration is called Annular–Stratified as in Al-Sarkhi and Hanratty [9]. The case for the angle 1.28^{o} the final configuration with DRP was stratified but for the angle 2.4^{o}, the final pattern was pseudo slug.

Table 1: Flow patterns with and without 100 ppm polymers (Ann means annular and Strt means Stratified).

U_{SG} m/s	U_{SL} m/s	Without DRP all angles	With DRP (θ=0°)	With DRP (θ=1.28°)	With DRP (θ=2.4°)
38	0.10	Ann	Ann w/o D.W	Ann w/o D.W	Ann w/o D.W
38	0.08	Ann	Ann w/o D.W	Ann w/o D.W	Ann w/o D.W
38	0.07	Ann	Ann-Strat	Ann w/o D.W	Ann w/o D.W
38	0.05	Ann	Ann-Strat	Ann w/o D.W	Ann w/o D.W
38	0.04	Ann	Ann-Strat	Ann w/o D.W	Ann w/o D.W
33	0.10	Ann	Ann-Strat	Ann-Strat	Ann w/o D.W
33	0.08	Ann	Ann-Strat	Ann-Strat	Ann w/o D.W
33	0.07	Ann	Ann-Strat	Ann-Strat	Ann w/o D.W
33	0.05	Ann	Ann-Strat	Ann-Strat	Ann w/o D.W
33	0.04	Ann	Ann-Strat	Stratified	Ann w/o D.W
28	0.10	Ann	Ann-Strat	Stratified	Ann w/o D.W
28	0.08	Ann	Ann-Strat	Stratified	Ann-Strat
28	0.07	Ann	Stratified	Stratified	Ann-Strat
28	0.05	Ann	Stratified	Stratified	Stratified
28	0.04	Ann	Stratified	Stratified	Stratified
24	0.10	Ann	Ann-Strat	Stratified	Annular - pseudo slug
24	0.08	Ann	Ann-Strat	Stratified	Ann-Strat
24	0.07	Ann	Stratified	Stratified	Stratified
24	0.05	Ann	Stratified	Stratified	Stratified
24	0.04	Ann	Stratified	Stratified	Stratified
19	0.10	Ann	Ann-Strat	Stratified	Ann -pseudo slug
19	0.08	Ann	Ann-Strat	Stratified	Stratified
19	0.07	Ann	Stratified	Stratified	Stratified
19	0.05	Ann	Stratified	Stratified	Stratified
19	0.04	Ann	Stratified	Stratified	Stratified

At the highest U_{SL} and U_{SG} the annular air and water flow contains many of the high amplitude disturbance waves. The pressure gradient is very high. Adding small amount of polymers to the flow causes the pressure gradient to start to drop down and the disturbance waves to start to disappear. With adding enough polymers (reaching 100 ppm) maximum drag reduction is achieved and beyond that amount there was no more drag reduction with adding more polymers, this situation is described as an annular with out disturbance waves (Annular w/o D.W). At lower gas velocity (33 m/s) and same U_{SL} = 0.1 m/s the same sequences happened but the final pattern was stratified-annular instead of an annular for the horizontal and 1.28^{o} angles and annular with out disturbance waves (Annular w/o D.W) for the 2.4^{o} angle.

3.2 Drag reduction

The effectiveness of the polymer is expressed in terms of the drag-reduction (DR) defined as in eqn. (1), where $\Delta P_{withDRP}$ is the pressure drop when drag-reducing polymer was present and $\Delta P_{withoutDRP}$ is the pressure drop in the absence of drag-reducing polymer.

$$\mathrm{DR} = \frac{\Delta P_{withoutDRP} - \Delta P_{withDRP}}{\Delta P_{withoutDRP}} \tag{1}$$

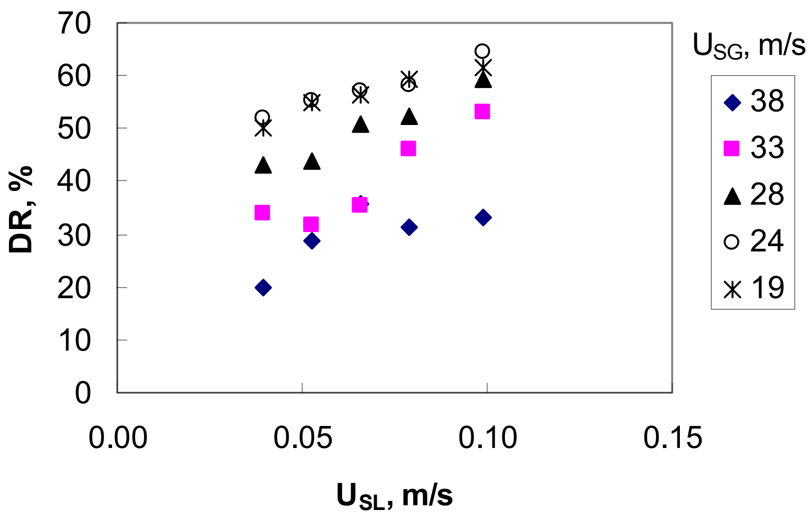

Figure 2: Drag reduction variation with superficial liquid velocity, θ=0°.

Figures 2 to 7 show plots for maximum DR versus U_{SL} and U_{SG} respectively. Figures show that DR is very sensitive to U_{SG} and U_{SL}. The DR and pressure drop increases with increasing U_{SL}. Drag reduction increases with increasing U_{SG} at lower U_{SG} values and then decreases with increasing U_{SG} at higher U_{SG} values. Effect of pipe inclination can be appeared on two things; the first is the changes on the flow pattern with addition of the DRP and the second on the DR. In general, all angles have the same trend of DR with U_{SL} and U_{SG}. The case of 1.28^{o} inclination has the highest DR and the case of 2.4^{o} has the lowest DR. The maximum DR among all experiments occurs at 1.28^{o} inclination and lowest U_{SL} and highest U_{SG}. The effect of pipe inclination also appears on the changes of the flow pattern with adding DRP. At the lowest two U_{SG} (19 and 24 m/s) and the highest U_{SL} (0.1 m/s) the final pattern for air and water with 100 ppm of DRP at inclination of 2.4^{o} was pseudo slug while at 1.28^{o} was stratified and at zero inclination was an annular-stratified. Noting that the maximum DR occurs for the case of 1.24^{o} inclination in which the flow pattern changes from the annular to stratified.

This behaviour agrees with all previous studies, which indicated that the maximum DR accompanied always with change in the flow pattern from annular to stratified.

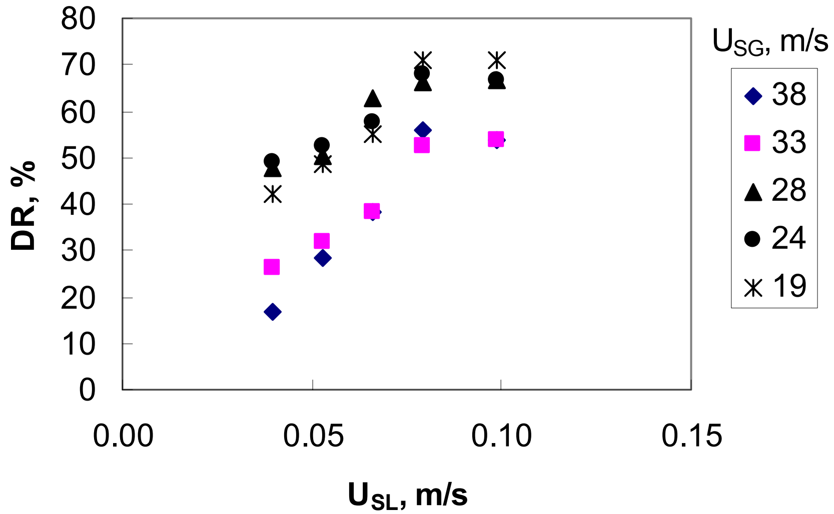

Figure 3: Drag reduction variation with superficial liquid velocity, $\theta = 1.28^o$.

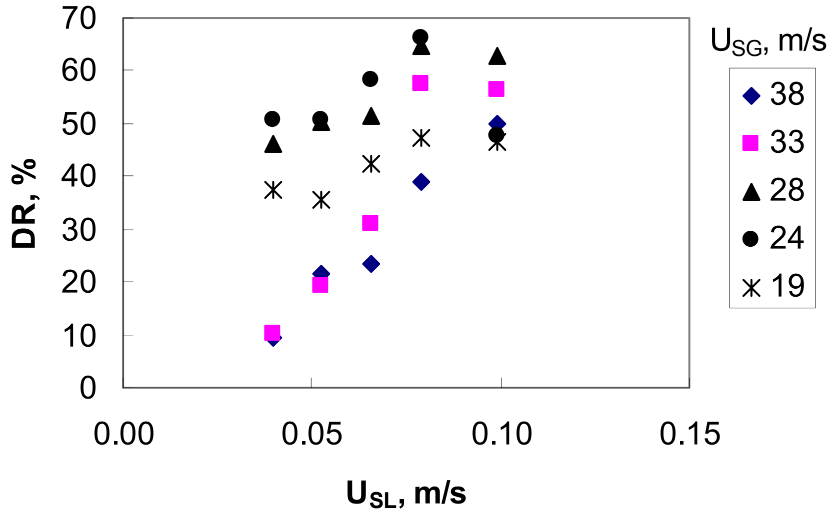

Figure 4: Drag reduction variation with superficial liquid velocity, $\theta = 2.4^o$.

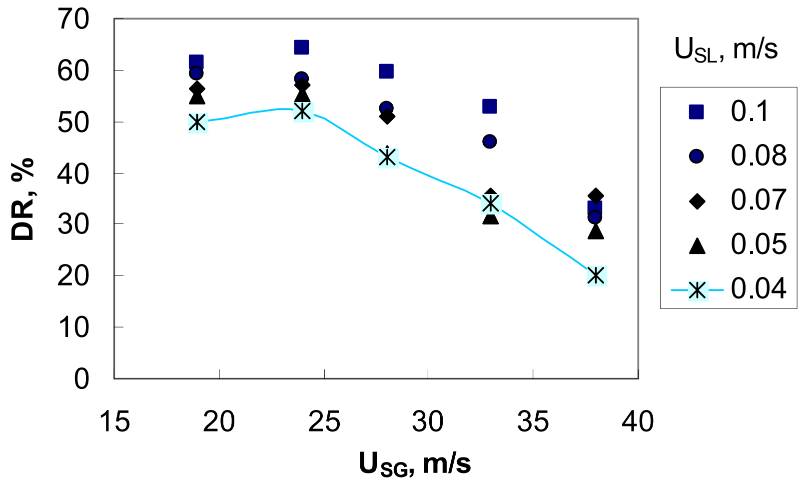

Figure 5: Drag reduction variation with superficial gas velocity, $\theta = 0^o$.

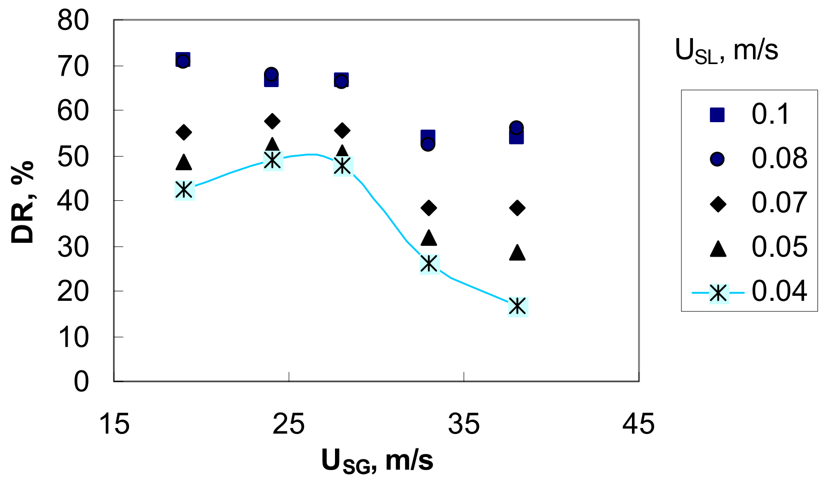

Figure 6: Drag reduction variation with superficial gas velocity, $\theta = 1.28^o$.

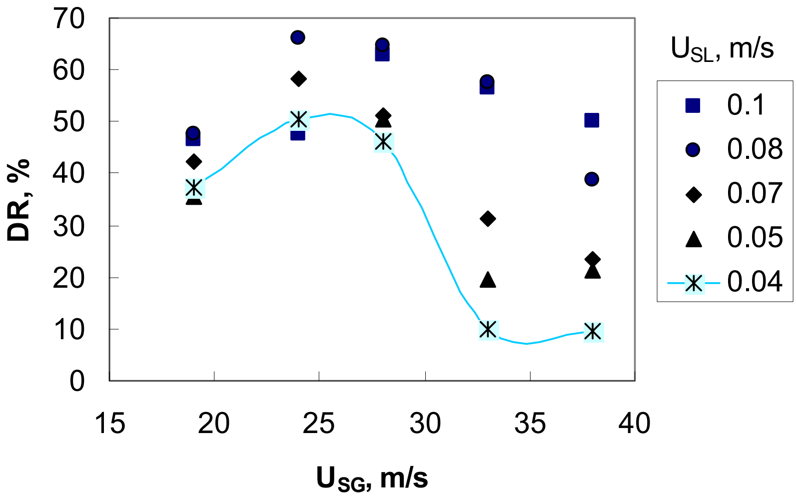

Figure 7: Drag reduction variation with superficial gas velocity, $\theta = 2.4^{o}$.

4 Discussion and conclusions

The injection of polymer solution into an air-water flow that has an annular configuration in an inclined 1.28^{o} pipe can produce drag-reductions of about 71%. The polymer destroys the turbulent disturbance waves, which are the cause of drop formation and which help the water film to spread upward around the pipe circumference.

Visual observation of the pattern changes due to injection of polymers to an annular flow revealed that an annular flow pattern changes to stratified pattern at low superficial liquid and gas velocities. An annular flow pattern changes to an annular-stratified at higher gas and liquid velocities and finally, at highest superficial liquid and gas velocities an annular flow remains an annular but without disturbance waves.

At lowest gas velocities, highest liquid velocity, and highest pipe inclination (2.4^{o}) an annular flow changes to pseudo slug in the presence of DRP which is expectable due to the tendency of accumulation of the liquid at the inlet of pipe with increasing the pipe inclination. The pressure gradient of annular patterns of air and water in the absence of polymers are higher than that of air and water at same liquid and gas rates in the presence of polymers. The maximum drag reduction was achieved in the case of pipe inclination of 1.28^{o} at the lowest superficial gas velocity and the highest superficial liquid velocity. The minimum drag reduction was achieved in the case of pipe inclination of 2.4^{o} and at highest superficial gas velocity and lowest superficial liquid velocity.

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