The flow of foam through constrictions

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Received 26 August 1986 and accepted for publication 19 February 1987

Experiments have been carried out to investigate the effect on liquid-gas foam of the flow through constrictions such as valves of various types. It is found that high rates of shear, such as may be found in globe valves, can severely degrade foam. Smooth profiled symmetrical passages do not degrade foam. There is a residence time effect: Foam may not be degraded by severe shear so long as it is not sustained for too long. Foam is able to expand through angles approaching 180° without appreciable separation.

Keywords: foam; flow; constrictions

Introduction

Liquid-gas foams are highly non-Newtonian in their flow behavior.[1] Their behavior is dependent on the flow properties of the base fluids (in this case water plus surfactant and air), the expansion ratio (foam to liquid volume ratio), and the distribution of bubble sizes.

In flow situations, the flow properties may be locally modified, for example, by migration of bubbles from one region to another, or globally modified, for example, by shear changing the average bubble size. This means the current state of a foam is a function not only of the current flow situation but also of its history.

For the flow of an incompressible Newtonian fluid, a constriction may be created as a "black box." The pressure drop it produces may be described by a dimensionless coefficient, which is a function primarily of Reynolds number, and frequently may be approximated by a constant. This is not the case for a foam; the state of the foam after one constriction producing a certain presure drop may be very different from that after another with a different internal configuration but the same overall pressure drop.

This phenomenon was observed in the course of a foam project[2] where a globe valve was fitted in series with a restrictor. The resulting foam was of poor quality. It was highly nonhomogeneous, almost to the point of having degraded to a slug flow of alternate very large bubbles and very wet (low expansion) foam. It was also unstable, draining very quickly. Replacing the globe valve and restrictor with a gate valve giving the same overall pressure drop and volumetric flow rate overcame this. We mentioned this to an engineer in the fire-protection industry, who commented that "Everyone knows that you cannot use a globe valve with foam." However, no reference to this phenomenon has been found in the published literature. It appears to be a topic known to specialist engineers in a rather narrow field but has not been systematically investigated.

We have carried out two projects[3,4] to investigate this area further. The first concentrated on the effects of flow through valves of various types on the properties of the foam. The second was concerned with flow visualization of foam in constrictions of various geometries.

The work reported here is very preliminary and is almost completely of a qualitative nature. The development of quantitative models in fluid mechanics invariably requires a physical appreciation of the kind of phenomena occurring. The behavior of foams is very different from that of Newtonian fluids. We hope this work will provide a basis for more detailed investigation.

Pressure loss and foam property measurements

Apparatus

Foam was generated in an opposed jet type of foam generator (as described previously[1]). The foaming material was Kerr Hi-Foam synthetic fire-fighting compound used in 3% aqueous solution and at an expansion ratio of about 7. This was passed through one of three commercial valves of different types, all of nominal bore 13 mm. Figure 1 shows sketches of the internal passages of the valves. Note in particular that the ball valve was not a straight through type; when fully open, it presented a flow area of about 55% of nominal.

Three liquid flow rates were used: 7.9, 11.3, and 14.8 cm^3/s, corresponding to average foam velocities from about 43 to 81 cm/s.

Measurements were taken with the valves fully open and 25% open. This latter condition was defined by noting the pressure drops in the fully open conditions at the lowest flow rate were all

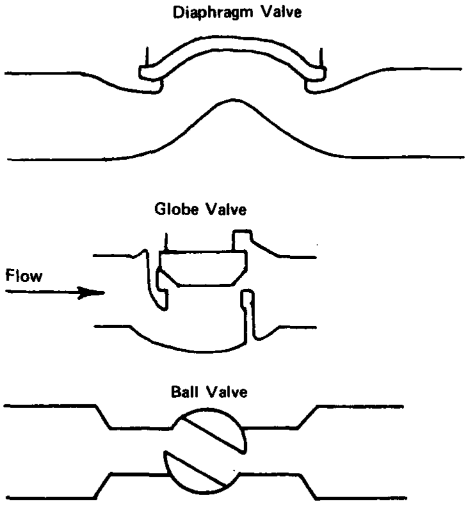


Figure 1 Sketches of internal profiles of valves

Table 1 Pressure drop in valves

Liquid Flow Rate (cm^3/s)	7.9	11.3 (kPa)	14.8
100% open			
Ball	2.3	3.4	3.6
Diaphragm	1.6	1.8	3.2
Globe	2.0	1.5	3.0
25% open			
Ball	7.8	14.9	21.6
Diaphragm	7.6	13.7	13.4
Globe	8.4	10.6	16.3

about 2.0 kPa. Therefore, 25% open was defined as the degree of opening producing a pressure drop of about 8.0 kPa at a liquid flow rate of 7.9 cm^3/s and an expansion ratio of 7.0. (This probably implies the minimum flow area was approximately halved.) Though the working point was not exactly the same for all valves, all measurements on any given valve were taken without changing its setting.

The foam expansion ratio was determined by collecting a sample of foam from the outlet pipe and is therefore at atmospheric pressure. The pressure drop was measured by mercury manometers at pressure tappings about four diameters upstream and downstream of the valves. Foam samples before and after the valve were taken by disconnecting the valve pipes as close as possible to the valve.

Three properties were used for assessing foam quality: the predrainage time (the time taken for the first liquid to appear at the outlet of the drainage vessel), the 25% drainage time (the time required for 25% of the liquid in the foam to drain out once drainage has started), and the average bubble size.

The drainage times are not absolute quantities, since they depend heavily on the geometry of the measuring vessel. However, for vessels of height to diameter ratio of around 1, there is not too much problem, and they provide useful comparative measures of foam quality. In view of the large variation of results always found in foam measurements, only broad agreement on drainage times is to be expected between different experimental results. The drainage vessels in this program were cylinders 17 cm high and 15-cm diameter, open topped, with a conical base 3 cm deep. At the center of the base is a 13-mm diameter drain tube loosely packed with wire gauze.

Average bubble size was estimated by counting the bubbles in a 1-mm square, through a low-power microscope. Since the bubble size was evaluated at atmospheric pressure, it was correlated back to rig pressure assuming adiabatic conditions. (Since all measurements were made under conditions different from those in the valve, the actual values must be treated with caution. Only before-and-after comparisons on a particular piece of apparatus are likely to be valid unless measurements can be made under actual rig conditions.)

Results and discussion

All the results showed a substantial amount of scatter (around 20%). The results we present are averages of three or more separate readings.

Pressure drop

Table 1 gives the pressure drops in the fully open condition. The change with liquid flow rate (and thus with foam flow rate, since expansion ratio is constant) is less than would be expected for laminar flow of a Newtonian fluid. Foams are known to exhibit yield stress and pseudoplastic behavior,[1] which is consistent with these observations.

There is an anomaly for the globe valve, which has a lower pressure drop at the intermediate point than at the lowest flow rate. This suggests the possibility of a change in flow regime internally. Some sign of similar behavior also occurs in the diaphragm valve.

Table 1 also shows the equivalent results for 25% open. (Since the condition was defined in terms of pressure drop, no conclusions can be drawn from the absolute values.) The most significant feature is the lower pressure drop of the diaphragm valve at the highest flow rate, compared particularly with the ball valve. As will be seen, it is at the highest flow rates that foam degradation takes place in the ball and globe valves.

Predrainage time

The predrainage times for all samples taken upstream of the valves were between 20 and 50 s. There was a noticeable trend to the higher end with increased flow rate, which must be a characteristic of the foam generator.

Table 2 shows the percentage change (to the nearest 5%) in predrainage time of the foam after passing through the valve. It may be seen that the fully open valves produce either little change or an increase. The 25% open valves mostly produce an increase, except for a reduction for the globe valve at maximum flow rate.

These observations may be considered in the light of the effect of shear on foam bubbles. A moderate degree of shear will tend to distribute the liquid more uniformly through the foam, which would be expected to increase the predrainage time. A severe shearing will break the bubble boundaries, leading to an increase in average bubble size and a corresponding increase in size of interbubble liquid drops, thus reducing the predrainage time. In general, both effects will occur simultaneously in different parts of the flow. The partly open valves will, in general, produce higher shear than the fully open valves. It appears that the better internal profile of the partly open diaphragm valve avoids the destructive effects of shear, which dominate at the highest flow rate for the other partly open valves.

25% drainage time

The 25% drainage times follow a pattern very similar to the predrainage times. The upstream values were between 300 and 550 s, again with a trend to higher values at higher flow rates.

Table 3 shows the percentage change between upstream and downstream of the valve, again to the nearest 5%. The trends are very similar to those for predrainage time, though less extreme. A very similar argument can be used to explain them.

Table 2 Percentage change in predrainage time

Liquid Flow Rate (cm^3/s)	7.9	11.3	14.8
100% open			
Ball	20	0	65
Diaphragm	0	15	25
Globe	10	10	66
25% open			
Ball	40	30	0
Diaphragm	50	0	85
Globe	25	5	−20

Average bubble size

The bubble size results were subject to considerable scatter owing to the rather crude measurement method. However, some trends can be observed. The upstream bubble diameter fell from about 115 μm at the lowest flow to about 75 μm at the highest. For the fully open valves, the downstream values were about 5% lower than the upstream for the lower two flow rates and about 5% higher for the highest flow rate. These variations are probably not significant in view of the scatter, but they did appear on almost all sets of results.

The diaphragm valve had little effect on the bubble size when 25% open; the other two valves also had little effect at low flow rate. The globe valve had a significant effect at the two higher flow rates, as did the ball valve at the highest. This effect was that the bubble size population divided to produce one set of bubbles of roughly the same size (around 70 μm) as the diaphragm valve and another set much larger (5 to 10 mm). These last could not be measured accurately, being observed passing through the transparent pipework. It was not possible to estimate the proportion of the total air contained in the larger bubbles.

These observations are consistent with the preceding discussion; that is, low shear rates (low velocities and smooth passages) tend to produce a slight reduction in bubble size, whereas high shear rates (high velocities and tortuous passages) lead to large-scale foam breakdown and the formation of very large bubbles. (There could also be an element of centrifugal phase separation in regions of high transverse pressure gradient.)

Table 3 Percentage change in 25% drainage time

Liquid Flow Rate (cm^3/s)	7.9	11.3	14.8
100% open			
Ball	0	0	−5
Diaphragm	0	15	5
Globe	0	10	0
25% open			
Ball	0	20	10
Diaphragm	20	5	0
Globe	15	0	−5

Conclusions from valve flow measurements

Flow through a valve can lead to degradation of foam (characterized by breakdown into very large bubbles and a reduced drainage time). The magnitude of the effect depends on both flow rate and the internal profiles of the valves. In general, the higher the flow rate and the more tortuous the passage, the larger the effect. Conversely, a valve with a smooth internal profile at all openings (such as a diaphragm valve) does not degrade foam and may even enhance its stability.

The pressure drop and flow rate characteristics of valves carrying foam are not straightforward, and further experimental work is needed to fully understand the results obtained here.

Flow visualization

To gain more insight into these processes, flow visualization experiments were carried out.

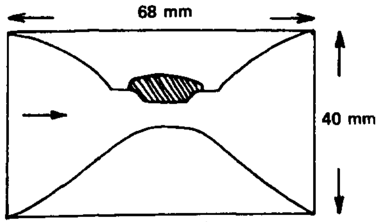
The same foam generator was used with the same foam compound. However, we found it more satisfactory to use a higher expansion ratio (about 12) and a lower velocity (about 5 cm/s) than in the previously described experiments. The results, therefore, are not strictly comparable, but it is expected that the phenomena observed will be relevant.

Apparatus

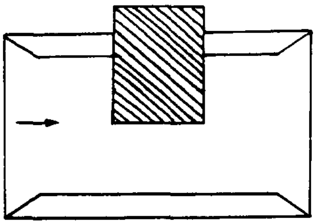
Four different valve models were made: diaphragm, globe, gate, and ball. These were two-dimensional models of uniform depth 20 mm and upstream width 40 mm constructed from perspex. All except the diaphragm valve were infinitely adjustable between fully open and closed. The diaphragm valve was provided with an insert, allowing it to be fully open or 50% (by area) open. Figure 2 shows the valve models. The degree of opening of the valves is defined in terms of the position of the moving part.

The models were mounted between rectangular ducts, 20 mm × 40 mm, 200 mm long upstream and 140 mm long downstream.

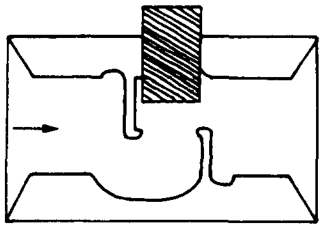
Drainage time measurements were made to relate visual observations to foam degradation. However, in this case, the



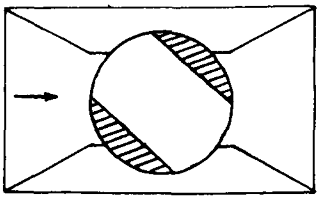
Diaphragm Valve



Gate Valve



Globe Valve



Ball Valve

Figure 2 Flow visualization models

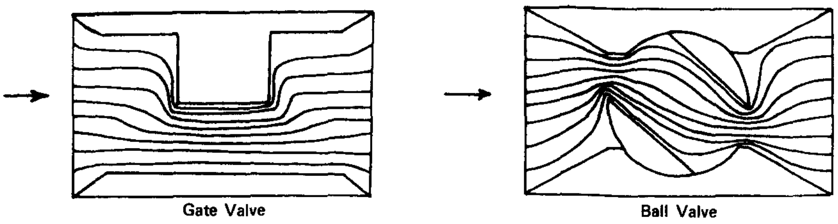


Figure 3 Streamline patterns–gate valve and ball valve, 50% open

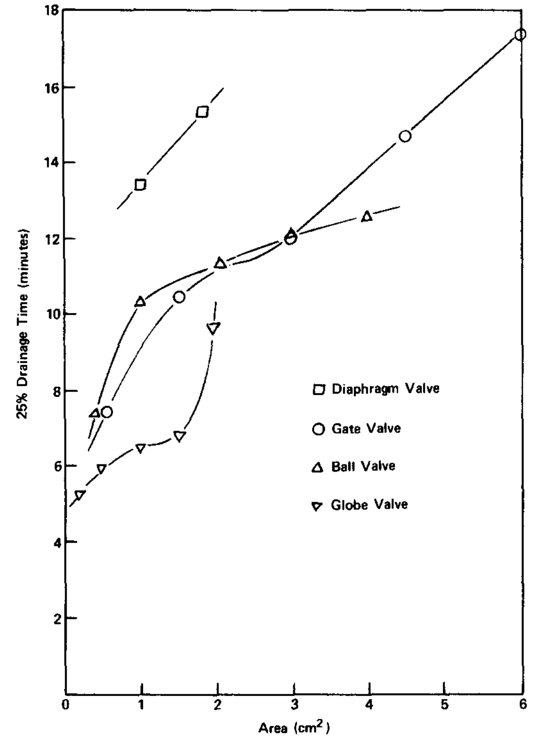


Figure 4 Effect of minimum flow area on 25% drainage time

predrainage time was not measured separately (and is therefore included in the 25% drainage time).

Observations were made visually using a low-power stereoscopic microscope. Some photographic observations were also made, but these were less satisfactory owing to the lack of flow direction information.

Results and discussion

General observations

The immediate and striking observation was that foam does not appear to separate from sharp corners in the way that would be expected for a Newtonian fluid. Figure 3 shows sketched streamlines (in all sketches, there are eight streamlines equally spaced upstream) for the flow through the gate valve and the ball valve, both 50% open. As can be seen, the flow remains attached, or nearly so, throughout. In these cases, a Newtonian fluid would show large areas of separated flow and strong asymmetry between upstream and downstream. The foam appears to be able to expand without separation through angles approaching 180°.

25% drainage time

As mentioned, the 25% drainage time here includes the predrainage time.

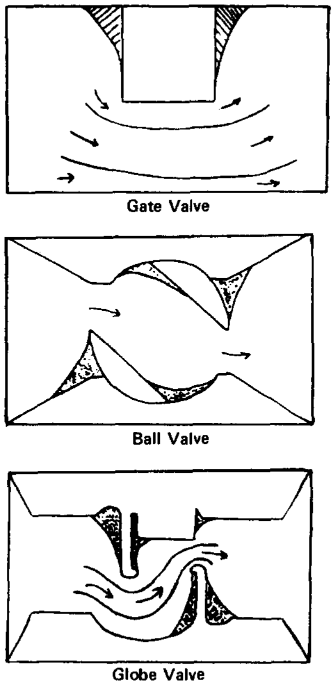


Figure 5 Stagnant regions of flow in 50% open valves

Figure 4 shows the 25% drainage time as a function of minimum flow area in the valve. (Because the fully open flow areas are different, this was found to correlate results better than using degree of valve opening.)

It may be seen that a very strong link exists between drainage time and area. The three valves with tortuous flow passages all produce very similar results, with foam degradation becoming progressively worse as area is reduced. The diaphragm valve, with its smooth passage, has a negligible effect in comparison with the others.

Flow patterns

In most observations, "stagnant" areas were present. These were areas where the velocity was very low, with the main flow passing outside them. They are equivalent to separation bubbles in a Newtonian flow, but they occur only in low-shear regions (for example, approaching stagnation points) and not in high-shear regions such a sharp edges. They are thought to occur where the local shear stress is below the yield stress of the foam, with the residual motion being allowed by the boundary lubrication (slip) layer.[1] Figure 5 shows sketches of the stagnant regions (shown shaded) for the gate, ball, and globe valves, 50% open. No such regions could be observed repeatedly for the diaphragm valve; when they were seen, they were very small. Similar patterns were observed at other valve openings. The low-speed motion in the stagnant regions is in the same direction as the external flow—no instances of recirculating flows were observed.

It was possible to make some estimate of the variation of velocity across the valve openings. In general, the velocity was considerably higher around projecting elements (for example, the gate of the gate valve) than in other regions of the flow. In both the gate valve and the diaphragm valve, there was a relatively low velocity region near the opposite wall and, at some valve openings, an unsheared plug-flow region in between. This means the shear rate was always highest around the projections, and the severely sheared proportion of the foam increased as the valves were closed. This is consistent with shear causing foam breakdown and thus reducing drainage times.

The globe valve has two projections at opposite sides of the flow. When fully open, the first could be seen to cause shear, but the second tended to reduce it again, giving the appearance of a solid body rotation. This effect disappeared rapidly as the valve was closed, with shear appearing at the second lip. This probably accounts for the very rapid initial deterioration in drainage time for this valve (Figure 4). Although the ball valve also has two projections, it does not show the same effects. This is possibly because there is a significant expansion, allowing the foam to recover between the two.

The drainage time results for the gate and ball valve are similar, although the ball valve appears to produce much more distortion of the uniform flow. The reason for this is probably related to the time-dependence of the foam properties. At low speeds, where individual bubbles can be followed, the bubbles are observed to elongate in the flow direction as they pass through the constriction. This is an unstable situation. The bubbles can revert to a stable state in two ways: by relaxing back to spherical as the flow slows down again or by merging with adjacent bubbles by a drainage process. This latter will take a finite time, so the amount of degradation will depend on the residence time in the constriction. The foam may partly recover after a short constriction, but not after a long one. Thus the degradation due to two short severe constrictions separated by an expansion (ball valve) may be comparable to that in one long one (gate valve). The residence times are of the order of 200 ms, so the characteristic time for drainage/degradation to occur might be of the order of 100 ms.

Conclusions from flow visualization

Foam can expand through very large angles without showing appreciable separation, although stagnant areas may form in regions of low shear.

The major determinant of foam degradation seems to be the combination of high shear rates and (relatively) long residence times. The effect of velocity is to increase shear while reducing residence time. Which effect will dominate is not obvious, although the valve test result suggests it will be the shear.

Conclusions

Foam can be severely degraded by flow through constrictions under conditions that combine high shear rates and long residence times.

To avoid degradation, constrictions should be designed to avoid high rates of shear. This will generally require avoiding tortuous passages such as those in a globe valve.

Conversely, foam may not be severely degraded by flowing through a smooth-profiled symmetrical constriction such as a diaphragm valve or venturi.

Foam seems to be able to expand through wide angles without significant separation or degradation. It would be of interest to carry out further work on this, for example, to study the flow through a sharp-edged orifice or a symmetrical smooth-contraction/sudden-expansion combination.

The behavior of foam flowing through constrictions is very different from that of a Newtonian fluid; this must be taken into account in theoretical modeling or practical design work.

Acknowledgments

The work described was carried out in the Mechanical Engineering Department, University of Southampton, by final year undergraduate students N. M. Hawley, S. Jones, and A. P. Holland. The foam generator was loaned and foam materials were supplied by the Fire Research Station, Department of the Environment.

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