Bubble size effects in foams

J. R. Calvert and K. Nezhati*

The problem of measuring bubble size distribution in liquid–gas foams is discussed. Results of some bubble size measurements are presented, and an attempt is made to relate the bubble size information to the rheological properties of the foam. A clear relationship is found, but more work is required to reduce the experimental uncertainties and explain some anomalous results. A preliminary investigation of the effect on the bubble size distribution of passing the foam through a pipe is presented. Definite effects are seen, and further work is planned in this area. A method of measuring bubble size distribution continuously in a small region of a flowing foam would be of considerable use. Various ways of doing this are being investigated.

Keywords: *foam, bubble size distribution, flow, rheology*

Introduction

Foams consisting of gas bubbles enclosed in a liquid matrix show highly complex flow properties. Their behaviour is non-Newtonian and time dependent, and they can also show apparent boundary slip effects and compressibility. Discussions of some of these features have been presented by the authors[1,2,3]. The study of foams is not aided by a general confusion in nomenclature; in this paper, terms used are as defined previously[1].

One of the problems with experimental work on foam rheology is that results tend to be unrepeatable. Unless conditions are very carefully controlled, results are chaotic and contradictory, and it is extremely difficult to draw any valid conclusions. Under controlled conditions, however, it is possible to get repeatability within about 20% in many cases. Correlation of results from different sets of conditions still poses problems. As an example of this, the authors have found that two foams of the same expansion ratio (foam to liquid volumetric ratio), generated by the same apparatus, have very different properties if the flow rate or generator pressure is changed, or if the generator gauzes become slightly contaminated. Foams generated in different apparatus would be expected to be even more different.

The flow properties of a foam must ultimately depend on the fluid properties of its constituents and on the geometry of its bubbles. For two foams of the same expansion ratio and made from the same materials, differences can only arise from variations in bubble size. In general, to understand the behaviour of a foam it will be necessary to have knowledge of the bubble size distribution near any point, and of how that distribution affects the flow properties and is itself affected by flow processes.

This paper is concerned with a discussion of the measurement of bubble size distribution and with an initial analysis of some experimental measurements of distributions and their relationship to a rheological model.

Measurements of bubble size

Ideally, a bubble size measuring system would give information about the distribution of bubble sizes near a point anywhere within the bulk of a foam. This is not generally possible since, even more than in simpler fluids, the measuring process is likely to alter the local structure. Remote measuring systems are usually either optical, requiring a reasonably transparent material, or ultrasonic, which is unlikely to have the resolution required for this type of application. Optical methods have been used, however (eg Ref 4). It is hoped in the future to develop a method using techniques similar to those used in laser Doppler velocimetry to give a continuous indication of bubble size and bulk foam velocity. It is possible that such a system could be used to make measurements a short distance inside the bulk of the foam.

A number of approaches to obtaining average values over a relatively large volume are possible. For example, the electrical conductivity of a foam will be a function of both bubble size and expansion ratio. Similarly, the speed of sound in a foam may be useable. However, both these approaches would need development, and might need an independent method of determining expansion ratio. They are unlikely to be able to give bubble size distributions, or measurements in a small enough region to obtain variations across a flow field. To achieve these results, it is necessary to examine the foam at the individual bubble level, rather than the bulk fluid level. A method which has been used in gas–liquid dispersions (equivalent in some respects to foams of expansion ratio approaching 1) is to use electrodes to detect the passage of individual bubbles (eg Ref 5). However, this method is not likely to be so effective at high bubble densities, and in any case could well modify the flow it is observing. It cannot be used for stationary foams.

Pending the outcome of new developments, simpler methods have been employed in the current investigation. These rely on direct observation of the foam at or very close to a free surface. This will inevitably introduce distortions, some of which can possibly be estimated and allowed for; others must await comparative measurements by other methods.

For early and restricted observations, a travelling microscope was used. A sample of foam was inspected to determine either the diameter of individual bubbles, or the number of bubbles in a prescribed area. This was extremely laborious and was subject to error arising from decay of the foam during the measuring period. For later observations, a sample of foam on a microscope slide was photographed at a magnification of between 40 and 80. The microscope was focused on the top of a small sample of foam lit from below (thus ensuring that most of the field was in reasonable focus and of uniform contrast). It was possible to take photographs well within the period (about 2 minutes) for which the foam was reasonably stable.

A simple alternative to this method might be to observe the foam through the microscope slide. This should give interesting information concerning the differences (if any) between the bubbles near to a free and a solid surface. A third approach would be to use a narrow gap cell between two plates. In this case, it should be relatively easy to measure individual bubbles, and to correct for the dimensional distortions introduced, although sampling errors could be hard to estimate and two solid surfaces would be involved. It is hoped to investigate all these systems in the future.

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* Department of Mechanical Engineering, University of Southampton, University Road, Southampton SO9 5NH, UK

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A typical photograph is shown in Fig 1. As may be seen, there are a few very large bubbles, which tend to dominate the picture, and a wide range of smaller ones. A typical print contains about 170 discernible bubbles; obviously this total varies (by about 2 to 1 in this work) according to the average bubble size. The prints are of poor contrast, although improvements in technique could improve this. It is possible to see small bubbles through large ones, and to identify the outlines of large bubbles below the outer layer; both these cause problems in analysis.

The photographs may be analysed manually, but various semi-automated methods were investigated. The first used a Quantimet image analyser (primarily designed for metallographic work). While suitable in principle, this was unsuccessful in practice because of the low contrast of the photographic prints and the ability to see small bubbles through larger ones. Similar problems occurred with two different commercially available microcomputer-based image analysis systems. In all these cases, it was necessary to select one bubble image, adjust threshold and contrast levels to isolate it, log its dimensions, and move on to the next—an extremely laborious process. More elaborate (ie expensive) image analysis systems could probably solve the problem, but were not available. Eventually, the analysis was done on a Zeiss TGZ3 device, which works by the manual matching of the size of a light spot to each bubble image, followed by automatic logging of the counts in each size range and marking of the image to avoid duplication. All the results presented below were obtained by this method.

Apparatus

The foam generator used consisted of air and liquid jets impinging, followed by an 'improver' consisting of a tube containing various baffles and gauzes. The air and liquid were supplied under pressure from the same source, thus ensuring consistent mixing ratio at different flow rates. The foam compound used was Kerr 'Hi-Foam' synthetic (fire fighting) foam compound at 3% concentration in water. The liquid flow rates used were between 0.5 and 2 litre/min.

Rheological measurements were made with a specially made cone and plate head on a Contraves Rheomat 15 rheometer, as described previously[1].

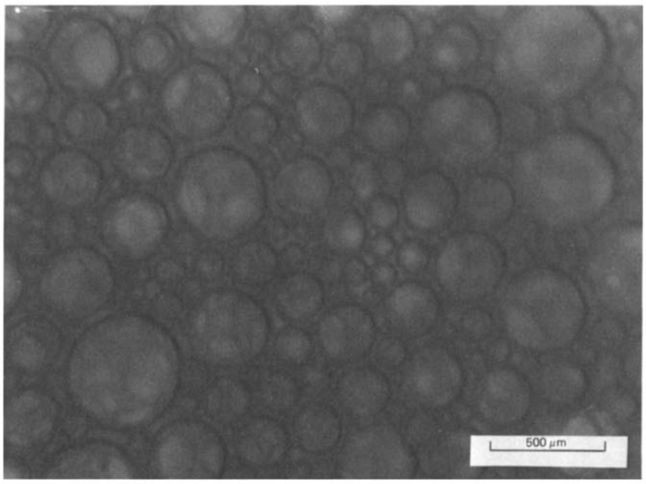

Figure 1 Typical foam photograph (R=4.2, W=15)

Bubble size distributions

Some typical bubble size distributions are shown as histograms in Figs 2 to 5 and as cumulative distributions in Fig 6. (The photograph in Fig 1 corresponds to the distribution plotted in Fig 2.) All distributions are based on bubble count; it may be argued that bubble volume should be used, as it relates to the bulk structure of the foam, or alternatively that bubble diameter is important in determining the relationship locally between shear rate and diameter. A case could also probably be made for bubble area, in relation to surface tension effects. However, sampling errors for the very few large bubbles presented have an unduly large effect on cumulative volume distributions, and it was decided that, initially at any rate, count alone would be used.

It may be seen that there is a fairly sharp cut-off at bubble sizes below about 50 µm. This is not thought to be a consequence of the measuring technique—50 µm corresponds to an image size of about 2.2 mm on the photographic print, and the smallest interval on the analyser was centred at 1.5 mm. The number of bubbles in the two smallest intervals was generally less than 1% of the total population. Similarly, there are few bubbles above about 250 µm, although they contribute quite a lot to the total volume and dominate the photographs. Most of the intervals above 250 µm contain 2 or less bubbles each out of a total count of 150–200.

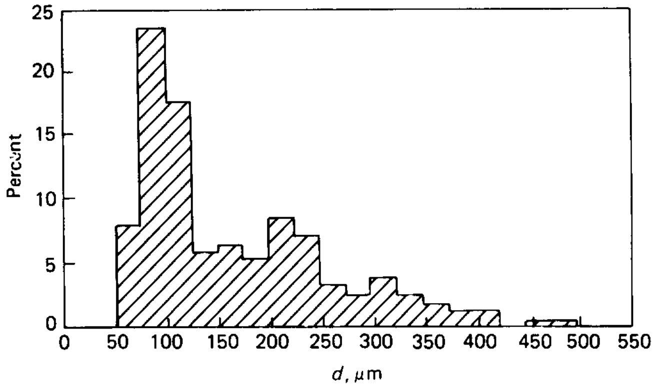

Figure 2 Bubble size distribution at R=4.2, low flowrate, W=15, d_{av}=169 µm, N=154

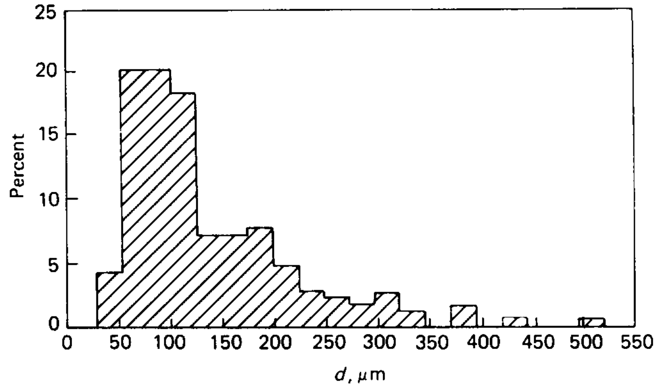

Figure 3 Bubble size distribution at R=4.2, medium flowrate, W=20, d_{av}=136 µm, N=201

Notation

d	Bubble diameter, µm
d_{av}	Average bubble diameter, µm
k	Consistency } parameters of rheological model, SI units
n	Flow index } parameters of rheological model, SI units
N	Number of bubbles in sample
R	Expansion ratio—ratio of foam volume to liquid volume
W	Foam generator water flow rate, arbitrary volume units
δ	Slip layer thickness, µm } parameters of rheological flow model
τ	Yield stress, N/m^2 } parameters of rheological flow model

Figs 2, 3 and 4 show distributions at about the same expansion ratio (4.2), but at different generator flow rates. It can be seen that they are in general of similar shape, but that the average bubble size tends to fall as the flow rate rises. Other distributions show the same trend, although perhaps not as clearly as these. They all have a peak at about 90 μm; there are also fairly consistently smaller peaks at larger sizes, but these are probably unreliable because of sampling errors.

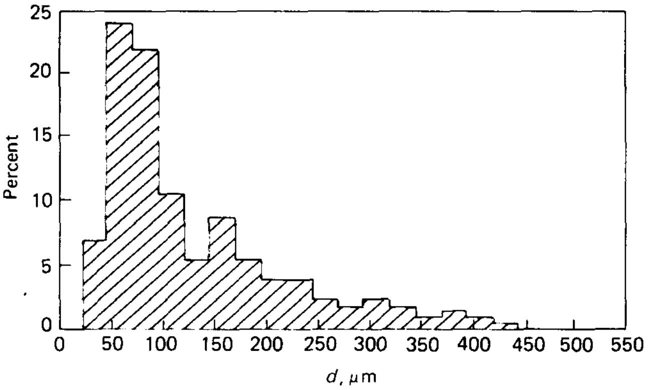

Figure 4 Bubble size distribution at $R=4.2$, high flowrate, $W=25$, $d_{av}=133\,\mu m$, $N=231$

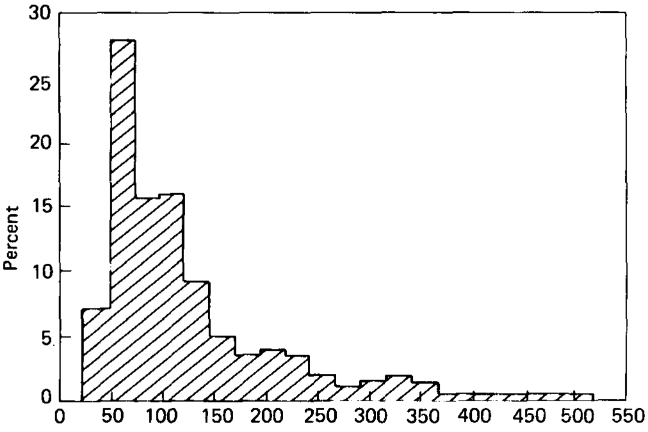

Figure 5 Bubble size distribution at $R=5.2$, low flowrate, $W=15$, $d_{av}=132\,\mu m$, $N=210$

Fig 5 shows a distribution at the same (water) flow rate as Fig 2, but a higher expansion ratio (5.2). The distribution is much the same. The average bubble size is rather less; however, although this can be seen on a number of distributions, it is by no means as definite a trend as that between bubble size and flowrate at the same expansion ratio.

Fig 6 shows the cumulative bubble size distributions for the same data, plotted on a log–normal basis. The graphs corresponding to Figs 3 to 5 are almost straight lines (virtually indistinguishable from each other over much of their range), suggesting that the bubble sizes are log–normally distributed. The graph corresponding to Fig 2 is displaced upwards, reflecting its larger average bubble size, and is also less straight than the others; further investigation is needed to decide whether this is a repeatable result for these conditions, or if this data set is in some way 'incorrect'. The log mean bubble sizes for the other 3 sets are around 110 μm, consistently a little greater than their median values of about 95 μm. The standard geometric deviations are about 2.

Relation between bubble size and rheology

It is possible to detect some relationship between average bubble size and rheological properties. It has been shown[1] that the flow properties of the foams considered here may be described by a 4-parameter model, involving yield stress τ, consistency k, flow index n and slip layer thickness δ (not strictly slip but rather a consequence of selective migration of large bubbles away from a wall), and that good correlations are obtained by assuming values of about $k=2.5$ and $n=0.4$ for all the foams tested. We may, therefore, seek relationships between yield stress, slip layer thickness, average bubble size and expansion ratio. Further refinement would replace average bubble size by some more detailed description of the size distribution. Table 1 gives some experimental results (including those of Figs 2 to 5) for these quantities.

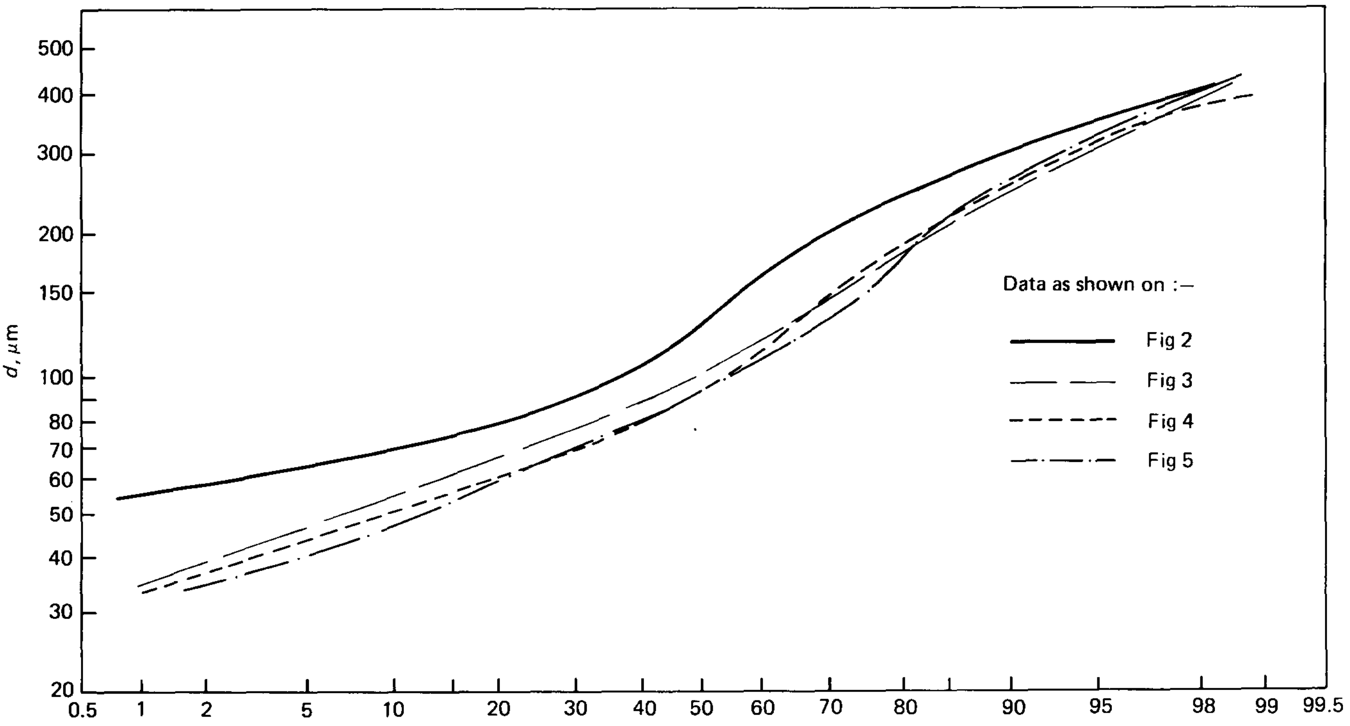

Figure 6 Cumulative bubble size distributions

Table 1 Dependence of slip layer thickness and yield stress on bubble size and expansion ratio

Expansion ratio R	Mean bubble size d, μm	Slip layer thickness δ, μm	Yield stress τ, N/m^2
2.3	155	74	1.0
2.6	153	49	0.6
2.7	139	90	1.0
3.0	121	40	1.2
3.0	201	64	1.0
3.1	165	54	1.3
3.5	146	49	0.9
3.6	127	33	1.2
3.7	188	35	1.0
4.0	186	51	1.2
4.2	133	35	0.3
4.2	136	37	0.4
4.2	169	23	0.5
5.0	148	33	1.0
5.2	132	26	1.5
5.3	180	27	1.0
5.8	219	23	3.1
6.1	207	23	3.0
7.1	150	23	2.7

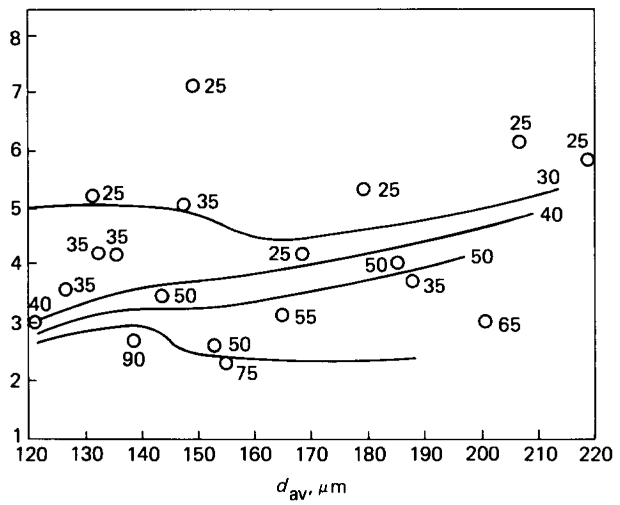

Figure 7 Variation of slip layer thickness with expansion ratio and bubble size. Numbers are values of δ in μm (rounded to nearest 5 μm)

There is considerable variation in the figures in Table 1, but some trends can be discerned. The slip layer thickness tends to increase as expansion ratio falls, and, to a first approximation, is independent of bubble size. This can be seen a little more clearly on Fig 7, where spot values of slip layer thickness (rounded to the nearest 5 μm) are plotted against expansion ratio and bubble size, with some contours of constant slip layer thickness sketched in. At expansion ratios greater than 4, δ is relatively uniform at about 30 μm, while at lower expansion ratios it increases fairly rapidly. This is likely to be connected with the transition between polyhedral and spherical geometry which occurs around this area[1].

The yield stress seems to go through a minimum at an expansion ratio of about 4. This may be seen on the sketched contours of Fig 8, and, again, this is probably related to the polyhedral/spherical transition. It also falls with falling bubble size, in general agreement with experience in the fire protection industry, where smaller bubbles are considered to lead to a more fluid foam. The increase of yield stress at lower expansion ratios is unexpected, since in the limit of unity expansion ratio the foam becomes pure liquid—in fact almost pure water—and the yield stress must become zero.

Effect of pipe flow

It is a belief in the fire protection industry that passing a foam through a rough pipe improves its quality, although quite what is meant by improvement is not always clear. This operation cannot change the expansion ratio of the foam (except for a secondary effect arising from the higher internal pressures of smaller bubbles), and any effect must arise from redistribution of bubble sizes. Two effects are possible: mild shearing could promote bubble coalescence and so increase the average bubble size, while severe shearing could break up bubbles into smaller ones. It is also probable that there will be a spatial redistribution of bubble sizes across the pipe area.

In order to investigate this, foam was passed through a 2 m length of 25 mm diameter steel tube, and the bubble size distributions at outlet were compared with those of foam which had not undergone pipe flow. The method used, of course, cannot easily handle variation across the pipe, and this will therefore increase the experimental uncertainty. (To avoid compressibility effects, the overall pressure drop across the pipe was kept small—of the order of 1 kPa.)

Some of the results are shown in Figs 9 and 10. In both cases, but particularly in Fig 10 (the lower expansion ratio), the average bubble size has increased, mainly as a result of elimination of the smallest sizes. Fig 10 also shows a substantial increase in the larger bubbles. The results have not yet all been fully analysed, but inspection of average bubble sizes before and after pipe flow shows no clear trend. Out of 10 sets of results, 5 showed an increase, 3 a decrease and 2 no change. It is probable that both further analysis and improved experimental techniques will be required to make any further progress.

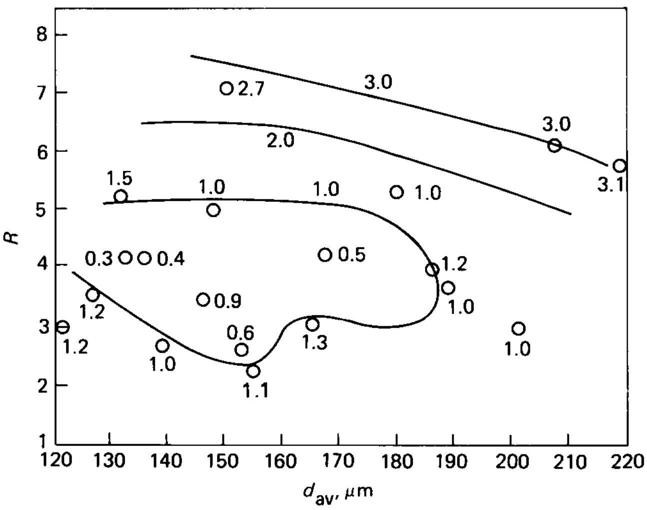

Figure 8 Variation of yield stress with expansion ratio and bubble size. Numbers are values of τ in N/m^2

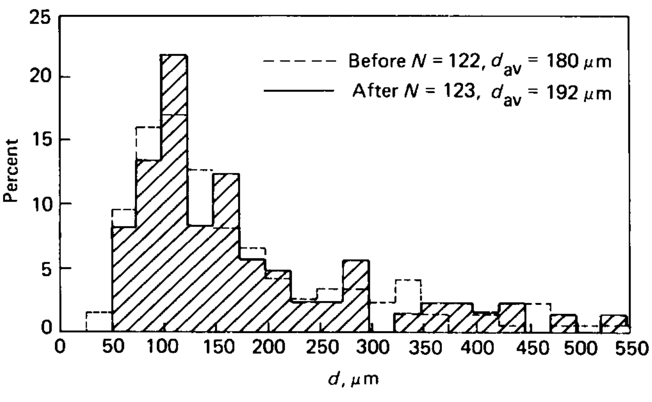

Figure 9 Effect of pipe flow, $R = 5.4$, low flowrate, $W = 10$

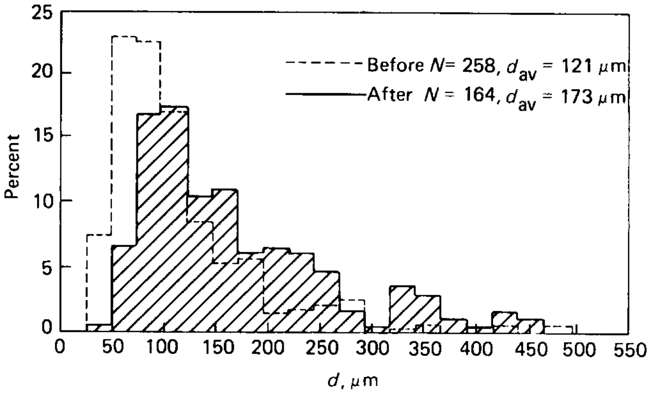

Figure 10 Effect of pipe flow, R=3.1, high flowrate, W=25

No rheological data are available for the foam which travelled through a pipe; this is another area where more work would be useful.

Conclusions

Relatively straightforward methods can be used to study the bubble size distributions in liquid–gas foams. The results can be related to the measured rheological properties of the foams. In order to obtain consistent results, it is essential to control experimental conditions very closely.

To a first approximation, the slip layer thickness is a function of expansion ratio only, and independent of average bubble size. The yield stress depends on both expansion ratio and average bubble size, and is a minimum at expansion ratios around 4 and for small average bubble size.

If a continuous method of measuring bubble size distributions were developed, it should be possible to improve the observed correlations considerably. It might also then be feasible to work backwards and develop a foam generating system to produce a foam with some desired rheology.

Foam is modified by flowing through a length of rough pipe. Further work is needed to clarify the effects of both bubble size distribution and rheology.

Acknowledgements

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Book review

High Temperature Heat Exchangers

Eds Y. Mori, A. E. Sheindin and N. Afgan

This book is a collection of forty-five papers from the XVII Symposium of the International Center for Heat and Mass Transfer on High Temperature Heat Exchangers, held in Dubrovnik, Yugoslavia in August 1985. The book is structured into four sections: (1) High temperature heat exchangers development, (2) Basic problem in high temperature heat exchangers, (3) Heat exchangers for high temperature recovery, and (4) High temperature heat exchangers for future power plants and industrial process applications. Each section contains one keynote paper which overviews the subject. Two additional summary papers are included, one on high temperature reactors and one on energy recovery programs in the Economic Commission for Europe (ECE).

Being a collection of symposium papers, the book is not organized by topic to facilitate quick location of the valuable content of the papers. Included in the text are three papers on convective heat-transfer augmentation, four papers on radiative heat-transfer augmentation, one on temperature dependence of fluids, 21 papers on performance modelling, and seven papers describing processes and plant systems.

Both regenerative (including packed beds) and recuperative types of heat exchangers are modelled in some analytical treatment in a total of 21 papers. Design information, presented in 17 papers for regenerative types and 14 papers for recuperative types, includes convective performance, radiation effects, and techniques to accommodate thermal strain. Materials for high temperatures are discussed in seven papers.

Specific applications describe in this book for high-temperature heat exchange include energy conservation in process industries, high temperature nuclear reactors, nuclear gasification of lignite or hard coal, and magnetohydrodynamic systems. One novel system described in this text recovers heat from molten slag at 1500°C. Hot slag is normally dumped into a cooling yard and left to warm the atmosphere.

All but three of the papers in this volume were contributed by non-USA authors, mostly from Japan, Germany, and the USSR. Because of the many different topics covered and lack of focus, this volume would be valuable only to those individuals involved in specific high-temperature heat exchange. However, the valuable information warrants that this book should be avaialble in technical libraries.

James R. Mondt
Staff Research Engineer,
GM Research Laboratories,
Warren, MI, USA

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