Quantitative estimation of polydispersity of gas–liquid foams

Abstract

The expansion of equivalent (spherical) foam is suggested as a macroparameter characterizing high-expansion foam polydispersity. This parameter represents the role of foam polydispersity in various processes well. A simple device for this parameter measurement is described below. As an example of the capabilities of the method under consideration the results of the curves of change of the sparging foams polydispersity in time are given.

Keywords: Spherical foams; Foam expansion; Polydispersity; Measuring device; Measurements

1. Introduction

The main feature of gas–liquid foams that distinguishes them from other dispersed systems is that foams have a certain *structure*. Foam structure is defined by three parameters—foam expansion, average bubble size and polydispersity. Foam expansion is the only macroscopically characteristic feature (foam expansion $K = V_f/V_l$, where V_f is foam volume and V_l the volume of a liquid contained in it).[1] There is no macroscopical criterion for the estimation of foam polydispersity.

Polydispersity of foam is intuitively understood as the distribution of foam bubbles in their sizes. Some authors [1–3] tried to describe this distribution by any universal dependence. These attempts appeared unsuccessful for two reasons:

(1) The distribution of foam bubbles in their sizes (as well as the average bubble size) depends on the method and conditions of foam making [4].
(2) This distribution continuously varies in time (owing to diffusion of gas between bubbles-*coarsening*).

The curves in Fig. 1 show, how the function of bubble size distribution transforms in time τ from the moment of foam making (figure is taken from the monograph [3] referring to [2] and concerns sparging foam with initial expansion 25). It is obvious, that these curves cannot be described by one dependence.

All this makes the estimation of foam polydispersity by using the function of bubble distribution in their sizes inconvenient, and practically meaningless.

2. Theoretical

Manegold [5] subdivided foams into spherical, cellular and polyhedral. There is no precise demarcation between cellular and polyhedral foams. But the concept of "spherical foam" is quite definite:

> *Spherical* foam is a dense package of spherical gas bubbles in a liquid.

If all bubbles have the same diameter, such spherical foam is a *monodisperse* one. It is known, that a dense package of identical balls forms a hexagonals or a cubic structure where the elementary cell is a plane-centered cube. The simple geometrical dependences (see, for example, [6]) produce a gas fraction volume of the following structure $\Phi_g = 0.740$, that corresponds to expansion $K_o = 3.855$ (≈ 4) (see footnote 1).

By filling in backlashes between monodisperse spherical foam bubbles with much smaller ones, it is possible to receive any kind of polydisperse spherical foam expansion. Thus, spherical foam expansion K_o can be anything—from 4 up to ∞.

Note, that the larger the variety of sizes of the bubbles, the larger the spherical foam expansion will be, i.e. the larger is its *polydispersity*. In other words there is a correlation between expansion and polydispersity of spherical foam. Our suggestion is to regard the expansion of spherical foam K_o *simultaneously* as the characteristics of its polydispersity.

The pressure in foam liquid (in foam channels) p_c, as a rule, is less than the external (atmospheric) pressure p_a by $\Delta p_c = p_a - p_c$, which we named *capillary rarefaction*. Spherical foam (any polydispersity!) can exist only at $p_c = p_a$ and $\Delta p_c = 0$. With the growth of capillary rarefaction the foam bubbles are

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[1] Expansion is connected with gas content Φ_g through the relationship $K = 1/(1 - \Phi_g)$.

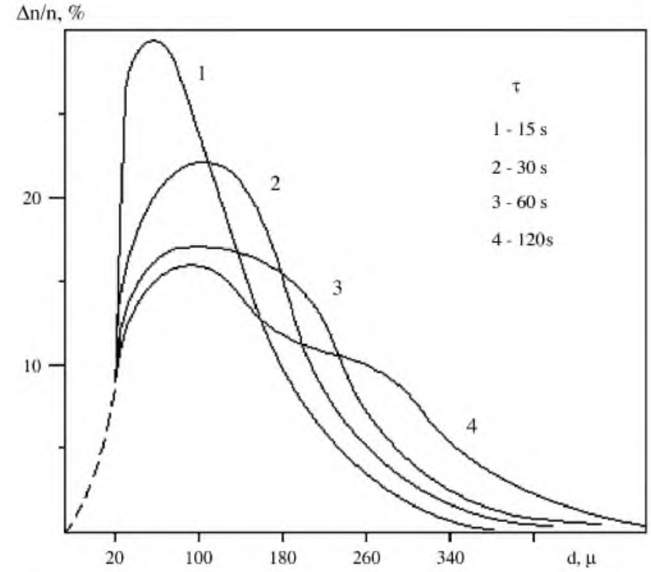

Fig. 1. Change of foam bubbles size distribution in time (according to [2]).

deformed and foam expansion grows. By changing capillary rarefaction, it is possible to change foam expansion.

In Fig. 2 the device that allows to change the foam expansion by handling its capillary rarefaction is shown. The foam is located in vessel 1 with the foam-forming solution 2 between double walls. The foam sample 3 has a free surface facing the atmosphere. The bottom of the internal vessel is a small-grain ceramic filter 4 through the pores of which the foam liquid contacts the liquid in the external vessel.

Let us fill the device vessel with *spherical* foam. The pressure in the foam liquid is equal to atmospheric pressure p_a (to make things simpler we assume that there is no gravitation). If pressure p_e in the external vessel is atmospheric, the whole system is in balance (Fig. 2a). Through a branch pipe 5 we shall pump out air from the external vessel until we reach pressure $p_e < p_a$ (Fig. 2b). The difference in pressure $\Delta p = p_a - p_e$ causes the foam liquid to flow through the filter into the external vessel until the pressure in the foam channels decreases to $p_c = p_e$. The foam expansion increases, foam bubbles are deformed, and the foam becomes *cellular* (an average expansion foam).

Let us continue to pump out air from the external vessel. Capillary rarefaction and foam expansion K_o will grow, and the gas bubble shape will gradually approach the polyhedral one. That way, from spherical foam it is possible to receive "dry" foam of any (however large) expansion (Fig. 2c).

If we continue to increase pressure p_e in the external vessel, the process as shown in Fig. 2, will be reversed. In particular, when pressure p_e becomes equal to atmospheric, the foam again becomes spherical.

With these transformations gas bubbles change their *shape* from spherical to polyhedral and back again. But if the gas diffusion carryover between bubbles does not occur *every single* bubble will keep its *volume*. It means that not only the average size bubbles but also their distribution in size is preserved, i.e. foam *polydispersity* is preserved. It allows regarding the foam in Fig. 2a as *spherical foam*, which is *equivalent* to high-expansion foams.

So, foam polydispersity in Fig. 2b and c is the same, as the one in the equivalent spherical foam in Fig. 2a. But we have decided to describe polydispersity of spherical foam by its expansion K_o. The definition is as follows:

> Polydispersity of any (high-expansion) foam is determined by expansion K_o of its equivalent spherical foam.

How does polydispersity influence foam properties and processes proceeding in them? If there is no quantitative criterion for the estimation of foam polydispersity, it is impossible to answer these questions. We shall take a look at how these questions are solved with the help of parameter K_o.

Example 1. *How does the distribution of volume gas fraction (foam expansion) along the foamy column in a state of hydrostatic balance depend on polydispersity?*

The distribution of expansion K along the foamy column z in a state of hydrostatic balance is derived from the differential

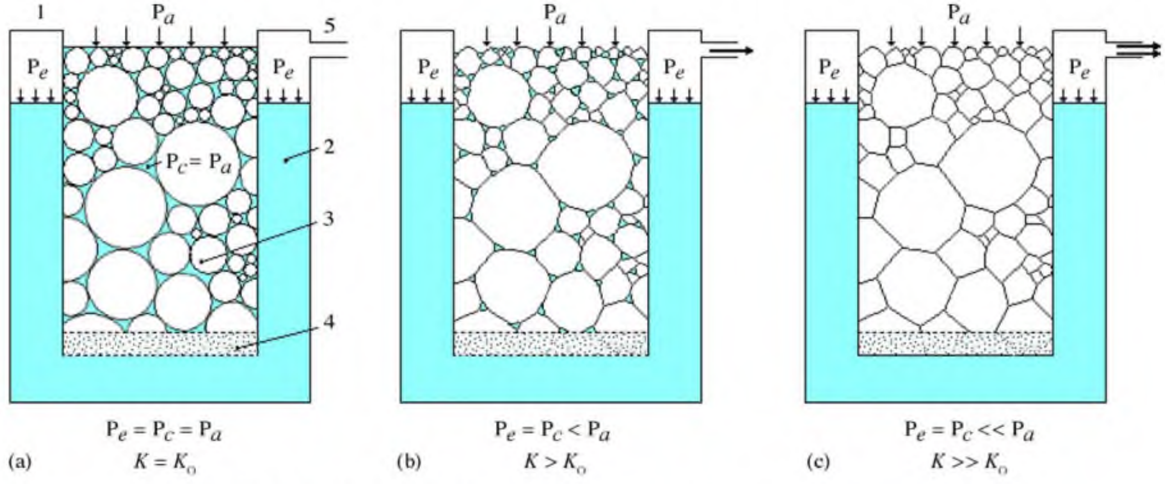

Fig. 2. The device that allows to change the form expansion by handling its capillary rarefaction.

equation

$$\frac{\mathrm{d}p_c}{\mathrm{d}z} + \rho g = 0,$$

where ρ is liquid density, and g the gravitational acceleration [7].[2] The solution of this equation is function

$$K(z) = \left(az + \sqrt{K_o}\right)^2,$$

where the integration constant is defined by a boundary condition $K(0) = K_o$, and $a = constant$.

This dependence determines the influence of foam polydispersity on volume gas fraction distribution along the foamy column in a state of hydrostatic balance.

Example 2. *How do foam filtration properties depend on polydispersity?*

The flow conductivity of foams is determined by factor k in the Darcy law: $q = k\rho g$. In [7] (see also [9]) the value factor of gravitational filtration of foams was received:

$$k = \frac{d^2}{36\mu(K-1)^2 K_o}$$

where d is the average (equivalent) diameter of foam bubbles and μ the liquid viscosity.

Thus, the liquid flows faster of all through *monodisperse* foam. With the increase of polydispersity the hydraulic resistance of foam increases proportional to K_o.

Example 3. *How does polydispersity influence foam drainage?*

In literature many cases of theoretical and experimental research of foam drainage have been described. But there is not a single one where this problem has been researched. Sometimes it is possible to judge polydispersity of the investigated foams from some casual data.

For a long time it has been known, that the drainage of liquid from foams begins with some delay τ_r. In some cases it takes 5–6 min from the moment of foam making to the beginning of drainage (see, for example, [10]). But in some cases drainage begins practically instantly. In 1978 we explained this phenomenon in the following way (see [8]): after foam generation some time is required for spherical foam to be formed at the bottom of the foamy column as a result of liquid running into it. Thus, the pressure in the bottom of the column becomes equal to the atmospheric one and drainage begins. If the foam becomes spherical from the very beginning, drainage starts immediately after its making.

Parameter τ_r is very important for the use of foam in the extinction of flammable liquid fires. In September 1975 at a symposium in Brunel University Corrie presented the results on research in the field of the properties of fire-fighting foams [11]. In particular, the dependence of the drain beginning time on the foams received by shaking two different surfactant solutions (Fig. 3) was identified. It came as a surprise to discover that foam, which allowed a faster growth τ_r with expansion K increasing (in sample 2), allowed instant drain ($\tau_r = 0$) at *a greater* expansion, than in sample 1.

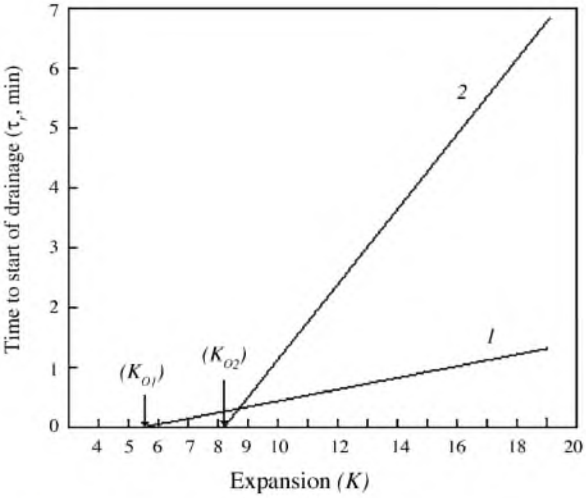

Fig. 3. Dependences of the drain beginning time on the foam expansion (according to [11]).

If we take into account, that liquid drainage begins, when the foam becomes spherical (in the bottom section) it becomes clear, that the segments of straight lines $\tau_r(K)$ on an expansion axis, give value of expansion K_o of *spherical* foam. From Fig. 3 it can be seen, that polydispersity of the first sample is equal to $K_{o1} \approx 5.5$, and the second $K_{o2} \approx 8.2$. The rate of liquid flow in the foam is inversely proportional to its polydispersity (see Example 2). Therefore, dependence 2 is more abrupt, than dependence 1.

As the parameter describing foam polydispersity, value K_o is included into parities of foam conductivity, of dependence of the form foam bubbles on capillary rarefaction, etc.[3] In all cases such estimation of foam polydispersity appears to be convenient and sufficient, and the knowledge of bubble sizes distribution function is superfluous.

Any macroscopical parameter should be measured. Going back to the description of the processes schematically submitted in Fig. 2, it is possible to offer such a program for parameter K_o measurement:

(1) High-expansion foam needs to be transformed into its spherical foam equivalent. For this purpose it is necessary "to return" the liquid to it so that $\Delta p_c = 0$ (namely $p_c = p_a$).
(2) To measure expansion K_o of this spherical foam. This will be the value of polydispersity of the initial foam.

The practical implementation of this program faces two obstacles:

(a) The reverse process of transforming high-expansion foam to spherical requires time, during which (because of coarsening) the disperse structure of foam changes. As a result,

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[2] The foreign reader can get acquainted with this essay in its translated (English) version Kolloidn. Zh. [8].

[3] These parities are received only in our essays published in Russian.

the received spherical foam appears *not to be* equivalent to the initial foam.

(b) In a gravitational field spherical foam can exist only in a thin layer (a few flakes of gas bubbles). Measuring the expansion of such foam technically is not simple.

3. Experimental device

In an attempt to define the polydispersity of various foams a simple device in which both these difficulties have been overcome was made. The measuring cell is a glass vessel 1 filled with foam-forming liquid 2 (Fig. 4a). A glass tube 3 was soldered into the top part of the vessel. The end of the tube is flattened out so that a thin horizontal flat clearance (~1 mm) is formed. This clearance is located close above the liquid surface. The siphon device 4 provides a permanent liquid level in the vessel. The experimental foam moves to the bottom part of the vessel through tube 5. The foam penetrating the liquid breaks up into separate bubbles, which *instantly* make a spherical form emerging to the surface. As the ascending bubbles do not stick together and do not break apart, the polydispersity of low-expansion foams formed on a liquid surface is the same, as the polydispersity of the initial foam at the moment of its penetrating the vessel. Some layers of bubbles, directly adjoining the liquid surface are strictly spherical. In order to measure expansion K_o in this thin layer, a certain volume V of spherical foam is sucked away through a horizontal clearance in tube 3 into a thin-walled glass tube 6. The weight m of this foam is determined by weighing it on analytical scales. The expansion of foam is defined by the formula

$$K_o = \rho V/m$$

where ρ is liquid density.

The described device has allowed to study the change of polydispersity of sparging foams in time [12]. For this purpose a sparging generator shown in Fig. 4b was made. A siphon device 8 provided the permanent liquid level in sparging column 7, and a constant flow of air was admitted to the generator from the peristaltic pump 9. It allowed to keep the foam-generation process within a permanent for a considerable length of time. The output of the foam-generator 10 was connected to an input 5 of the measuring cell (Fig. 4a).

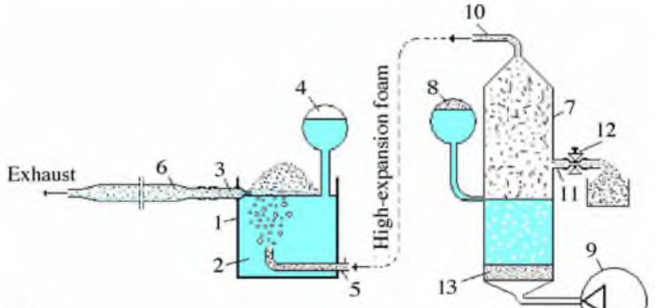

Fig. 4. The experimental device for measurement of foam polydispersity.

There was a foam output in the wall of the sparging column 11. A screw clip 12 adjusted the volume of foam that was extracted through the foam output. The larger the foam output, the slower the foam remaining in the sparging column moved, and the more time τ it took from the moment of foam making on the filter 13 till the moment of its penetrating the measuring device. This time was measured directly (by the speed of the moving foam in the sparging column) and was controlled by rates of air and foam, extracted through the foam output 11.

4. Results and discussion

The design of the sparging column allowed to change the porous filters 13 (Fig. 4b). Foams were produced from a 1% water solution of surfactant sulfanol NP-3. The foam expansion was measured on foam output 11 and was 23 ± 1, and the average bubbles size was ~0.2 mm.

Fig. 5 shows the curve changes of polydispersity K_o of two sparging foams in time τ. It is important to note, that both foams have been received on a small-grain ceramic filter with the same factory marks (POR-40), i.e. the same porosity. Therefore, the average bubble size for both foams was the same. But the distribution of filter's pores (which have no technical specifications), apparently, varied. It is possible to explain, that two samples of foam at the moment of making already had *different* polydispersity. At the entrance to the measuring cell of foam 1 polydispersity was $K_o = 4.25$. The first ~90 s a foam polydispersity grew. At this stage the intensive diffusion carryover of gas from smaller bubbles into big ones occurred and the difference in bubble sizes increased. As the smaller

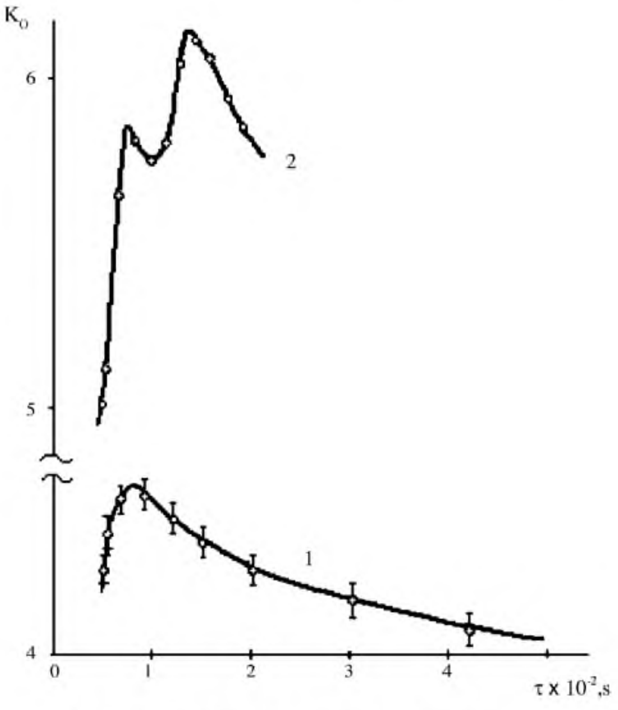

Fig. 5. Change of sparging foams polydispersity in time.

bubbles started to disappear the growth of polydispersity slowed down, dependence reached a maximum, the disperse structure began to level out and polydispersity began to decrease.

The second foam (curve 2) was more polydisperse from the very beginning. At the moment of entering the measuring cell its polydispersity was $K_0 \approx 5$. This foam identified a different course of change of polydispersity in time. But also in this case after the passage of maxima the foam polydispersity began to decrease monotonously. This result coincides with Manegold's observation [5] who noted, that in due course the share of bubbles in the foam, having some ("critical") size grows. According to the author [3] the critical size for sparging foams is $\sim$120–160 μm.

On curve 1 (Fig. 5) the limit errors of K_0 measurements are marked. It can be seen, that the errors of the offered method is $\sim$2.5%, and repeated measurements have shown quite a good reproducibility of the received results.

It is necessary to note, that the experimental results submitted in Fig. 5, are shown here only for the purpose of demonstrating the opportunities of the method. Consequently, we are going to carry out extensive research of foam polydispersity received in different ways, and the dependence of this parameter on different factors—the surfactant nature and its concentration, foam expansion, viscosity and temperature of foam-forming solution, etc.

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