Research on foaming systems with application to problems in the oil industry at the University of Minnesota (Joseph's lab)

by D.D. Joseph, August, 1998

The research focuses on studies of three-phase solid/liquid/gas flows in vertical foaming bubble reactors. Two categories of applications are being considered. (1) Refining, focusing on the role of catalyst particles in hydrocarbon streams which foam at high pressure and temperature and (2) Particle transport in foam applied to drill cuttings and proppants.

The purpose of this document is to draw attention to obstacles that prevent our University-based research on fundamentals actually useful in the applications previously mentioned. I am certain that the way to make progress is by continuous interaction of the U of MN and Intevep on a nearly weekly basis. The directions of the research in both places must be by mutual interaction.

Literature generated at the University of Minnesota. The evolution of our research and thinking on foams can be found in the following four references, listed chronologically.

1. J. Guittian and D.D. Joseph, How bubbly mixtures foam and foam control using a fluidized bed. *Int. J. Multiphase Flow.* **24**, (1), 1-16 (1998).

2. D.D. Joseph, Understanding foams and foaming, *J. Fluid Eng,* **119**, 497-498 (1997).

3. C.Mata & D.D. Joseph, Foam Control using a bed of hydrophobic particles, *Int. J. Multiphase Flow.*

4. C. Mata, Three-phase gas/liquid/solid foaming bubble reactor and self-lubricated transport of bitumen froth, Ph.D. Thesis, University of MN, Dept of Aerospace Engineering & Mechanics, (1998).

5. Ling Jiang, Fluidization of particles by a gas stream through a batch particle/liquid suspension in a tubular bubble column. Masters Thesis (1998).

I. Preliminary observations to orient the reader.

The three phases in our solid/liquid/gas flows can be described differently as

(1) solid/bubbly mixture/foam flows; the bubbly mixture and foam are different (different phases) of gas/liquid flow. Therefore we can describe the flow of bubbly mixtures and foam as two phase two-phase flows (the reader should try to understand the meaning of all these repeated words).

As in all multiphase flow work, here three phase (1) flows, it is necessary to generate "flow type" charts in which the qualitatively different distribution of phases appear. In the case of (1) there is only the literature previously cited, just touching the edge of this massive problem It can be said that "flow types" for the phases (1) in vertical bubble columns have as yet to be catalogued.

Catalogues of flow types are indexed to the flow rates which are inputs. We don't input foam and bubbly mixture; so foaming systems in which the phases (1) are more complicated; the phases are not inputs but arise as a consequence of the fluid dynamics of foaming liquids. The inputs for our works are flow rates for *gas, liquid* and *solids* which are loaded in the column but not injected during the operation are *loaded in batch*. When they are injected continuously they are said to operate in a *continuous mode*.

The table-top cylindrical glass column described by L. Jiang (1998) operates with batch liquid and particles and continuous gas. The big slit column used for research of Guitian and Joseph [1998] and Mata & Joseph [1998] is also batch in solids but has continuous input of both gas and liquid. A small slit column in which provision is also made for the continuous injection of particles is described in Chapter of Mata's [1998] Ph.D. thesis.

This column is also equipped with an excellent mechanism for measuring solid *hold up* which is discussed just below.

The *hold up* of one phase relative to another is the ratio of their average velocities. Suppose that Q is the volume flow rate of a certain phase. In steady state this is uniform and equal to the input value. Let $W(L)$ be the volume of the phase in the length L of the column. Then the average area $A(L)$ of the phase is given

$$A(L) = \frac{\Omega(L)}{L}$$

and the average phase velocity is

$$V(L) = Q / A(L)$$

To compute $V(L)$ we must measure $W(L)$.

A direct measurement of the holdup of solids, liquids and gas can be done with the device described in Chapter of Mata's thesis. Hold up data can also be obtained by measurements of pressure as in the column by Guitian and Joseph. Unfortunately the small slit column in which we may implement continuous injection of particles together with a direct measurement of solid, liquid and gas hold up *has not yet been implemented with pressure trandusers.*

II. Refining

The problem is to understand foam control in a vertical reactor in which heavy crudes are broken down by hydrogen using catalyst particles. Foam appears at high temperatures and

pressures and it is not wanted; catalysts should contact liquid rather than gas. [I THINK THAT HIGH TEMPERATURE AND *NOT* HIGH PRESSURE PRODUCES FOAM??]

The *goal* of our refining research is to understand the role of fluidized particulates in a hydrocarbon stream. Carlos Dassori has a good idea for the goal of our research. He says that

"... We are interested in the area of foam control, that is, trying to minimize it or just trying to make it of a certain size and behavior.

At this point the first subject looks like the best candidate to begin with.

In particular, we are interested in continuous systems with gas, liquid and solids continuous feed. It would be quite relevant to obtain an expression that will tell the increase in solids holdup in the bubbly slurry section because of foam presence with respect to pure sedimentation case in the absence of foam. This expression will have to be a function of operating conditions and physical properties.

There will be necessary to have an additional expression to tell if foam occurrence is possible under such conditions.

In this way we'll draw a map of foaming region boundaries and a similar map for solids holdup enhancement (probably), in terms of a set of parameters to be identified.

This kind of product will be quite valuable from an engineering point of view."

Before we enter into this program we must consider whether or not our aqueous system can give the information needed for a commercial hydrocarbon reactor. Since at Minnesota we don't work with high temperature foaming hydrocarbon streams we have defined our problem as:

- Find the aqueous foaming system (fluid, surfactant, particles and operating conditions) which most closely models the foaming hydrocarbon system. Let's refer to this as a "model aqueous foaming system."

II.1 Model aqueous foaming system

We don't know where the foam is or any of the other details about the real reactor. All the knowledge is deduced from the output data; you can't look into the reactor. This means the problem of finding a "model aqueous system" is not properly posed since we don't know enough about the system we are trying to model.

II.2 Matching the characteristics of hydrocarbon streams

We need to identify the characteristics of the hydrocarbon streams relevant to a determination of model aqueous system. The catalyst particles used in the hydrocarbon streams are silicates, alumina or coke. I want to know which of these particles is oleophilic and which oleophobic; it makes a difference. Certainly coke is oleophilic. An oleophilic particle in a hydrocarbon stream is equivalent to a hydrophilic particle in an aqueous stream. We know that hydrophobic particles are more effective in suppressing foam (Mata & Joseph, 1998); they are also more effective in transporting particles in foam (Mata, 1998) because of air attachment. These properties of hydrophobic particles in aqueous solutions may be taken up by hydrophilic particles in a hydrocarbon stream. This could be important for suppressing foam in commercial hydrocarbon reactors.

We can study the action of oleophilic particles in a hydrocarbon stream using hydrophilic particles in an aqueous stream. This suggests that we may get an active foam suppression in a hydrocarbon stream with hydrophilic particles like glass or possibly silicate.

The foam quality and the disposition of the foam is important but evidently is not known.

Matching of the model foaming system with the CANMET reactor can be achieved, but not uniquely. Mata and Joseph (1998) showed that such a matching could be achieved with different surfactants. This is positive, for obvious reasons, but the gas holdup vs. gas velocity is only one property, certainly important, of the system. It does not determine the partition of foam and bubbly mixture; the foam quality and stability is not determined since the same result can be achieved using different surfactants. For this, and other reasons, the matching of the e_g vs. U_g with CANMET will not tell us about the comparative response of these two systems to foam suppression using fluidized particles.

For a more complete matching of the commercial and model systems we should attempt to match the solids hold up. Unfortunately the solids hold up in the commercial reactor is not known. One possible method of inducing such a match is to choose the density of the particles in the model system to match the drag/weight ratio in the commercial system in which particle densities are in the range 1.1 to 1.4 g/cm^3. Later I will argue that we can use a Stokes drag in the commercial and model reactor because the Reynolds number based on the slip velocity of particles and their small diameter is small. I would like us to consider making the estimate of drag/weight ratio in the commercial system.

The Reynolds number may be important for dynamical similarity. For this we need to know Ura/m where U is the average velocity of the bubbly mixture, r is its density, m is its viscosity and a typical length. The data I have so far from Carlos Dassori and other sources (CANMET)

U from 0.2 to 20 cm/sec

r from r_l (1-f); we might take $f = 0.4$, then $r = 0.6r_l$. Maybe the liquid in the hydrocarbon stream r_l= 1gm/cc, $m = 0.3cp$; this is about 1/3 the viscosity of water.

I would like these values to be reviewed. The Reynolds numbers coming from these estimates is

$$\frac{Ura}{m} \approx \frac{U \times 0.6 \times 100}{0.3} = 200aU$$

There are two Reynolds number, a flow and particle *Re*. For the flow Reynolds number we may estimate $U = 10$ cm/sec and *a* is the diameter or gap size of the reactor $Re \approx 2000a$. for the laboratory columns the gap size $a = 0(1)$cm and $Re \cong 2000$, still laminar. We see turbulent flow when the liquid and gas are introduced through conical distribution but the flow appears to be more laminar when the gas is first passed through a fixed bed of large spheres. With good distributors, the flow is much more laminar.

The diameter of Canmet's commercial reactor is $a = 100$ cm, hence Re = 200,000. This corresponds to a mildly turbulent flow.

The flow Reynolds number of laboratory and commercial reactors cannot be matched without making an overly heroic effort. The flow Reynolds number is important for flow resistance and mixing of particles. The estimates just given suggest that we will get better mixing in commercial reactors. Flow resistance is small in any case. We could hope that flow Reynolds numbers are not of great importance in commercial reactors and that they need not be manipulated in our model system.

A typical diameter for a particle in the commercial reactor is 500μm = .005cm. Moreover the correct *U* is a slip velocity, much smaller than 10 cm/sec. So we find that with such a small U 0(1) cm/sec and $a = 0.005$ cm, $Re = 0(10^{-1})$.

The particle drag forces are close to Stokes drag D = 6pamU locally.

We should make a tentative assessment of the effects of the Reynolds number. The analysis I just gave suggests that we get a laminar drag locally on the small particles both in the commercial and model reactor. However there will be much more intense mixing in the Commercial reactor.

III. Particle transport in foam applied to drill cuttings and proppant

Aqueous foams are used to transport drill cuttings in underbalanced drilling for cleaning drill holes of cuttings and to transport proppants in fractured reservoirs. Hydrocarbon foams appear not to be used in these applications.

Many of the holes which are shallow enough for underbalanced drilling using foams are horizontal and the general configuration of transport of proppants in fracture models is a long thin slot in which sand is injected horizontally and moves forward as it falls. Our bubble columns are all vertical, hence are not matched to these applications.

The vertical bubble column described in Chapter of Mata's thesis is uniquely suited for the vertical transport of particles in foams. To my knowledge, results giving solids hold up in foaming bubble columns with continuous injection of particles have not been given before.

III.1   Research project for particle transport in foams

The following is taken from a proposal I wrote two years ago. The projects mentioned there are still worth discussing.

Summary.

The project is to correlate the properties of aqueous foams used in practice with the size, weight and hydrophobicity of particles. The impact of segregation of foamy liquids into bubbly mixtures and foams on transport and levitation of particles in horizontal, tilted and vertical holes is to be assessed. Holdup of particles, liquid and gas injected continuously in foaming slit flow loops will be measured. Methods of enhancing particle transport by creating foam downhole will be studied.

Principles.

We carried out studies of aqueous foams, foam formation and segregation and the fluidization of hydrophobic and hydrophilic particles in foams and bubbly mixtures. These are described in three papers listed at the end and a little appendix on the shaker bottle. The experiments were carried out in a vertical bubble column of slit type described by Guitian & Joseph [1997], and Mata & Joseph [1998].

The following ideas came out of experiments:

- There is a critical condition for foaming

- Foams segregate into bubbly mixtures below and foam above

- You can create foam downhole and in fixed beds

- You can control the size of the bubbles and foam with a good distributor

- You can suppress the formation of foam with a fluidized bed of hydrophilic particles and even more with hydrophobic particles

- The ability of a given foam to carry particles can be tuned to the size of particles; particles which are too large or too small cannot be well suspended.

Explanations.

Foam appears above a bubbly mixture when the superficial gas velocity is greater than critical. In the case of continuous injection of gas and surfactant-water the bubbly mixture will not foam unless the gas velocity U_g is greater than the value $U_g=aU_l+b$ where a and b depend on the foam and U_l is the liquid velocity. At any fixed gas velocity U_g, foam may be eliminated by increasing U_l so that $U_g < aU_l + b$. Foam is above because it contains much more gas, say 85% instead of 40% in the bubbly mixture; it's important to know when and where foams occur. You can foam *in situ*, without an interface, only if the gas holdup in the bubbly mixture reaches a close packed limit in which bubbles are forced together and change topology. Foam will stratify and then segregate; water falls out; when too much water is on the bottom the foam will change to bubbly mixture or even pure liquid.

Particles don't really fluidize in foam; they can carry particles however. Particles are carried away by foam or they drop out of the foam, but they don't circulate. Moreover, foams which will carry some particles will not carry others. Aqueous foams carry hydrophobic particles better than hydrophilic.

Implications

The tendency of flowing foams to segregate means that in horizontal drilling the bubbly mixture below should have a harder time levitating particles off the bottom than if the hole were full of foam. Segregation and transport times should be known in practical applications. it is best to inject foam under particles because if particles enter the bubbly mixture below they will not get into the foam. This opens the strategy of downhole and in-situ foaming for hole cleaning of transport application. We would introduce foam by rapid

bubbling of gas through liquid downhole, under the foam. It is necessary to recognize the type of particles, size, weight and degree of hydrophobicity, which can be suspended in the foam used in field application. Foams, and distributors controlling the size of bubbles in the foam can be tuned to the actual cuttings or propants being used. You ought to know what particles can be carried by your foam.

III.2   Shaker Bottles

These are used to measure foaminess and stability of foams. You shake the foaming water in a controlled way; you get a foam head and the head height gives the foaminess. The rate of collapse of the head gives the foam stability. We can use this technique to test your oils.

My student Ling Jiang has used shaker bottles to test stability of foams when particles are present. She did one test with different size particles. Small and large particles fall out of the foam. Intermediate size particles do not fall out. There is an optimal size for which the solids fraction of particles stuck in foam to the total volume of particles (fixed and the same for all tests). So a given size cutting will be effectively removed by a foam drilling mud, with removal of other sizes being less good (see Figure 1).
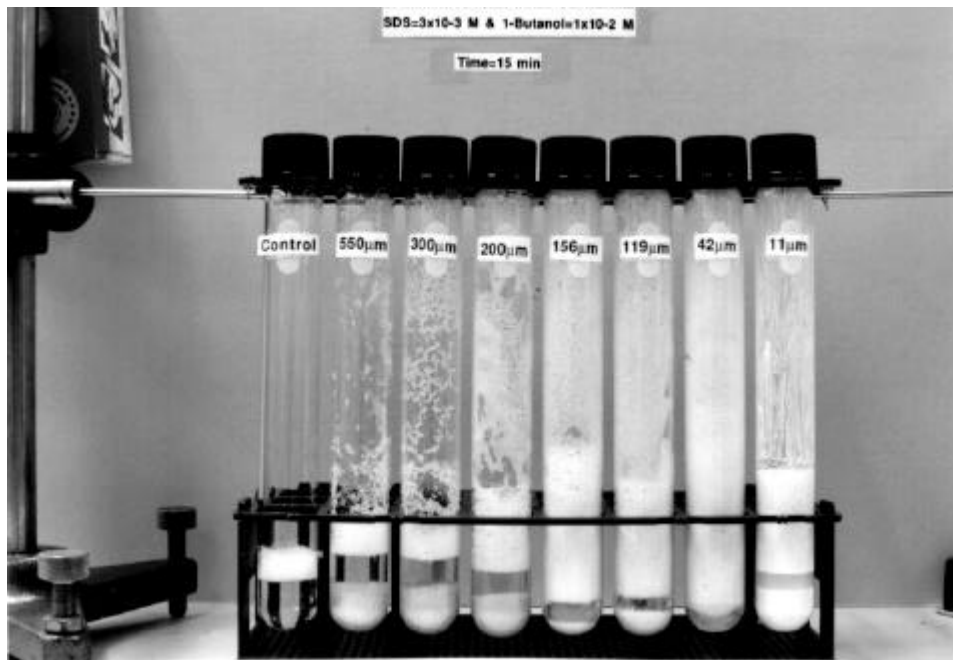
(a)
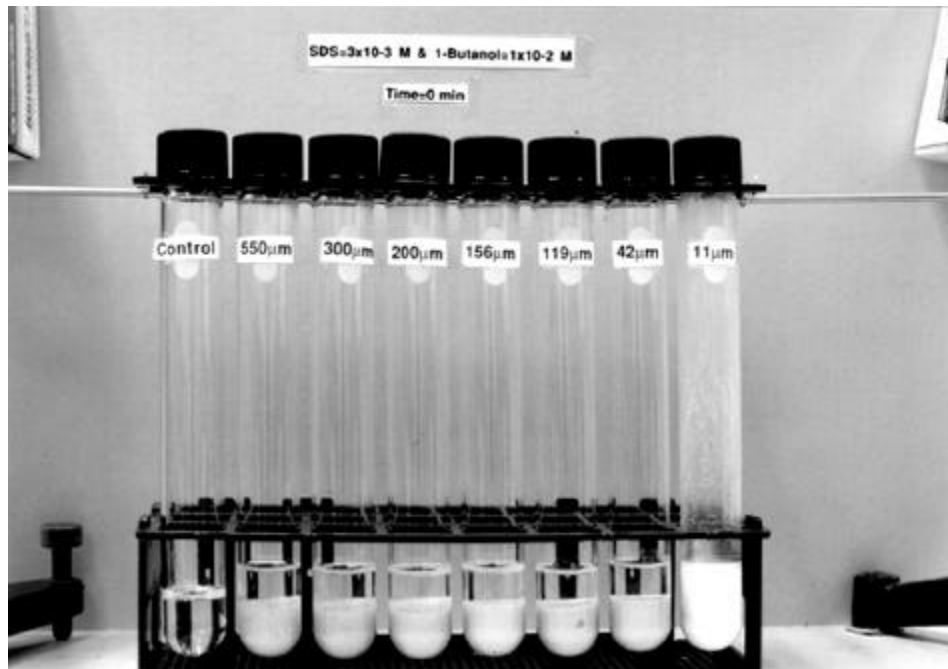
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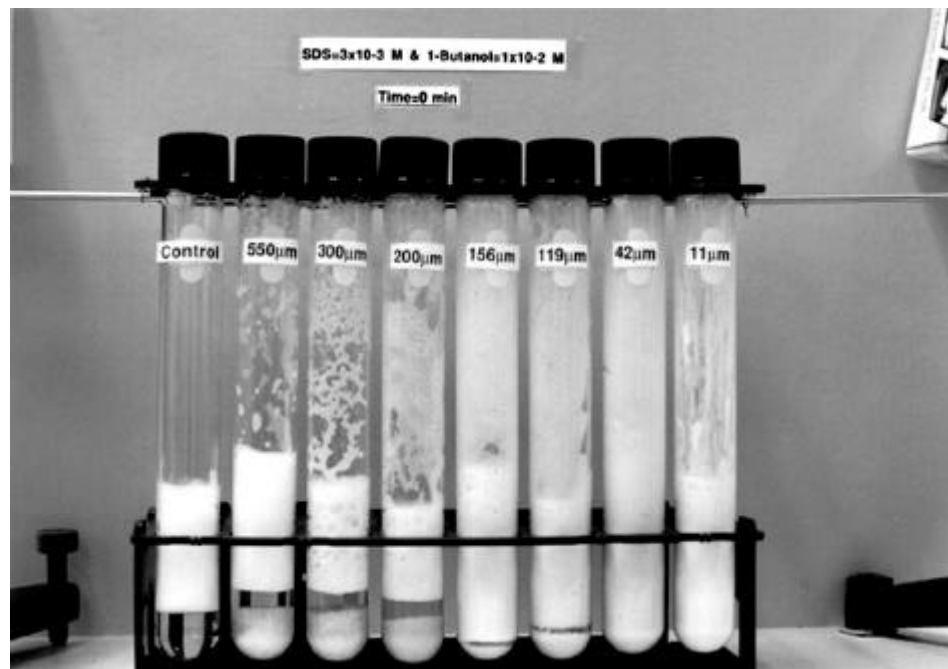
Figure 1. *(Continues, next two pages)* 10 gms of glass of different sizes marked on the bottles are put in 7cc of surfactant solution (a) before shaking, (b) just after shaking, (c) 15 min. later, (d) 30 min. later, (e) 1 hour later. The optimal size of cutting for this foam is $d = 156$ μm.

(c)

(d)

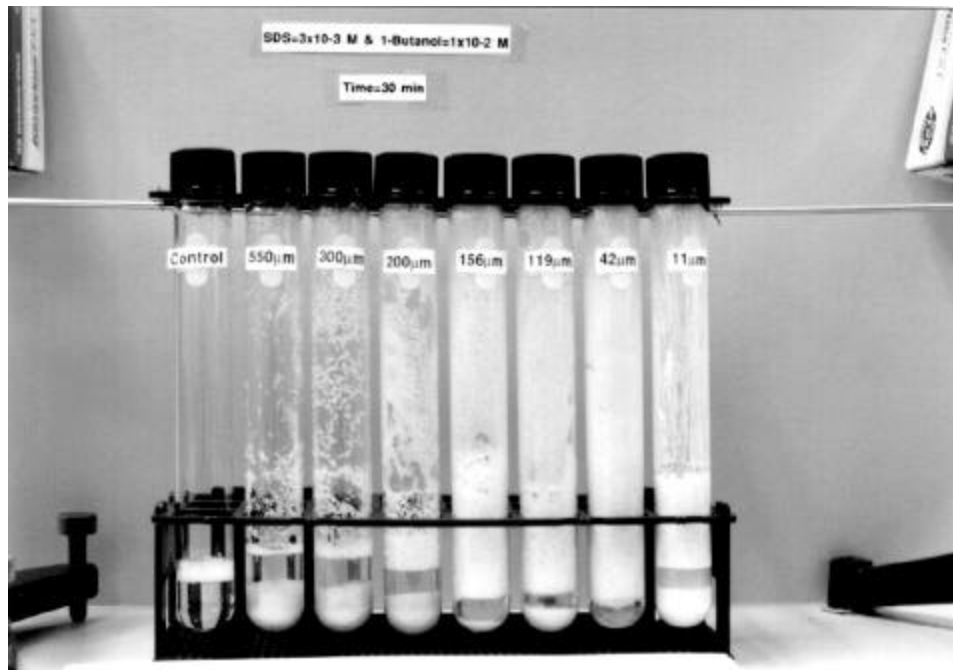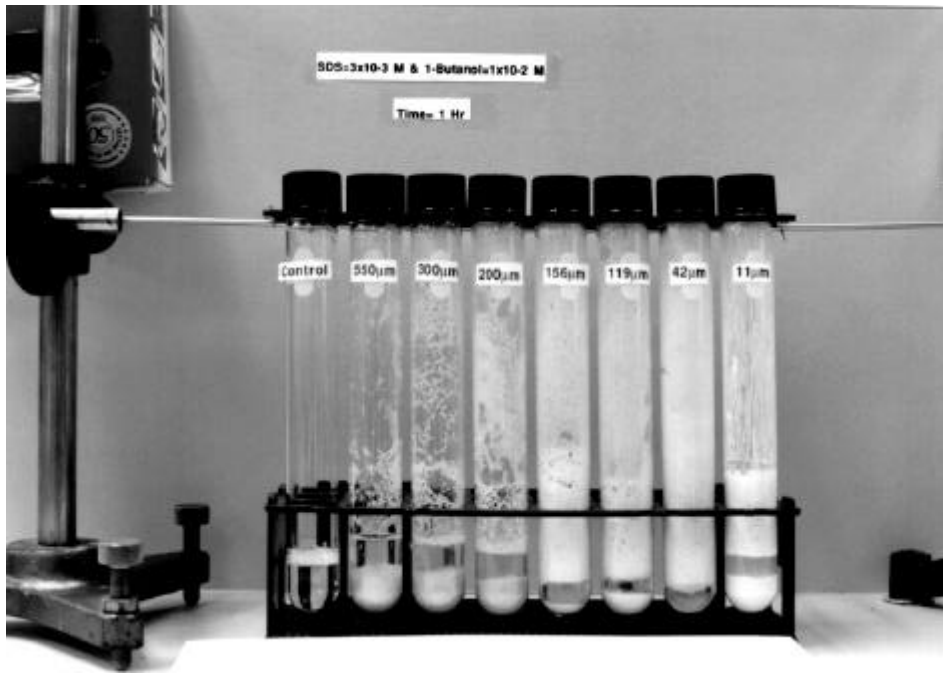
Figure 1, *cont.*

(e)

III.3 Fluidization of particles by a gas stream through a batch particle/liquid suspension in a tubular bubble column

A schematic of this bubble column is shown as figure 2, a photograph of the apparatus is shown as figure 3. Liquids and solids are loaded into this device and gas is bubbled through, creating foam and lifting particles. The device can be used without particles to study the effects of different surfactants and polymers on foaminess (the height of foam reached under a continuous injection of gas) and on the stability of foam (the collapse time of the foam head after the apparatus is shut down). This kind of information is available from the shaker bottle, but in a less controlled way.

The device may also be used to study the problem of which particles may be lifted by a given foam: find the size and weight of particles of different type (hydrophobic or hydrophilic) which may be suspended in a given foam. This kind of information is also available from the shaker bottle in a less controlled manner.
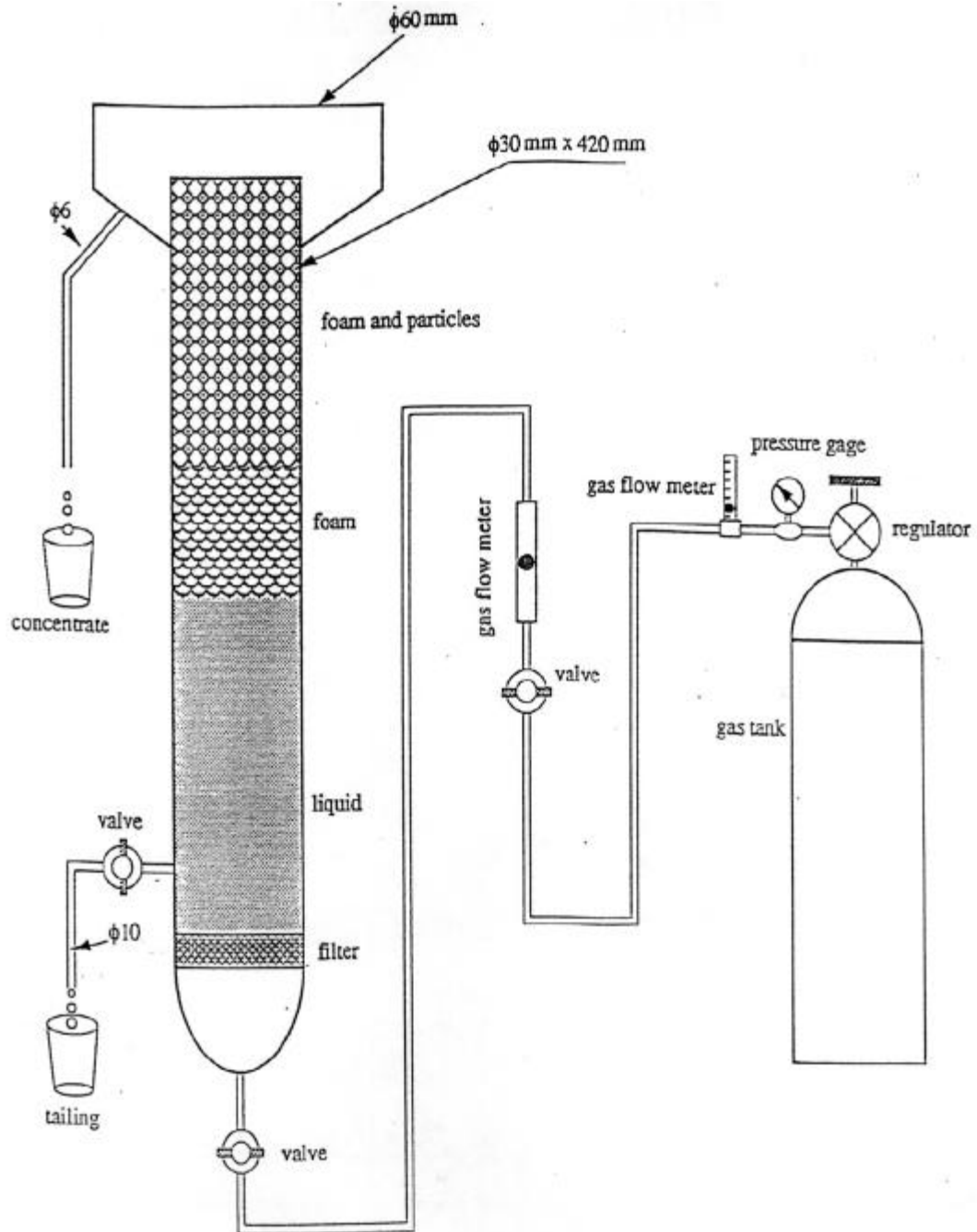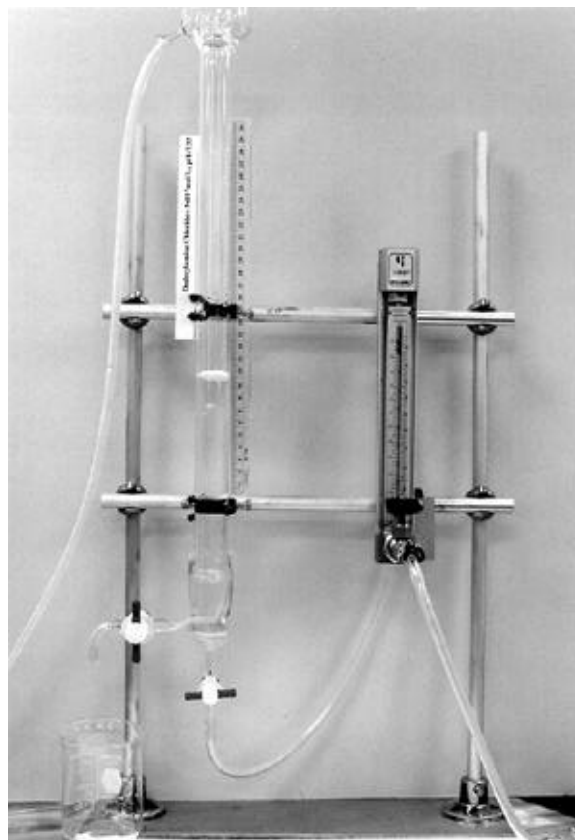
Figure 2. Schematic diagram of experimental apparatus.

Figure 3. Experimental instrument.