

YIELD STRESS OF FIREFIGHTING FOAMS

Bruce S. Gardiner, Bogdan Z. Dlugogorski, and Graeme J. Jameson
Centre for Multiphase Processes, Department of Chemical Engineering
The University of Newcastle
Callaghan, NSW 2324 AUSTRALIA

and
Raj P. Chhabra
Department of Chemical Engineering
Indian Institute of Technology
Kanpur, 20816, INDIA

ABSTRACT

This paper reports measurements of yield stress (τ_y) of firefighting foams using a simple and inexpensive pendulum device. This device allows transient measurements at very low shear rates, as the gas fraction (ϕ) and average bubble size ($\langle R \rangle$) increase with time. The yield-stress measurements are supplemented by the determination of the surface tension (σ), the local gas fraction and the bubble-size distribution. The local gas fraction is obtained from the measurements of sonic velocity and the bubble size distribution is acquired from foam photographs. The results demonstrate that yield stress of firefighting foams depends strongly on gas fraction, surface tension, and the average bubble size. This illustrates that the measurement of yield stress must be performed in conjunction with the measurements of gas fraction, surface tension, and bubble size. It is found that, firefighting foams investigated in this study display yield stress of between 2 and 4 Pa. By taking into account the present measurements and the data extracted from a wide range of studies on yield stress of foams and emulsions, the following correlation is obtained for practical engineering calculations ($\phi > 0.64$):

$$\tau_y = 0.0336 \frac{\sigma}{\langle R \rangle} \left[\frac{\phi^{1/3}}{(1 - 0.99999\phi)^{1/4}} - 1.1125 \right]$$

INTRODUCTION

Yield stress is a property that determines whether firefighting foams applied to vertical surfaces would remain attached to those surfaces, or whether they would flow downward. In practical situations, firefighters may cover trees and free-standing structures, in forested areas, with a layer of foam before an approaching fire. The foam layer acts as a heat sink to the thermal radiation emitted by the fire. From this perspective, usefulness of foam as a barrier to thermal radiation depends on the foam's ability to remain attached to the wall until the fire arrives.

Yield stress also determines the flow properties of foam in other firefighting applications. It affects the velocity profiles during pumping of the so-called compressed-air foams (CAF) in hoses, decreasing their throughput at a given pumping pressure [1]. In addition, during the application of foams onto horizontal surfaces of burning liquid and solid fuels, the yield stress

determines how rapidly the foam flows away from the point of application. It is for these reasons that we have embarked on the present investigation.

Previous studies on foams and concentrated emulsions indicate that the yield stress of these materials rises sharply with gas fraction [2-6]. One can also surmise by analogy to the Laplace and Young law, that yield stress may increase with the surface tension and decrease with the size of foam bubbles, necessitating measurements of these parameters in separate experiments.

The measurement of foam yield stress is particularly difficult because the drainage of foam solution due to gravitational forces and the transport of air from small to large bubbles due to the Laplace pressure results in the evolution of foam with time. As foam changes, so does its yield stress. Therefore, transient experimental techniques are required to account for this evolution. To avoid complications associated with evolving foams, some of the past experimental work on foam rheology has actually been performed on concentrated emulsions [3-5]. In this paper, however, **our** interests lie in the direct investigation of yield stress of aqueous foams, motivated by applications of foams to firefighting.

The measurements reported in the subsequent chapters were carried out on compressed-air foams. The foam generator used to produce the foam is described briefly in the next section together with the experimental techniques to measure gas fraction and bubble sizes. This is followed by a description of the pendulum device and an expression to calculate yield stress. We then proceed to discuss the present results. The paper concludes with the summary of major finding from this investigation.

FOAM GENERATION AND CHARACTERIZATION

The surfactant solution, used in this investigation, was prepared from a class B foam concentrate by mixing 3 volumes of the concentrate with 97 volumes of deionized water (Table 1). Foam was then produced by aerating the solution with compressed-air in a foam generator, described in detail elsewhere [1]. The mixing between the foam solution and the compressed air takes place in a pipe's T-junction filled with compacted steel wool. The foam is then passed along 10 m of flexible rubber tubing, which acts as a foam improver. This method of foam generation allows **an** accurate control of the air gas fraction (ϕ) and produces foams characterized by narrow bubble-size distributions, which leads to slower inter-bubble diffusion delaying foam coarsening.

It is very important to characterize foam as it evolves during each experiment, as both ϕ and $\langle R \rangle$ are expected to vary during the yield-stress measurements. In the present work, the bubble size was determined from images captured by a CCD camera, at pre-selected time intervals. The images of foam cells were then processed by calculating surface area of each bubble, equating this area to a circle, and then computing an equivalent radius. The equivalent radii of all bubbles were averaged at each time step. In obtaining the average radii we assumed, following Cheng and Lemlich [7], that the distribution of bubbles at the wall, where the photographs were taken, adequately approximates the true distribution in the bulk. The variation of the average bubble radius is shown in Figure 1.

Table 1. Composition of the foam concentrate used in the generation of the aqueous foams."

Chemical	Trade name	% by weight	Function
Fluro-alkyl surfactant	FC-100	12	Surfactant
Phenyl sulfate surfactant	Triton X-305	11	Surfactant
Sodium octyl sulfate	-	13	Surfactant
Diethylene otycol monobutyl ether	-	9	Stabilizer
Water	-	55	Solvent

^aThis concentrate was mixed with deionized water in the volume ratio 3:97.

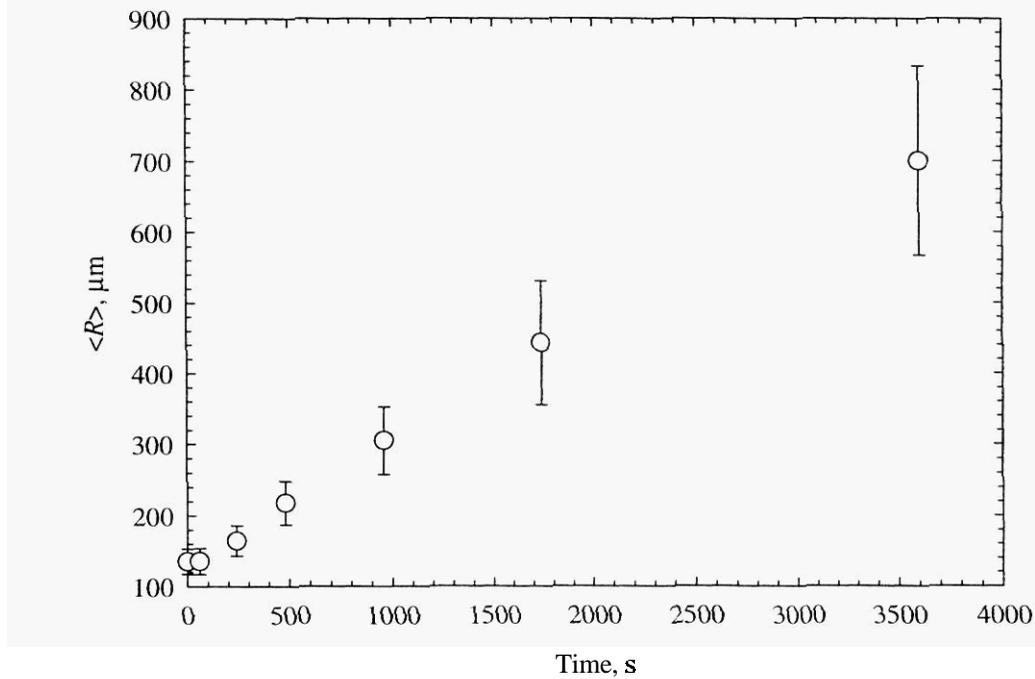


Figure 1. The variation of the average bubble diameter in the foam with an initial gas fraction of 0.95; the measurements were recorded at half height of the foam cell ($h/H=0.5$). Error bars represent the sum of the standard errors associated with sampling size and measurement precision.

A convenient way to obtain the gas fraction at the height of the pendulum bomb is to measure the speed of sound, at the same locations. Note that the sonic velocity in foams is less than the velocity of sound in water and in air, and it is linked to the gas fraction through the following expression [8]:

$$c^2 = \frac{\gamma}{\rho_L} \frac{(2-\phi)^2}{(1-\phi)}, \quad (1)$$

where γ is the so-called polytropic-expansion exponent.

The sonic velocity was obtained by placing two microphones, separated by a distance of 65 mm, and a speaker into the foam, and then recording the time interval between the arrivals of a short ($-500\mu\text{s}$) pulse. The technique was verified by confirming the sonic velocity in air, and was further validated by measuring the sonic velocities in foams, with known gas fractions. The foam generator was capable of producing foam with gas fraction between 0.8 to 0.97, and the agreement between the experimental data and equation 1 was excellent in that range.

Using the measurement of the speed of sound in foam, we characterized the change of gas fraction with time at various heights in the foam. Initially, the gas fraction is uniform with height. As the drainage begins, the top of the foam rapidly becomes *dry*. Subsequently, foam at progressively lower layers becomes depleted of the surfactant solution. The change in the local liquid fraction in the foam reflects the balance of the liquid flowing in and out of a foam region. Figure 2 provides an example of the gas-fraction profile in the foam at various times.

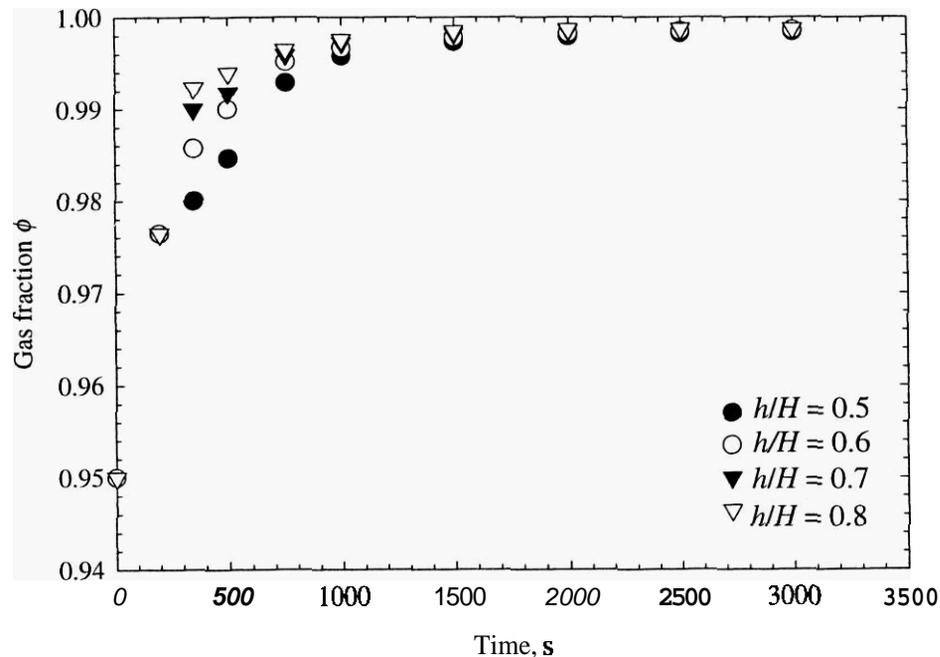


Figure 2. Typical drainage profiles for the foam used in this study as determined from the local sound speed measurements; h/H is the height in the foam, normalized with respect to the initial foam height H . Initial gas fraction is 0.95.

YIELD-STRESS MEASUREMENTS AND CALCULATIONS

The pendulum method was first introduced by Uhlherr and coworkers for measuring yield stress in solutions of carbopol (e.g., [8]). The method operates on the principle that a pendulum bob released from above a fluid surface will stop at angle away from vertical, if the fluid displays yield-stress behavior. The final angle is governed by the balance between the weight of the pendulum, buoyancy forces, and the force on the surface area of the pendulum bob due to the fluid yield stress.

Figure 3 depicts the pendulum geometry used in these experiments. With reference to Table 2 and Figure 3, the plate-like bob (1) is attached to a length of thin-walled aluminum tubing (2), which is in turn connected to another length of aluminum tubing (3) of larger diameter that acts as a low friction bearing. The plate (bob) surface is roughened to minimize wall slip. The angle of the pendulum from vertical θ is measured using a protractor. During each experiment, care was taken to minimize vibrations.

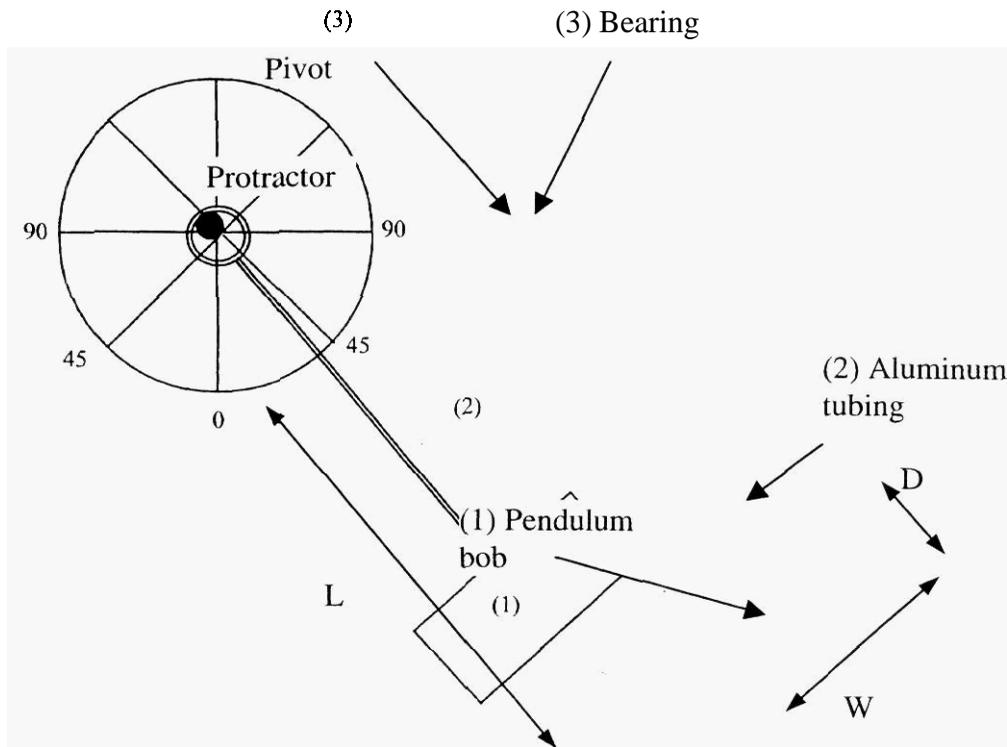


Figure 3. Pendulum design; labels indicate components listed in Table 2.

Table 2. Geometries and construction materials of the components of the pendulum.

Component	Length	Width/ Diameter	Thickness/ Internal Diameter	Density	Material
(1) Bob	50 mm	25 mm	1 mm	1273 kg/m ³	Stiff plastic
(2) Tubing	150 mm	2 mm	1 mm	2540 kg/m ³	Aluminum
(3) Bearing	50 mm	10 mm	9 mm	2540 kg/m ³	Aluminum

By equating the moments about the pivot point due to the pendulum's weight, buoyancy forces, and the foams yield stress, the following expression is obtained for the pendulum described in Figure 3,

$$\tau_y = g \sin \theta \frac{[M_{eff}(2L + D) + M_a L - \rho_f \pi R_a^2 L_s (2L - L_s)]}{2WD(2L + D)} \quad (2)$$

In deriving equation 2, the stress due to the fluid on the aluminum tubing has been neglected, since a large portion of the tube length was above the foam surface. In addition, the surface area of the submerged portion of the tube was much smaller than that of the pendulum plate. The effect of the bearing at the pivot point was also neglected, as the close proximity of the bearing to the pivot produces negligible additional torque. Finally, the plate-like shape of the pendulum minimized the magnitude of the normal forces acting in the direction of motion.

RESULTS AND DISCUSSION

In a series of preliminary experiments, the pendulum motion was examined in glycerol, which is a viscous Newtonian fluid. As expected for a liquid with no yield stress, the pendulum fell to a vertical position. We also observed no effect of releasing the pendulum from different heights above the foam surface on the final position of the bob. In every case, the bob decelerated very rapidly in the foam matrix. Even if the pendulum is removed from the foam, after it has reached a relatively stable angle (say, after -30 min), and then dropped again in the foam at a different site, it returns to the same angle within 2 to 3 min. These observations suggest that the motion of the pendulum is governed by the change in yield stress with a changing foam structure, which evolves in response to changing gas fraction and bubble size, and not by the lack of a yield stress. Thus the instantaneous pendulum angle reflects the dynamic yield stress of the particular foam matrix, existing in the vicinity of the bob. This is a very useful result as it allows the examination of the yield stress over a range of gas fractions and bubble sizes, by assuming quasi-static equilibrium. The quasi-static equilibrium implies a vanishing resultant force acting on the pendulum bob.

Although most of the following experiments were performed over a period of an hour, we initially allowed the pendulum motion to progress for a 24-hour period in a covered container to reduce evaporative bubble rupture. After 24 hours, the pendulum remained at a reproducible non-zero angle of 10°, corresponding to a yield stress of 1.5 Pa, or to $\tau_y/(\sigma/\langle R \rangle) = 0.56$, for $\sigma = 20$ mN/m. This scaled yield stress is of the same order of magnitude as the predictions from the various two and three-dimensional models of dry foam [9-13].

The experimental results are plotted in Figure 4. Different foam heights correspond to different submerged pendulum wire lengths. If the data in Figure 4 are converted to the yield stress values, by taking into account the local foam density at the height of the pendulum bob, then no dependence on initial foam height was seen, as is illustrated in Figure 5. This result confirms that, the yield stress on the submerged aluminum wire may be neglected.

If the yield stress data plotted in Figure 5 are scaled by $\sigma/\langle R \rangle$ and displayed, as done in Figure 6, along with the experimental results of others, the general behavior is as expected. The scaled yield stress increases with increasing gas fraction. This result also illustrates the importance of the bubble size and surface tension measurements, which must be carried out in conjunction with yield-stress experiments.

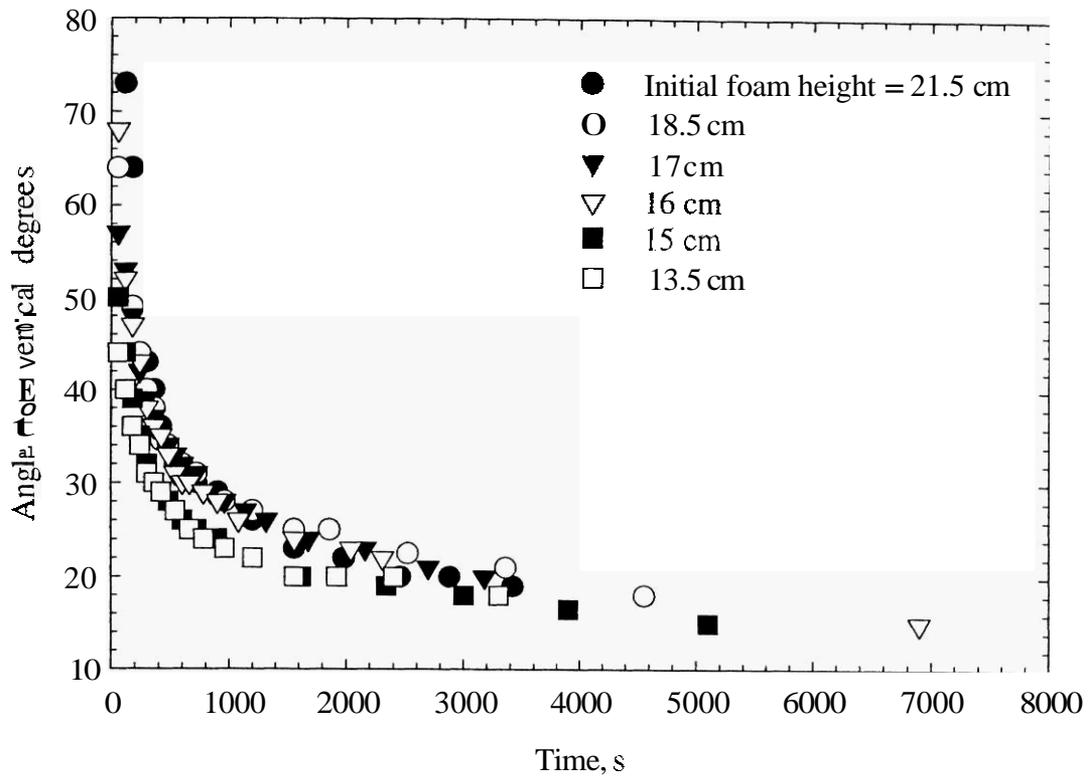


Figure 4. Variation of the pendulum position for various initial foam heights with time.

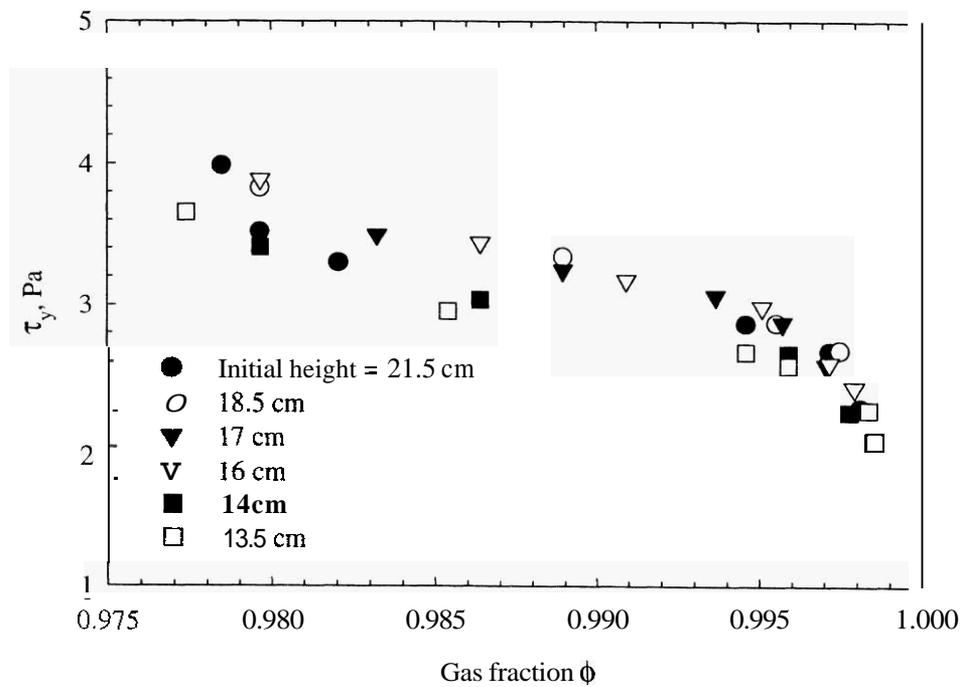


Figure 5. The change of the yield stress with gas fraction. The unexpected reduction in yield stress with an increasing gas fraction is due to a changing bubble size (see Figure 1).

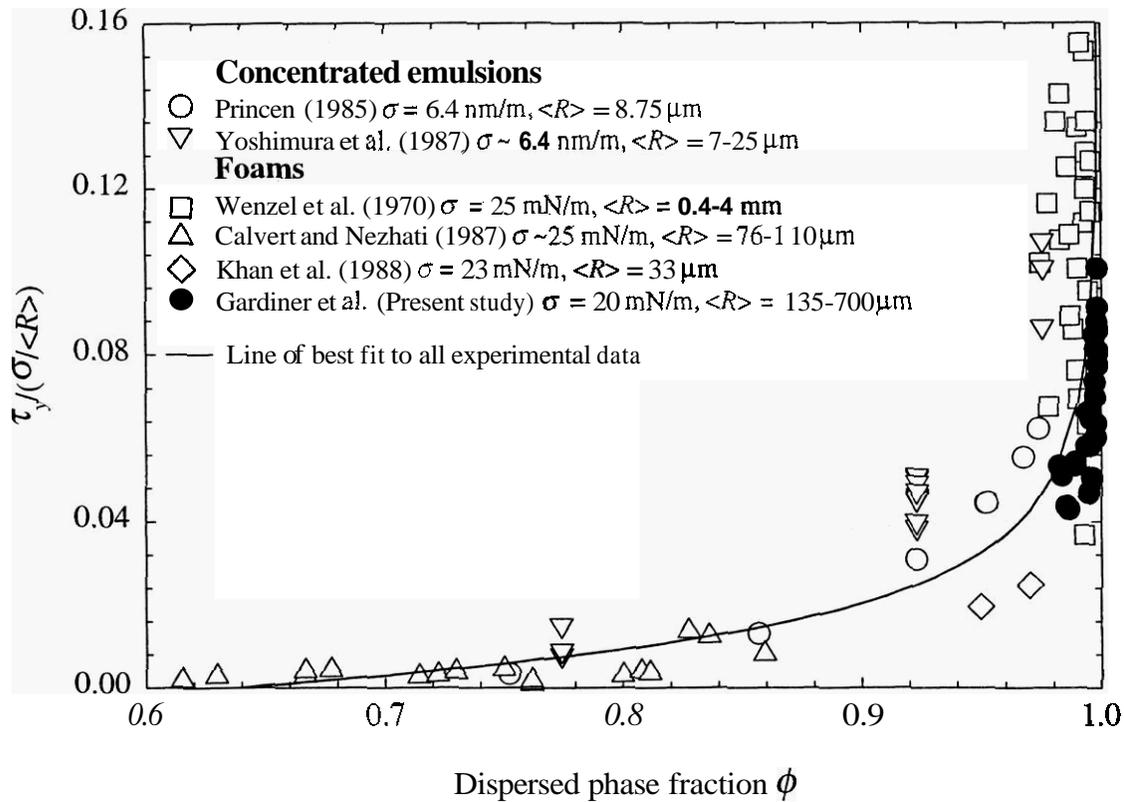


Figure 6. Comparison of the present and literature data on yield stress of *foams* and emulsions. All data are scaled by $\sigma/\langle R \rangle$. Our estimate of $\tau_y/(\sigma/\langle R \rangle) = 0.56$ for $\phi \cong 1$ is not included in the graph to obtain a better resolution for lower values of $\tau_y/(\sigma/\langle R \rangle)$.

Finally, the following correlation is obtained for practical engineering calculations ($\phi > 0.64$) on the basis of all data sets presented in Figure 6

$$\tau_y = 0.0336 \frac{\sigma}{\langle R \rangle} \left[\frac{\phi^{1/3}}{(1 - 0.99999)} - 1.1125 \right] \quad (3)$$

CONCLUSIONS

In this paper, we collected new results of yield stress of firefighting foams. These results were then combined with the data available in the literature on similar foam and emulsion systems. Equation 3 and Figure 6 summarize the most significant findings from the present investigation, especially:

- The yield stress of foams scales with the surface tension and the average bubble diameter. Consequently, one must know the surface tension and the average bubbles diameter to obtain the yield stress from Equation 3.

- The yield stress increases monotonically with the gas fraction, starting with $\tau_y = 0$ at $\phi = 0.64$ to reach $\tau_y = 0.56$ for dry foams ($\phi = 1$).
- The experimental data sets plotted in Figure 6 show significant scatter. This may indicate that other variables not included in the present analysis, such as the bubble-size distribution, may affect the yield stress of foams.

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NOMENCLATURE

c	sonic velocity [m/s]
D	dimension of bob in direction parallel to main axis of pendulum [m]
g	acceleration due to gravity [m/s ²]
H	initial foam height [m]
h	height within foam [m]
L	length of aluminum tubing [m]
L_S	submerged length of aluminum tubing [m]
M_a	mass of aluminum tubing [kg]
M_{eff}	effective mass of the submerged bob [kg]
R	bubble radius [m]
$\langle R \rangle$	average bubble radius [m]
R_a	radius of aluminum tubing [m]
t	time [s]
W	dimension of bob perpendicular to main axis of pendulum [m]
γ	polytropic exponent [-]
ϕ	volume gas fraction in foam or dispersed phase fraction in emulsions [-]
θ	angle of the pendulum, away from vertical [-]
ρ_f, ρ_L	density of foam, foam solution, respectively [kg/m ³]
σ	surface tension [N/m]
τ_y	yield stress [Pa]

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