

Effect of a Silicone Defoamant on the Motion of Single Air Bubbles Rising in Lubricant

Joosup Shim, Wonoh Cho, Keunwoo Chung* and Young Woon Kim

Korea Research Institute of Chemical Technology

Abstracts : The velocity and motion of single air bubbles rising through lubricant have been experimentally investigated to test the effect of silicon defoamant. The investigation reveals that the velocity is markedly retarded by the addition of small amount of silicone defoamant. This retardation of rising velocity of air bubbles is proposed by increasing of Drag force or reducing of Buoyancy force around the surfaces of the bubbles.

Key words : single air bubble, silicone defoamant, velocity

Introduction

Excessive air in hydraulic or turbine oil can lead to foaming and air entrainment (small air bubbles entrained in oil). Foaming can be usually controlled by the use of defoamant, particularly silicone polymer, which very rapidly breaks up surface foam, even at very low concentration. Although effectively suppressing foaming and the initial amount of air entrained, silicone defoamant invariably causes an increase in air release value (ARV: the time for air content to reduce to 0.2 percent by volume), as exemplified in Figure 1 and produces environment in which oil tends to form smaller air bubbles, as shown in Figure 2. These negative effects create a serious problem in hydraulic and turbo machinery systems, largely producing great variation in the compressibility, effective volume and viscosity of oil [1,2].

In view of this, many works [3,4,5,6,7,8] reviewed air entrainment properties in oil, reporting how silicone defoamants and other additives, and contaminants affect the foaming and air entrainment characteristics of oil in different lubrication systems. Based on field experiences, Fowle [7] surmised a mechanism by which a silicone defoamant reduces ARV. However, no specific experiment was conducted to support his hypothesis. These earlier works have clearly indicated that the subject of air entrainment in oils is complicated and often confusing because air may be entrained in different ways, thereby causing different problems in the field. Also, the transient behavior of air bubbles rising in oils further complicates the investigation of the subject even in the controlled laboratory.

In spite of these complexities, the motion of a swarm of air bubbles rising through fluids has been studied both experimentally and theoretically [9,10]. Once again, the literature available on the effect of additives, particularly

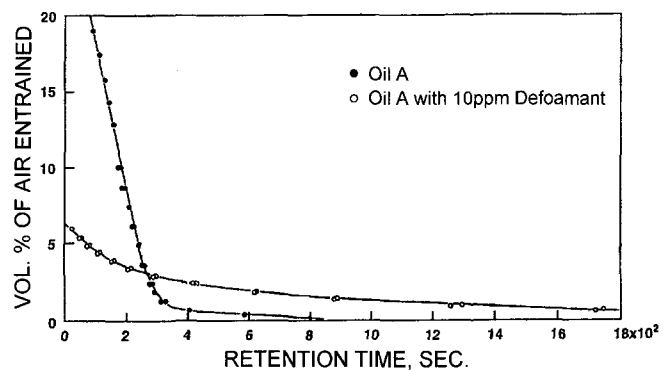


Fig. 1. Typical air release curves of oil A and oil A containing 10 ppm silicone defoamant determined by ASTM D3427 method.

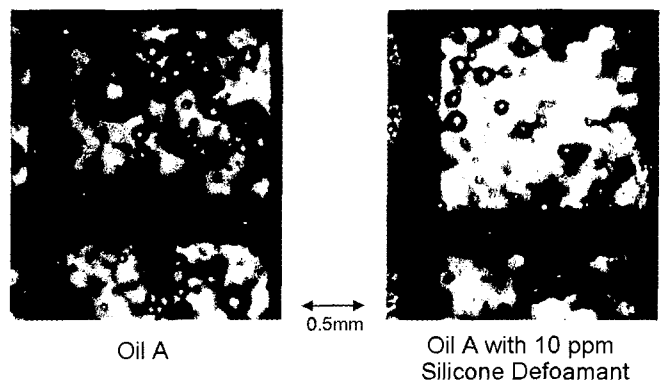


Fig. 2. Enlarged photograph (35x) of air bubbles entrained in the oil samples taken from ASTM D3427 measurement.

defoamant, on single bubbles rising in oil, is very scanty, although defoamant, even in small quantities, seems to retard the motion of bubbles. Such retardation has been evidenced in the published results on a study of foam stability [4] and the rise of air bubbles in lubricant [11]. The results have generated

*Corresponding author; Tel: 82-42-860-7600; Fax: 82-42-860-7669
E-mail: kwchung@pado.kRICT.re.kr

our interest and curiosity to know what role, if any, defoamant plays in the retardation of bubble motions.

The present work, therefore, is mainly directed toward determining the velocity of single bubbles rising in a lubricant and investigating the role of a silicone defoamant in the lubricant under a controlled laboratory condition, hoping to shed some lights on much of the often confusing behavior of the silicone defoamant observed in both laboratory and field applications.

Theoretical Considerations

The motion of a swarm of air bubbles rising through liquid is dependent upon many factors such as the viscosity, surface tension and density of liquid and the size and fraction of air bubbles in the suspension. The development of theoretical expressions relating to the motion is not easy task. Because of this belief, some researchers [12] have attempted to relate the rising velocity of a swarm of bubbles to the velocity of a single bubble by taking the Stokes' law. The Stokes' classical equation of the velocity for a particle (rigid sphere) falling slowly in an infinite medium is expressed as

$$U = \frac{2}{9} \left(\frac{gR^2}{\nu_o} \right) \left(\frac{\rho_o - \rho_a}{\rho_o} \right) \quad (1)$$

where U = Velocity of a single bubble
 R = Bubble radius ($D = 2R$)
 ν_o = Kinematic viscosity of lubricant
 g = Gravitational constant
 ρ, ρ_a = Density of lubricant and air, respectively

In later years, many investigators have tried to modify the Stokes' relation for gas bubbles to include considerations of slip at the interface, of the deformation of bubbles, and of the effects of surface viscosity caused by a thin boundary layer. Their modifications are generally expressed as

$$U = \left(\frac{gR^2}{\nu_o} \right) \left(\frac{\rho_o - \rho_a}{\rho_o} \right) \varphi(\eta_o, \eta_a, R) \quad (2)$$

where η_o, η_a = Dynamic viscosity of lubricant and air, respectively

And their experimental values of $\varphi(\eta_o, \eta_a, R)$ varied widely. For example, Hadamard postulated a theory that internal circulation and reduced drag are associated with the quality of velocity in each fluid phase at the interface, thus giving the true velocity expressed as

$$U = \frac{2}{9} \left(\frac{gR^2}{\nu_o} \right) \left(\frac{\rho_o - \rho_a}{\rho_o} \right) \left[\frac{3\eta_a + 3\eta_o}{3\eta_a + 2\eta_o} \right] \quad (3)$$

Equation (3) in square bracket corrects for the effect on velocity of internal circulation of air due to viscous drag, has a value of approximately 3/2 when η_a/η_o is small, and independent of the radius of the bubble.

The quantitative results of experimental data are usually presented using the drag coefficient, C_D , which is defined by

$$C_D = \frac{8gR(\rho_o - \rho_a)}{3U^2 \rho_o} \quad (4)$$

The Stokes' relations found to be empirically correlated to the drag coefficient of rising air bubbles and relevant to this work, are presented below:

$$C_D = \frac{24}{N_{Re}} \quad (\text{Stokes' law}) \quad (5)$$

$$C_D = \frac{16}{N_{Re}} \quad (\text{Hadamard's law}) \quad (6)$$

where N_{Re} = Reynolds number $\left(\frac{DU}{\nu_o} \right)$

Other modifications of size, shape and behavior have been suggested for some systems under special conditions. But, Equation (4), (5) and (6) would suffice in this study for consideration of the effect of defoamant on rising air bubbles in lubricant.

Experimental

Experimental Apparatus

A schematic diagram of the experimental apparatus is depicted in Figure 3. The jacketed burette is 70 cm long with a 4.0 cm I.D. sufficiently large to make any wall effect negligible. Temperature of the burette is measured by a thermometer and controlled at $20 \pm 0.2^\circ\text{C}$ by circulating water from a constant temperature bath. The bubble generating device includes two micro Hamilton syringe A and B to contain air and oil, respectively. These syringes are fitted to one end of a L-shaped capillary cell of uniform bore, and are supported by a standard ground joint to fit in the oil filled burette. Capillary cells with bores of 0.30, 0.52, 1.10 and 1.51 mm are employed. The tip of each cell is tapered almost to its bore size. The L-shaped capillary cell is calibrated to measure the lengths of small bubbles formed in the vertical section of the cell.

Two arbitrary points, a known distance apart (26.75 cm) in the burette, provide the distance for the terminal velocity measurements. The time taken for the bubbles to traverse the pre-determined distance is measured by an electric timer.

Procedure

After introducing 650 ml of the oil to be tested into the burette and bring it to the desired temperature, pass freely air dried in a calcium chloride adsorber through the oil in order to saturate it, thus alleviating any tendency of the bubbles under study to diffuse into the oil. Wait till the oil to clear free from any air bubbles and then introduce a single bubble in the horizontal section of the capillary cell by carefully pressing syringe A which contains dried air. When a pre-determined quantity of air penetrates the oil in the cell, then squeeze syringe B which contains the test oil, thus cutting off the desired volume of air.

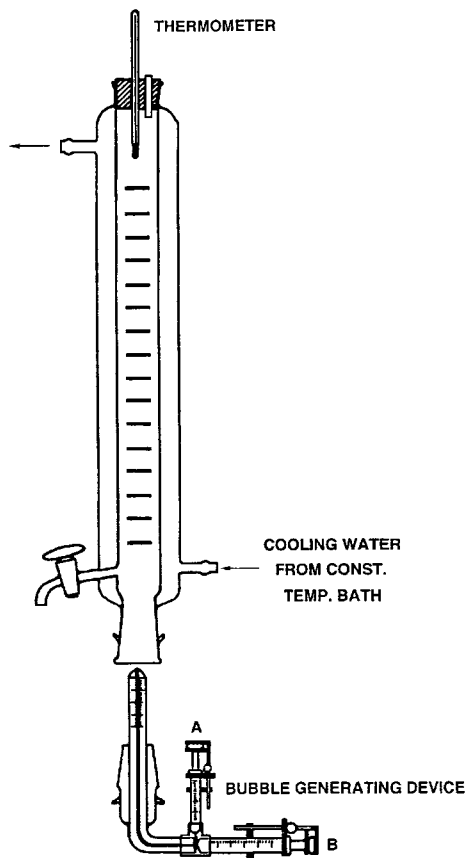


Fig. 3. Schematic diagram of experimental apparatus

By continuously pressing syringe B, advance the bubble up to the vertical section of the cell and here, once again, determine its length against finely calibrated division. Following these delicate operations, force the bubble into the oil column at the orifice and gently release from the orifice. Permit the bubble to reach a steady-state, then, start recording the time taken for it to cross the markings. Allowing sufficient time for the wake effects of the previous bubble to be dissipated, form another bubble and repeat the process.

Knowing the volume of a bubble measured from the vertical section of the capillary cell and assuming the bubble is spherical, the equivalent diameter of the bubble can be easily calculated from

$$D = \left[\frac{6}{\pi} V \right]^{1/3} = \left[\frac{6}{\pi} A \cdot h \right]^{1/3}$$

where D = Equivalent diameter of air bubble

V = Volume of air bubble

A = Cross-sectional area of capillary cell

h = Capillary cell length of bubble

Experimental Materials

A paraffinic mineral oil and its blends containing different amounts of a silicone defoamant are included in this study. The defoamant used is a polydimethylsiloxane (PDMS) polymer with a kinematic viscosity of 60,000 cSt at 25°C. Being insoluble, the silicone defoamant exists in the oil in the form of finely dispersed droplets [13, 14]. Accordingly, to ascertain uniform and stable dispersions, the defoamant was dispersed with use of the blending technique recommended by Beerbower and Barnum [13], requiring a moderately high temperature (90°C) and agitation (1,800 rpm). After blending, the oil samples were used without having assessed in neither the drop size measurement nor the stability. The pertinent physical properties of test oils are summarized in Table 1.

Results and Discussion

Since the silicone defoamant demonstrated a pronounced effect on ARV (see Figure 1), Oil A and Oil A containing 10 ppm PDMS were examined exclusively at an early stage of this work in an effort to investigate how the defoamant retards the rate of air bubble rise. Early experimental results, however, showed that the difference in velocity between the two oils did not appear to be sufficiently large enough to warrant a claim that the defoamant had an effect on the rate of bubble rise in the oils. The results also revealed that the present bubble generating device failed to produce bubbles having the sizes of less than 0.3 mm diameter, not even with the smallest capillary cell, but it freely formed bubbles in the size range of 0.3 to 2.0 mm. This revelation has led the conclusion that at relatively large sizes of bubbles, the drag forces caused by the defoamant at 10 ppm level are too small in comparison with the buoyancy forces, and thus the defoamant is not an important factor for impeding bubble rise in oil. This conclusion along with the failure of being able to generate smaller desirable bubbles necessitated a new approach.

In order to accentuate the defoamant effect on bubble rise, this work, therefore, has applied high PDMS concentrations of 50, 100 and 500 ppm as the 10 ppm gave little difference in the rate of air bubble rise to permit a representative picture. The high concentrations, although larger than used commercially, were adopted throughout this work, as it was felt that they may not affect basic mechanism by which the defoamant retards the motion of bubbles rising in oil.

Table 1. Physical Properties of Test Oils

Test Oil	Density(g/cm ³), 20°C	Kinematic Visc., cSt		Surface Tension (dynes/cm), 25°C
		40°C	100°C	
Oil A	0.887	102.2	10.88	31.4
Oil A + 100 ppm Defoamant	0.887	103.2	10.92	31.2
Oil A + 500 ppm Defoamant	0.887	103.7	11.02	31.0

Table 2. Typical Experimental Data for Rise of Single Air Bubbles

Lubricating Oil	Column Length* (%)	Time (min)	Instantaneous Velocity (cm/min)	Bubble Diameter (cm)
Through Oil A	0	0.0	-	5.92×10^{-2}
	10	0.40	6.68	
	20	0.80	6.68	
	30	1.21	6.51	
	40	1.61	6.68	
	50	2.02	6.51	
	60	2.41	6.85	
	70	2.83	6.36	
	80	3.25	6.36	
	90	3.67	6.36	
	100	4.08	6.51	
Through Oil A containing 500 ppm Defoamant	0	0.0	-	5.44×10^{-2}
	10	0.82	3.26	
	20	1.71	3.38	
	30	2.64	2.87	
	40	3.64	2.67	
	50	4.69	2.54	
	60	5.78	2.45	
	70	6.93	2.32	
	80	8.14	2.20	
	90	9.39	2.14	
	100	10.68	2.06	

Av. Velocity = $26.75/10.68 = 2.50$ cm/min

*10% of column length corresponds to 2.675 cm

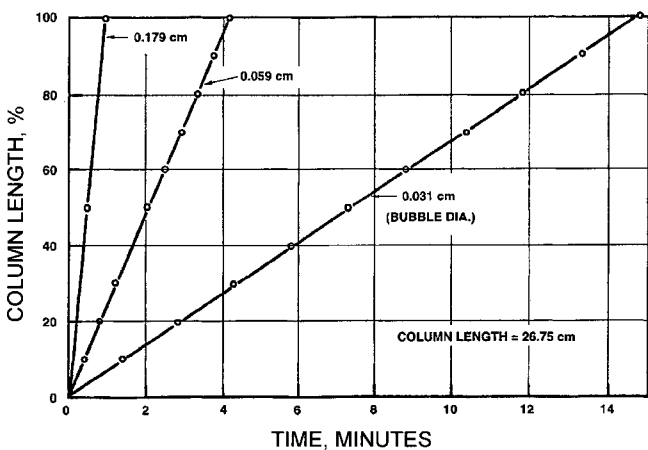


Fig. 4. Relationship between time and distance traveled by air bubbles of different sizes through oil A.

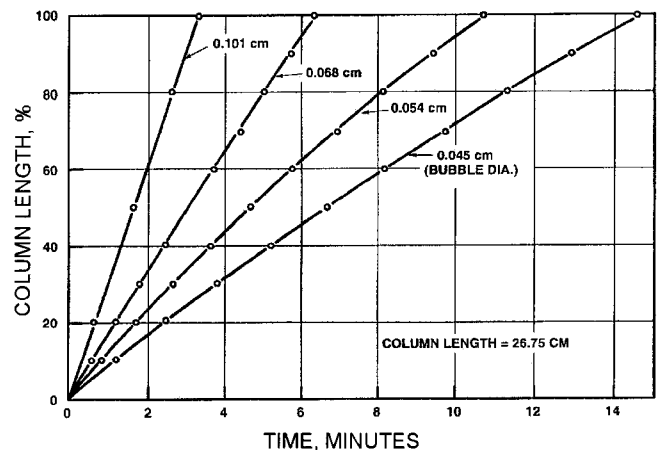


Fig. 5. Relationship between time and distance traveled by air bubbles of different sizes through oil A containing 500 ppm defoamant.

Table 2 lists typical experimental data on the velocity of single air bubbles rising through oil A and Oil A containing 500 ppm PDMS. Additional results are graphically presented in Figure 4 and 5 by plotting column length as percentage

versus time with bubble size as a parameter to show the relationship between time and distance traveled by the bubble of different sizes. It is apparent from these plots that a straight

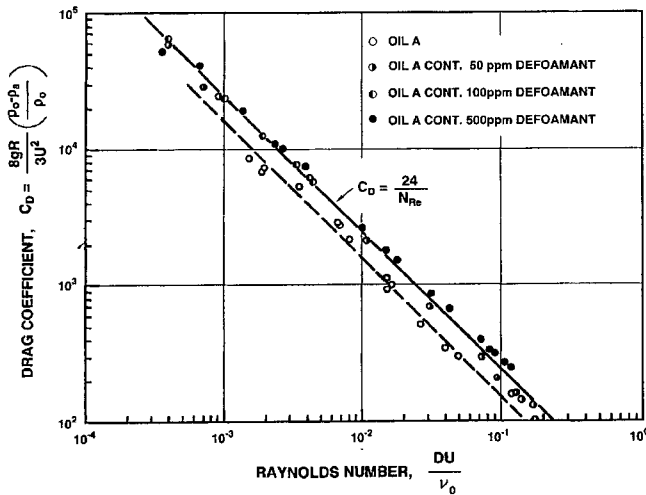


Fig. 6. Drag coefficient versus Reynolds number-effects of a silicone defoamant and its concentration on air bubbles rising through oils.

line relationship exists for all different sizes of bubble in Oil A, but no such a relationship exists in Oil A containing 500 ppm PDMS. The velocity plots in Figure 5 show definitive curvatures for bubble size less than 0.06 cm, but not for bubble size larger than 0.06 cm. The bubbles large than 0.06 cm diameter appear to be large for their velocities to be affected by presence of the defoamant, i.e. their buoyancy forces are far greater than the drags added by the defoamant.

Comparison of the instantaneous velocities in Table 2 and the velocity curves in Figure 4 and 5 discloses that the bubble velocity in Oil A containing 500 ppm PDMS is significantly slower than that in Oil A for a given size of bubble and decreases with increasing the distance traveled by the bubbles. It was also observed during the experimentation that the bubbles rising through Oil A containing 500 ppm PDMS appeared to take spiral paths and zigzag more about their vertical paths during ascent. This aspect will be further addressed in a later section.

In order to aid in presentation of the drag force induced by presence of the defoamant, the velocity results, expressed by plotting drag coefficient versus Reynolds number, are shown in Figure 6. For the purpose of comparison, the Stokes' relation for the drag coefficient, $C_D = 24/N_{Re}$, is also presented along with the experimental data. It is interesting to note from Figure 6 that the drag coefficients for Oil A containing the defoamant are directionally higher than those for Oil A at the same Reynolds number and they seem to increase as the defoamant concentration increases. Also, the drag coefficient of air bubbles in Oil A is more closely related to the Hadamard's equation, $C_D = 16/N_{Re}$, shown by the dotted line. These clearly indicate that the effect of the defoamant on bubble rise is very significant.

The values of $(R/R^*)^2$, R is actual bubble radius and R^* is the bubble radius calculated by using Equation (1), were calculated to further analyze the variations in drag coefficient caused by the defoamant and to equitably compare the experimental results against the Stokes' relation. These values

Table 3. Effects of a Silicone Defoamant and its Concentration on the Average $(R/R^*)^2$ Value of Air Bubbles Rising Through Oils

Test Oil	Av. $(R/R^*)^2$ Value
Oil A	0.74
Oil A + 50 ppm Defoamant	0.85
Oil A + 100 ppm Defoamant	0.93
Oil A + 500 ppm Defoamant	1.16

R : Actual bubble radius

R^* : Bubble radius calculated by using Equation (1)

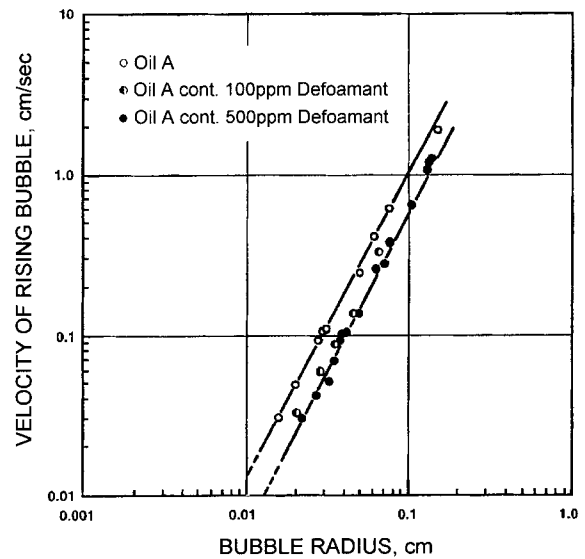


Fig. 7. Relationship between average velocity of air bubbles and bubble radius experimentally determined on different oils

are also equivalent to the ratios of the observed velocity of bubble to the velocity calculated from Equation (1). The calculated values are summarized in Table 3. Each value represents 15 experimental points and a statistical deviation of ± 6 percent.

Provided that the velocity of air bubble follows the Stokes' principal, then the average value of $(R/R^*)^2$ is expected to be unity. But, it is not the case, according to the results from Table 3. It is rather evident that the average values of $(R/R^*)^2$ vary dependent upon the level of defoamant concentration. They start from lower than the unity and eventually exceed it. The average $(R/R^*)^2$ value increases significantly as the defoamant concentration level rises. At this point, it was curious and quite interesting to know why the $(R/R^*)^2$ value changes with the defoamant concentration and deviates from the unity.

Possible reasons for the deviation may be attributable to two sources: (1) the velocity of bubbles are not related to the square of bubble radii or (2) the Stokes' relation, Equation (1), is inexact to predict the velocity of air bubbles rising in lubricant.

Experimental results are presented in Figure 7 by plotting the velocity of rising bubble against bubble radius in the log-log chart in order to confirm the square relationship. Once

again, a straight-line relationship exists for all cases. The slope of two straight lines, one for Oil A and the other for Oil A containing the defoamant at different levels, is approximately two. The slope represents the exponential value of bubble radius. Thus, this suffices the confirmation of the square relationship which effectively eliminates the first source of two possible reasons for the deviation of $(R/R^*)^2$ from unity. Accordingly, the deviation is most likely the result of the second source, i.e., the term of Equation (2), $\varphi(\eta_o, \eta_a, R)$ for a value of unity for the Stokes' relation, varies with the defoamant concentration level. For example, the average value of $(R/R^*)^2$ for Oil A is 0.74, suggesting the value of $\varphi(\eta_o, \eta_a, R)$ should be 1.35 to satisfy the Stokes' equation. The values of $(R/R^*)^2$ for Oil A containing the defoamant approach unity as the defoamant concentration is raised and eventually become greater than unity. The results strongly suggest that as Hadamard postulated, because of the internal circulation in bubbles, the drag at air-oil interface is probably mitigated so that the rising velocity of bubbles in Oil A is greater than that predicted by the Stokes' equation. With the introduction of the silicone defoamant, air bubbles act more like a rigid sphere, i.e., less internal circulation at the interface. With the results as they are presented, the only conclusion that can safely be drawn at present is that the PDMS defoamant retards the rate of air bubbles rising in lubricant. It is still not clear how the silicone defoamant impedes the motion of air bubbles.

With the results presented here combined with visual observations made during the experimentation, three possible mechanism are proposed: Firstly, as Hadamard postulated, when a bubble rises through Oil A containing the defoamant, insoluble silicone droplets may loosely adhere and slowly spread on the surfaces of bubble by virtue of its lower surface tension. The adherence of silicone droplets presumably increases surface fraction around the bubble surfaces, which in turn raises surface viscosity causing an added resistance to the velocity of rising air bubbles. Secondly, the silicone defoamant is about 18 percent more dense than Oil A and therefore, the attachment of even one large silicone droplet is bound to decrease their rate of ascent, and in the case of the small ones, to completely neutralize their buoyancy. The degree of slowing down of the bubbles probably depends upon the sizes and obliqueness with which they contact the surface of the defoamant droplets. Sufficiently small bubbles striking exactly normal to the surface of the droplets may, in theory, stop completely. But the bubbles, if large enough, carry the defoamant droplets loosely attached to the surface of the bubbles and a number of defoamant droplets with a bubble increases as the bubble travels vertically. However, when a certain number of defoamant droplets is attached on the surface of the rising bubble, the bubble tends to renew its surface so as to maintain only a limited number of defoamant droplets attached on the bubble surface. Thirdly, since the silicone defoamant is dispersed in the oil phase as droplets ($<100 \mu\text{m}$) and there is no particular attraction between air bubbles and defoamant droplets [3], the droplets which are suspended in the oil can be considered as movable (flexible) random packings or fluidized bed. Hence, a bubble, when it

rises through the oil phase packed with silicone droplets, may bump against the defoamant droplets which block the path of the rising bubble and rises slowly by taking zigzagging paths. The extent of zigzagging motions by the bubble is surely dependent upon the size and distribution of droplets. For example, it can be envisioned that for large bubbles, their buoyance forces are sufficiently strong enough so that the large bubbles could push droplets aside from their rising paths, without taking much zigzagging motions. Contrarily, for small bubbles, because of their low buoyancy forces, they tend to rise through the oil by taking more zigzagging paths. This appears to be in agreement with our observation that air bubbles zigzag more in Oil A containing 500 ppm PDMS than in Oil A.

In summing up, the first and second mechanisms are more attractive as an explanation of the effect of PDMS defoamant on the motion of air bubbles rising in lubricant-the silicone defoamant droplets locally increase surface viscosity and density at random sites on air bubble surfaces, thereby retarding the velocity of rising bubbles. It is still unclear, however, that which of the mechanisms is more predominant. Most likely, a combination of the mechanisms including the third simultaneously play some role at different degrees of dominance dependent upon conditions which the system is under. Clearly additional investigation is needed to de-couple this interdependence.

Conclusions

The velocity and motion of single air bubbles rising through lubricant have been experimentally investigated. The investigation reveals that the velocity is markedly retarded by the addition of minute amounts of a PDMS defoamant. The single air bubbles in the oil containing no defoamant appear to obey the Hadamard's relation, while the bubbles in the oils containing the silicone defoamant more closely follow the Stokes' relation, i.e., air bubbles behave like rigid particles. Accordingly, the bubbles in the oils blended with the defoamant give greater drags at any given velocity and travel slower for any given bubble size. The increase in drag and reduction in velocity of air bubbles are very likely affected by the defoamant which loosely adsorbed around the surfaces of the bubbles, thereby increasing surface viscosity at the interface and decreasing the buoyance force of rising bubbles.

Finally, the mechanisms proposed here may not be fully documented by the experimental results. But, it is hoped that this work provides a basis for more complete understanding of the behavior of silicone defoamant in lubricant experienced in the controlled laboratory conditions as well as in actual fields.

References

1. Hayward, A. T. J., The Viscosity of Bubble Oil, *J. Inst. Petrol.*, Vol. 48, pp. 156, 1962
2. Hayward, A. T. J., How Air Bubbles Affect the Compressibility of Hydraulic Oil, *Hydraulic Power Transmissions*, 384, June, 1962
3. Shearer, L. T. and Akers, W. W., Foaming in Lube Oils, *J. Phys. Chem.*, Vol. 62, pp. 1269, 1958

4. Awe, R. W., Silicone Antifoams for Lubricating Oils, SAE Paper No. 7774D, 1963
5. Claxton, P. D., Aeration of Petroleum Based Steam Turbine Oils, Tribology, Vol. 5, No. 1, pp. 8-13, 1972
6. Rowand, H. H., Patula, R. J. and Sargent, L. B., The Evaluation of the Air Entraining Tendency of Fluids, Lub. Eng., pp. 491-494, 1973
7. Fowle, T. I., Aeration in Lubricating Oils, Tribology Int'l. pp. 151-157, June, 1981
8. Biswajit, B., Subhash, C., et.al., Air Entrainment Phenomenon in Mineral Oils, ASLE Preprint No. 84-AN-4D-3.
9. Happel, J., Slow Motion of Fluids Relative to Beds of Spherical Particles, AIChE J. Vol.4, pp. 197, 1958
10. Marrucci, G., Rising Velocity of a Swarm of Spherical Bubbles, I.E. & C. Fundamentals, Vol. 4, No. 2, pp. 224, 1965
11. Robinson, J. V., The Rise of Air Bubbles in Lubricating Oils, J. Phys. Chem., Vol. 51, pp. 431, 1947
12. Levich, V. G., Physicochemical Hydrodynamics, Prentice-Hall, Inc., Englewood Cliffs, N.J., pp. 395-402, 1962
13. Beerbower, A. and Barnum, R. E., Studies on the Dispersion of Silicone Defoamer in Non-Aqueous Fluids, Lub. Eng., Vol. 4, pp. 283-285, 1961
14. Centers, P. W., Behavior of Silicone Antifoam Additives in Synthetic Ester Lubricants, Trans STLE, Vol. 36, No. 3, pp. 31-386, 1993