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EXPERIMENTAL STUDIES OF THE DISSOLUTION OF GAS BUBBLES IN WHOLE BLOOD AND PLASMA—II. MOVING BUBBLES OR LIQUIDS*†

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Abstract—Part I of the study is concerned with the dissolution of a gas bubble in quiescent, degassed blood and plasma. This paper is an extension of the experimental study to include the case in which the gas bubble dissolves in degassed blood and plasma impinging upon it. Results are compared with those of part I and the effects of relative motion between the bubble and the liquid are examined. It is disclosed from the comparison that the speed at which the bubble dissolves into the liquid is accelerated as the velocity of the flowing liquid is increased. The applications of the study include the dissolution of gas emboli in the human body and the extracorporeal oxygenation of the blood during open heart surgery.

1. INTRODUCTION

IN ENGINEERING, one of the important problems in the fields of hydrodynamics and heat transfer is the occurrence of cavitation in liquids induced by a decrease in pressure or boiling in liquids due to an increase in temperature, as evidenced by the coexistence of a gas or vapor phase with the liquid phase. This gas or vapor phase first becomes evident in the form of bubbles distributed throughout the body of the liquid. The significant problem one would have when cavitation appears, is the increase in drag experienced by submerged bodies moving through a liquid. In case of boiling liquids, the effects upon heat transfer rates due to the vapor phase are of great importance. Entirely analogous to cavitation or boiling in engineering is the problem of cavitation in biological fluids. One example is the formation of bubbles in the human body due to a sudden decrease in pressure, the circumstances experienced in diving and high-altitude flight. There are certain occasions under which the gas phase is introduced into the human body, for example, extracorporeal oxygenation of blood during open heart surgery. Of significance is the consequence resulting from the presence of this gas phase in the human body. That is the so-called gas embolism. Although it is relatively infrequent in medical practice, when it does occur, it may become catastrophic in some cases (Chang and Yang, 1969). To cope with the problem of gas embolism, it is advisable to understand the dynamic stability and rate of dissolution of the gas bubbles in whole blood and plasma (including other body fluids).

This paper investigates the important effect of translatory motion of the liquids or the bubbles during the dissolution of these bubbles. The analogous problems in engineering applications have been analytically studied by Ruckenstein (1959) and Tokuda *et al.* (1970). In boiling liquids, Ruckenstein has found that the size of vapor bubbles in quiescent liquid can be predicted by the expression

$$\frac{dD}{dt} = \beta D^{-1/4}$$

or

$$D - D_0 = \left(\frac{5}{4}\beta t\right)^{4/5}. \tag{1}$$

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where D is the diameter of the bubble, D_0 is the initial diameter, and t is the time. β is a constant defined as

$$\beta = 292\frac{k\Delta T_{sup}}{\rho_v \alpha^{1/2} h_{fg}}$$

in which $k\Delta T_{sup}$ and α are respectively the thermal conductivity, super-heating and thermal diffusivity of the liquid, ρ_v is the density of the vapor inside the bubble, and h_{fg} is the latent heat of vaporization. Tokuda *et al.* have obtained the growth of vapor bubbles in boiling binary liquid mixtures. Both studies by Ruckenstein and Tokuda *et al.* have concluded that translatory bubble motion results in a significant increase in the growth rate of the bubble. This can be shown by comparing equation (1) for moving bubbles and

$$D - D_0 \propto t^{1/2}$$

for a stationary bubble. In the present case, in addition to the effect of translatory motion, the effect of chemical reaction between the dissolved gas and reduced hemoglobin taking place inside the concentration boundary layer over the bubble surface is included in the dissolution of a gas bubble in the blood.

2. EXPERIMENTAL APPARATUS

The test apparatus used in this experiment is depicted in Fig. 1. The liquid reservoir (1) consists of two concentric plexiglas tubes of different heights, taller inner tube and shorter outer tube, mounted on a piece of flat plexiglas sheet. A series of ¼ in. diameter holes, appropriately spaced, are drilled on two opposite sides of the shorter tube and the upper portion of the taller tube. By plugging some of the holes, two different liquid levels can be created in the reservoir, higher liquid level in the taller tube and lower one in the shorter tube. A brass tube covered with a plexiglas sheet is mounted over the two concentric plexiglas tubes. This serves as an evacuation chamber (2) for the fluid reservoir. A Sarn 3500 model roller pump (3) is used to circulate the liquid which is spilled over the reservoir on the chamber floor back into the taller plexiglas tube of the reservoir.

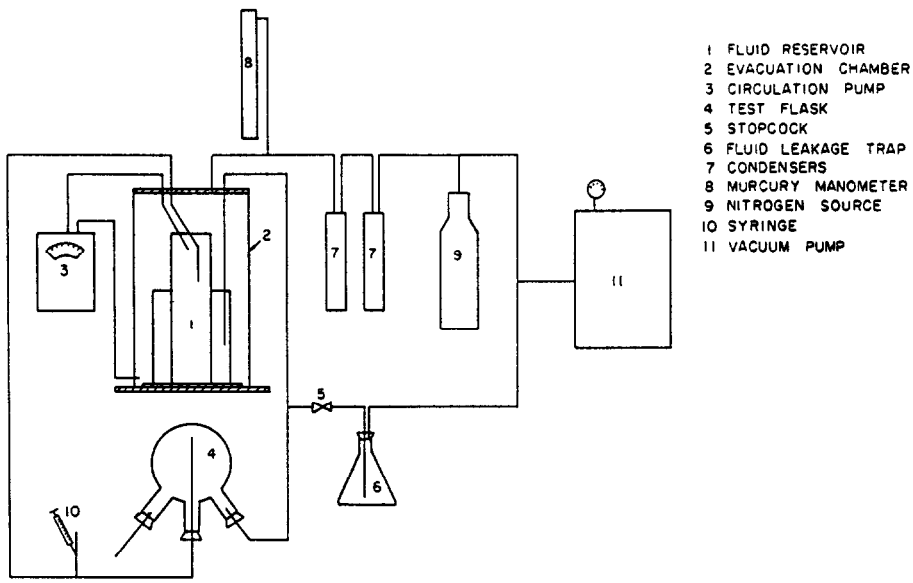

Fig. 1. Experimental apparatus.

Two condensers (7) each consisting of a flask placed in an ice bath are connected in series to trap water vapor before it enters a Cenco Hyvac-14 vacuum pump (11) during the degassing of the liquid. A mercury manometer (8) is connected to a line between the evacuation chamber and the condensers. After the degassing of the liquid is completed, the space above the liquid in the evacuation chamber is filled with gaseous nitrogen drawn from a nitrogen source (9).

The test flask (4) into which the gas bubble is injected is a 250 ml pyrex boiling flask which has three openings. A 6 mm i.d. glass tube is inserted through the stopper in the center opening until its tip is about 0·5 cm from the inner surface of the test flask. This glass tube will be used as the throat for producing a circular jet to impinge upon the gas bubble. The inner surface of the test flask, in the vicinity of the tip of the glass tube, is coated with a thin film of RTV adhesive so that a gas bubble injected into the test flask, through the liquid line, may stay on the inner surface of the test flask. The liquid in the upper level (inner tube) in the reservoir flows into the test flask through the center opening. It then flows back to the lower level (outer tube) in the reservoir through the second opening of the test flask. The third opening is used for venting entrapped gas or vapor in the test flask. When the stopcock (5) is opened, the flow of the liquid can be diverted to a 250 ml Erlenmeyer flask (6) which is connected with the line between the nitrogen source and the vacuum pump.

3. TEST PROCEDURE

The experiments were conducted in two steps; the degassing of blood and plasma and the injection of a gas bubble into the degassed liquid, followed by the measurements of the instantaneous bubble size.

After some of the holes drilled on the plexiglas tube walls were plugged for desired liquid levels in the reservoir (1), the test flask (4) was placed at a position above the evacuation chamber (2). The stopcock (5) was then closed, followed by closing the tubing leading to the nitrogen source (9) with a Hoffman pinchcock. The vacuum pump (11) was started. When a desired level of vacuum was established in the evacuation chamber, the stopcock was opened. The vacuum pump was turned off as soon as all evidence of 'boiling' within the evacuation chamber had ceased. Then the stopcock was closed, the roller pump (3) was started, and the test flask was lowered to a position below the evacuation chamber. The line leading to the nitrogen source was opened by removing the pinchcock until the system was filled with gaseous nitrogen at atmospheric pressure. When nitrogen bubbles were tested, the system was opened to atmospheric air instead of gaseous nitrogen. The gas or vapor entrapped in the test flask was vented through the third opening of the test flask.

After a small gas bubble was injected into the fluid by means of the syringe (10), the tubing leading from the evacuation chamber to the test flask was closed with a Hoffman pinchcock. Extreme precaution was taken to fill the needle on the end of the syringe with test gas so that air was not entrapped in the syringe. (In the interest of brevity, the method employed to fill the needle with the test gas is not included here.) The bubble was then brought to rest at the top of the inverted test flask and was positioned on the axis of the jet tube, as shown in Fig. 2 by adjusting the positions of the tubings and the test flask. Upon the removal of the Hoffman pinchcock, the liquid started to circulate in the loop between the evacuation chamber and the test flask and the jet of the liquid impinged upon the gas bubble.

The size of the gas bubble was measured by observing it through the bottom of the inverted test flask with the Edscorp comparitor. The size of the bubble was recorded as a function of time until its complete dissolution in the liquid. The flow rate at the given liquid level was known through the calibration of the Sarns roller pump used to maintain the liquid

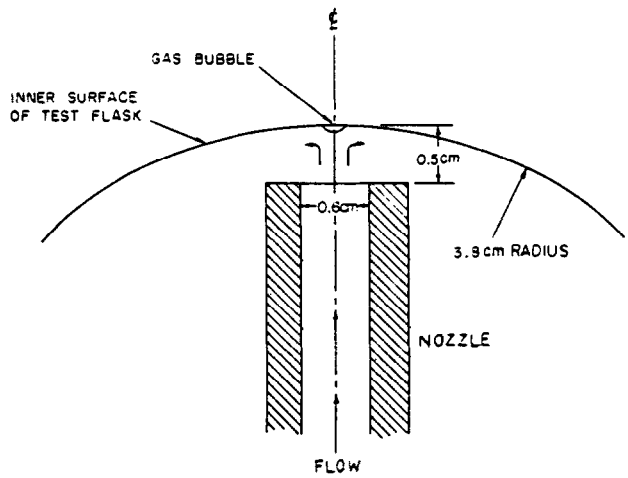

Fig. 2. Position of gas bubble in test flask.

level while the liquid flowed through the test flask.

The viscosity of the liquid was measured before and after each test as mentioned in part I, in order to check any possible change in the liquid property resulting from the degassing process or its continuous exposure to the room temperature and pressure.

4. TEST RESULTS AND DISCUSSION

The difference in the nature of dissolution of oxygen bubbles in the bloods and plasma has been disclosed in part I of the study. Like carbon dioxide bubbles in plasma, the dissolution of oxygen bubbles in the bloods is characterized by the occurrence of chemical reaction in the concentration boundary layer of the dissolved gas, as evidenced by a rapid decrease in bubble size or a very steep negative gradient of radius–time curve. This phenomenon is observed in a very short time immediately following injection. It is followed by a gradual shrinkage in bubble size which is attributed to diffusion of the dissolved gas in the bloods. The shape of the radius–time curve in this time period, which lasts until the complete dissolution of the bubble, is analogous to that of the radius–time curve for oxygen bubbles in the plasma. The mechanism of dissolution of oxygen bubbles in the plasma is due to diffusion alone.

When an oxygen bubble is in relative motion with the liquid such as the case when the liquid impinges upon the bubble, the bubble dissolves following the same mechanism as a bubble in a quiescent liquid. However, because of convective effects, the concentration boundary layer of the dissolved gas over the bubble surface becomes thinner than that of the latter case. As a result, resistance to the diffusion of the dissolved gas decreases. It decreases further as the relative velocity is increased. Thus, a gas bubble in a flowing liquid dissolves faster with an increase in the flow velocity. This is observed in the experiments whose results are depicted in Figs. 3 and 4 for the plasma and bloods, respectively. In both figures, the radius–time curves for oxygen bubbles in the quiescent liquids, reported in part I, are included for comparison. The diffusion coefficient $D = 2 \times 10^{-5}$ cm^2/sec has been used in calculating the dimensionless time.

It is seen in Fig. 3 that for oxygen bubbles in the plasma, or in the absence of chemical reaction, the radius–time curves appear very close to being straight lines. This observation agrees well with the theoretical

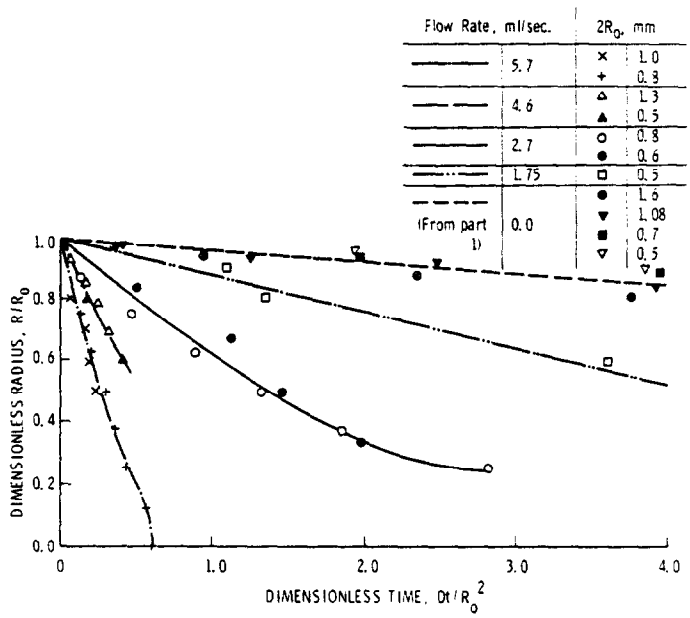

Fig. 3. Radius–time relation of oxygen bubbles in flowing degassed plasma.

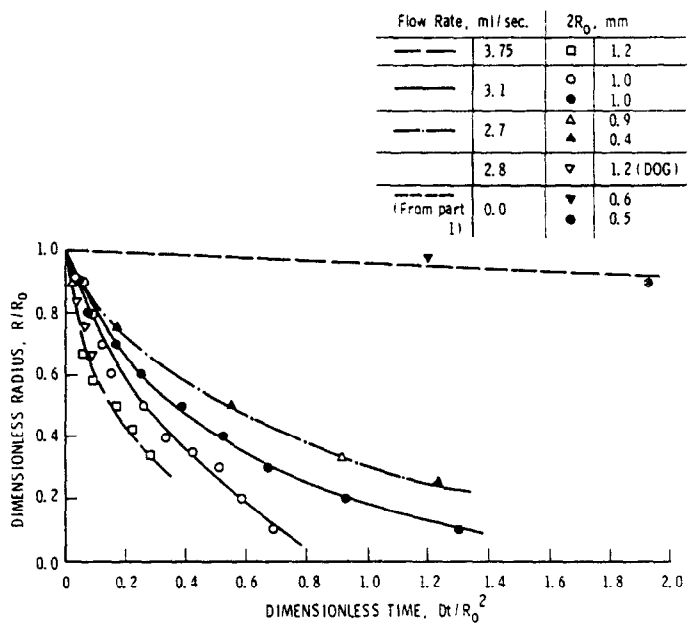

Fig. 4. Radius–time relation of oxygen bubbles in flowing degassed human and dog bloods.

prediction of Ruckenstein, equation (1), for a free ascending bubble in liquids. Physically, the two cases have very similar flow situation over the upstream half of the gas bubble where mass transfer to the liquid is dominating. Figure 3 also demonstrates how the dis-

solution of oxygen bubbles is accelerated by an increase in flow rate. Attention should be called to the curve representing the data expressed by × and +. Near complete dissolution, this curve has a shape resembling that for quiescent liquids in part I. This indicates that toward a complete dissolution, the shrinkage of the gas bubble is accelerated by the action of surface tension force.

For oxygen bubbles in the bloods, or in the presence of chemical reaction in the concentration boundary layer, the radius–time curves shown in Fig. 4 may be approximated as $R \propto t^n$ with n varying with time from 0·5 to 1. The lifetime of the bubble decreases with an increase in flow rate. It is seen in the figure that the dissolution of an oxygen bubble in the dog blood, as indicated by the symbol ▽, follows the same pattern as that of oxygen bubbles in the human blood. A comparison of Figs. 3 and 4 yields the conclusion that the dissolution of oxygen or gas bubbles in liquids is accelerated by the presence of chemical reaction.

5. CONCLUDING REMARKS

The dissolution of gas bubbles in the human dog bloods and plasma, at rest or in flow, impinging upon the bubbles, is studied experimentally. In the case of plasma, the bubbles of oxygen, nitrogen and carbon dioxide dissolve in the liquids through the mechanism of diffusion and convection (only when flow is presented). Whereas, in the case of the bloods, reversible chemical reaction plays an important role in the dissolution of the gas bubbles, in addition to the transport mechanism of diffusion and convection. As a result, the gas bubbles shrinks more rapidly in the presence of chemical reaction. This special feature is demonstrated in the radius–time curve in a form of very steep slope immediately following injection. In the subsequent time up to the moment of complete dissolution, the role of chemical reaction is reduced and the gas bubbles dissolve mainly by diffusion and convection. Convection accelerates the shrinkage of the gas bubbles and its effects are enhanced with an increase in flow rate.

In applications, although the situation for the flow of the liquids impinging upon the gas bubbles differs from that being observed in extracorporeal oxygenation of the bloods, the results indicate qualitatively the effects of flow rate on the dissolution of oxygen bubbles in the latter case. During extracorporeal oxygenation, there is a relative motion between oxygen bubbles and the bloods which is analogous, to some extent, to the impingement of liquids on gas bubbles. The dissolutions of nitrogen and carbon dioxide bubbles, gases commonly found in the body fluids, are also investigated. Plasma has been used as the test liquid for convenience in the visual observation of bubble behavior. It is disclosed that in quiescent plasma, the lifetimes of the gas bubbles are progressively longer in the order of carbon dioxide, oxygen and nitrogen, depending on the magnitude of the diffusion coefficients but not on their solubility. This observation may be applied to the bloods.

Next investigation is to use these experimental techniques and results to determine the diffusion coefficients of gases and mass transfer coefficients in the biological fluids, either at rest or in motion. Results will be presented in separate papers.

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