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Sinking Bubbles

Investigating Air Bubbles in Vertically Oscillating Liquids

We are used to bubbles rising in liquids. However, when a column of liquid is oscillated vertically, it is not always the case. Experiments were conducted to determine the critical conditions under which such a behaviour occurs. It is shown, that the experimental results are in good agreement with an equation given in literature. Lastly, the behaviour of bubbles in a vertically oscillating oil column was explained with a new equation and experiments verified its accuracy.

DIE JUNGFORSCHERIN

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1. Introduction

In 2019, I participated in the *Swiss Young Physicists Tournament* (SYPT). Out of the 17 problems proposed, problem number 16, *Sinking Bubbles*, immediately caught my interest. The task of the problem was described as follows "When a container of liquid (e.g. water) oscillates vertically, it is possible that bubbles in the liquid move downwards instead of rising. Investigate the phenomenon."

I was particularly curious about this phenomenon because it is very counterintuitive. A bubble of air can sink in water even though the densities have a difference of three orders of magnitude. What stroke me after studying the publications about this problem, is that none of them included experiments to confirm the theory. In an earlier publication on a similar matter [3], Rubin proposes a model that looks at the state of the vibrating bubble, whether it is rising, sinking or remaining at the same depth. In other publications for example [2, 7], one can find an equation of motion that aims to describe the bubble's position at any point in time. The results of the research in that topic is applicable in the development and optimisation of some relevant technologies like the floatation process.

This paper investigates the interesting phenomenon of sinking air bubbles inside a vertically oscillating container of liquid. Experiments consisting in introducing air bubbles into two different liquids were conducted (water and sunflower oil) varying parameters, such as, depth, amplitude, frequency and the liquid's density and viscosity. Moreover, some shortcomings of previous publications are highlighted and a variation of the theory one can use in a defined system is proposed. Lastly, for both equations of motion the conditions in which they accurately describe the behavior of sinking bubbles are elaborated.

2. Theory

Usually, bubbles in a liquid rise due to gravity and the density difference between the liquid and gas. A bubble in a liquid will experience a pressure according to its position. Hence, it will experience a pressure gradient. If one starts moving the column of liquid in an oscillating vertical motion e. g. using a vibration exciter, the pressure changes will also be dependent on the acceleration direction. When such an acceleration leads to a pressure inversion, e.g. if the column is accelerated downwards by more than the earth's acceleration, the bubbles will start moving towards the bottom, as they always go where the pressure is at the lowest.

The vertical oscillation may be considered as harmonic. This means the acceleration and so the buoyancy force acting on the bubble are time dependent. At a fixed depth you observe fluctuations in the pressure and the bubbles undergo a driven oscillation. The dotted function in Fig. 1 shows the dependency of the pressure as a function of the depth in a none vibrating liquid. In this case the formula $p(h) = p_0 + \rho g h$ is applicable. The functions left and right show the same dependency when the liquid is oscillating in a vertical direction. In those cases, the pressure, given by the non vibrating case for any depth h, will be decreased for a downward motion or increased for an acceleration in opposite direction.

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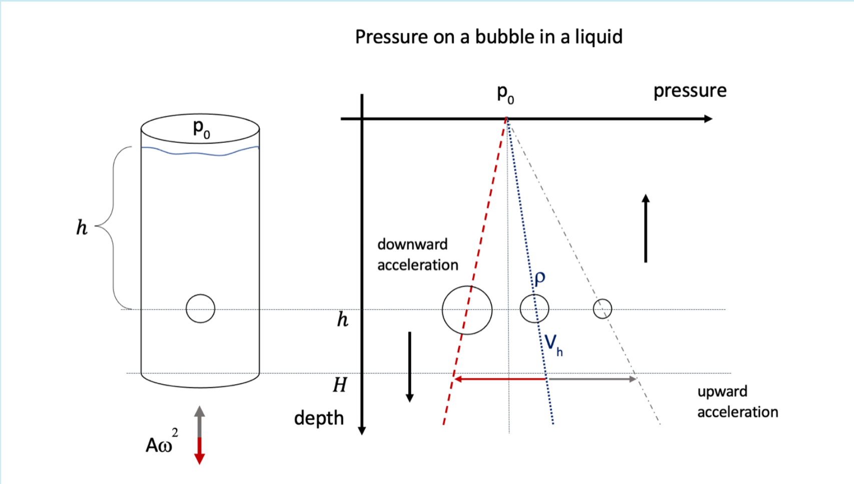

Fig. 1: Pressure on a bubble in a liquid. The dotted blue function shows the dependency of the pressure as a function of the depth in a none vibrating liquid. The functions left and right show the same dependency when the liquid is oscillating in a vertical direction.

In order for the bubbles to sink, the drive and the response must be in phase. According to the calculations, the Minneart Resonance of the bubble was [5]: $\omega_R = 3.3$ kHz. As the conducted measurements were in the frequency range f << 100 Hz, where the calculated phase shift is negligible.

In an upwards motion, the liquid at the bottom of the tube is compressed and the bubble experiences a higher pressure whereas during a downwards motion, when the acceleration acting on the column is above the earth's acceleration, g, the water is in a falling motion, which leads to an under-pressure at the bottom of the tube and so the pressure exerted on the bubble decreases.

2.1 The Static Case

Bubbles in a vertically oscillating liquid of density ρ experience a change in pressure p, which implies a change in volume V. If the average buoyancy force F_B over one period equals to zero, the bubbles stay at the same depth. In case the result is positive, the bubbles are rising and they are sinking if the value is negative.

The pressure on the bubble can be written as: Equation 1.

Where A is the amplitude and $\frac{\omega}{2\pi}$ the frequency of oscillation.

Since we look at the bubble at constant depth we can use

$$\Delta p(t) = p - p_0 = \rho A \omega_2 \sin(\omega t) h \,. \qquad \text{Eq. 2}$$

The buoyancy force can be expressed as:

Equation 3

For small bubbles where the pressure gradient is negligible, V_h is the volume of the bubble at depth h in the stagnant liquid and ΔV the change in volume during the oscillation. It is defined as:

$$\Delta V(t) = -\beta V_h \Delta p(t) \qquad \text{Eq. 4}$$

where the compressibility factor β is equal to

$$\beta = 1/\gamma p_0 \,. \qquad \text{Eq. 5}$$

γ is the polytropic exponent. If the compression is isothermal then $\gamma = 1$ and if it is adiabatic then $\gamma = 1.4$. The compression is assumed to be adiabatic since the oscillation happens so quickly that an exchange of heat is highly improbable.

Entering the expressions for β and $\Delta p(t)$ in the equation of the change in volume one gets

$$\Delta V(t) = -\frac{1}{\gamma p_0} V_h \rho A \omega^2 \sin(\omega t) h \,. \qquad \text{Eq. 6}$$

Insert the expression for ΔV in the equation 3: Equation 7.

To get the average buoyancy force the buoyancy force is integrated over one period and then divided by the period.

Equation 8

One can set the average buoyancy force equal to zero and obtain the conditions

Equation 1

$$p(t) = p_0 + \rho(g + A\omega^2 \sin(\omega t))h = p_0 + \rho g h + \rho A \omega^2 \sin(\omega t) h$$

Equation 3

$$F_B = \rho\, V(t)\, a(t)$$

$$F_B = \rho\, (V_h + \Delta V(t))\, \left(g + A\omega^2 \sin(\omega t)\right)$$

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Equation 7

$$F_B = \rho\left(Vh - \tfrac{1}{\gamma P_0} V_h \rho A\omega^2 \sin(\omega t) h\right)\left(g + A\omega^2 \sin(\omega t)\right) .$$

Equation 8

$$\langle F_B \rangle = \frac{1}{T}\int_0^T \rho\left(V_h - \frac{1}{\gamma P_0} V_h \rho A\,\omega^2 \sin(\omega t) h\right)\left(g + A\,\omega^2 \sin(\omega t)\right)\mathrm{d}t$$
$$= \frac{1}{T}\int_0^T \rho V h g + \rho V h\, A\,\omega^2 \sin(\omega t) - \frac{\rho^2}{\gamma P_0} V h\, A\,\omega^2 \sin(\omega t) g h - \frac{1}{\gamma P_0} V_h A^2 \omega^2 \sin^2(\omega t) h \mathrm{d}t$$
$$= \rho V h g - \frac{\rho}{2\gamma P_0} V h\, A\,\omega^4 h$$
$$= \rho V h g \left(1 - \tfrac{\rho A^2 \omega^4 h}{2\gamma g P_0}\right)$$

for a static bubble.

$$1 = \frac{\rho A^2 \omega^4 h}{2\gamma g\, P_0}$$
$$A\,\omega^2 = \sqrt{\tfrac{2\gamma g P_0}{\rho h}} \qquad \text{Eq. 9}$$

Equation 9 was found in [3] and is validated in section 4 on Fig. 6 and 7.

2.2 Dynamics

In literature [2, 7] you can find the following equation that is meant to describe the dynamic motion of a sinking bubble.

Equation 10

In this equation, C stands for the drag coefficient, A_B the cross-section of the bubble and V_B its volume.

It shows a correct qualitative behaviour. This paper however aims for a quantitative evaluation to measure the reliability of equation 10 (see section 5.1). Fig. 2 shows the forces used in equation 10, with F_F the friction force, F_G the gravitational force and F_B the buoyancy force,

$$F_F = \tfrac{1}{2} C\rho A_B \dot{x}^2 \qquad \text{Eq. 11}$$

$$F_G = m_B(A\omega^2 \sin(\omega t) + g)$$

$$F_B = \rho V_b\, (A\omega^2 \sin(\omega t) + g)$$

as well as a representation of the added mass, m_0, the mass of the water which oscillates along with the bubble,

$$m_0 = \tfrac{2}{3}\,\pi\,\rho\, r_B^{\,3} \qquad \text{Eq. 12}$$

where $\frac{2}{3}$ is the coefficient of added mass for a sphere [1] and r_B the radius. This coefficient seems to be an insufficient approximation. While the column oscillates, the bubble's shape does not maintain its round form, which means one cannot consider it as a sphere any longer (see Fig. 3).

The capillary length, λ_{cap}, is an indicator relating gravity and surface tension. The ratio of the radius of the bubble to the capillary length, indicates how close the bubble's shape will be to a sphere. If

Equation 10

$$\left(m_B + m_0\right)\ddot{x} + m_0\,\dot{x} = \tfrac{1}{2} C\rho A_B\,\dot{x}^2 + \left(m_B - \rho V_b\right)\left(A\omega^2 \sin(\omega t) + g\right)$$

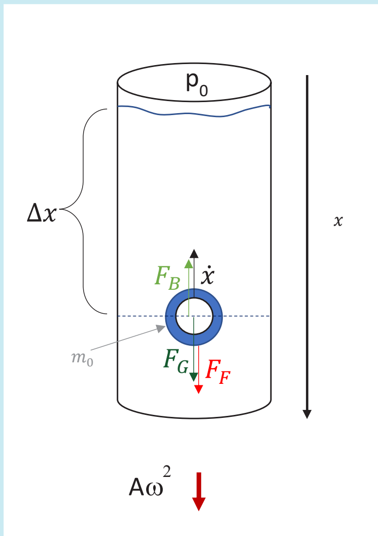

Fig. 2: This sketch shows the forces acting on a rising bubbles in a system that is being accelerated downwards. Please note that the x-axis is pointing downwards and represents the depth.

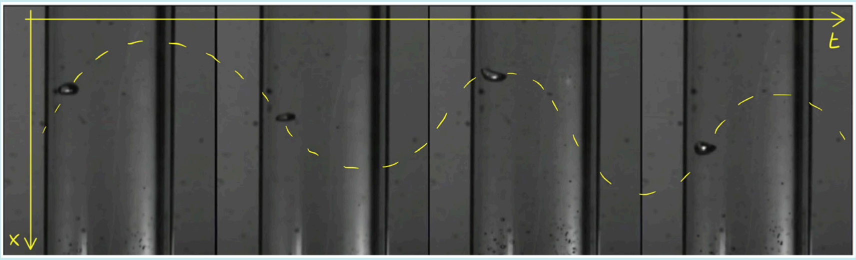

Fig. 3: Aspherical shape of a sinking bubble of large radius in a vertical oscillation over time.

Equation 15

$$\frac{d}{dt} m_B \dot{x} = -6\pi\eta\dot{x}r + (m_B - \rho V_b)(A\omega^2 \sin(\omega t) + g)$$

$$\frac{r}{\lambda_{cap}} = \sqrt{\frac{\rho g r^2}{\sigma}} \ll 1 \qquad \text{Eq. 13}$$

the bubble is spherical. The larger the result of the equation the more significant the deviation away from the sphere gets [4].

As the capillary length is constant for bubbles of air in water, the smaller the radius of the bubble the more spherical it will be. Which means one can try a workaround the problem by choosing the bubble's radius as small as possible. The change in volume is in such a case less important and there is a better chance for the experiments to be fitted accurately with equation 12. A smaller bubble implies a reduced velocity and both together speak for a low Reynolds number (see section 2.3). A further way to lower the Reynolds number is to change the fluid to a more viscous one e. g. sunflower oil. If equation 10 gives a relatively good simulation for water under certain conditions, changes will be made in the theory for the case in oil.

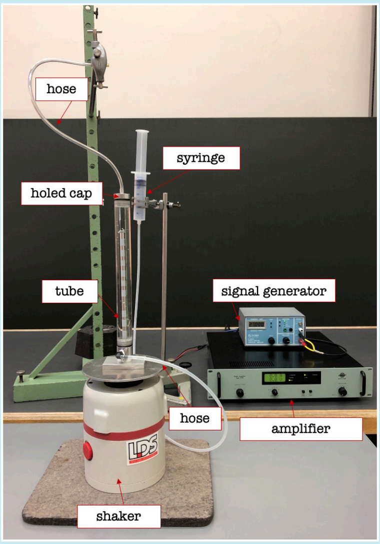

Fig. 4: Picture of the set up.

In our range of Reynolds number, the flow is laminar. However, Stokes' law can and must only be applied for lower Reynolds numbers. Consequently, I adapt the equation of the friction force F_F, where

$$F_F = 6\pi\eta\, \dot{x} r. \qquad \text{Eq. 14}$$

Furthermore, due to smaller accelerations, the oscillating mass around the bubble gets much smaller and can therefore be neglected. The resultant force is then written as follows:

Equation 15

2.3 The Reynolds Number

The Reynolds number, *Re*, of a motion is a number describing the flow of the liquid around the air bubble. It is the ratio between the inertia and the friction force. Hence, this number is dimensionless. The value of the Reynolds number can be found by applying the following equation

$$Re = \frac{vd\rho}{\eta} \qquad \text{Eq. 16}$$

and is dependent on v, the velocity of the bubble, d, its diameter, η the liquid's dynamic viscosity, and ρ the corresponding liquid density.

The Reynolds number permits to determine what equation shall be used for the friction force. For $Re \leq 2$ Stokes' law is very accurate. It is known that Stokes' law can be applied for values of the Reynolds number lower than 4. For larger Reynolds numbers, the more general Equation 11 can be used, where C depends *a priori* on the Reynolds number. In a very large range, C decreases with increasing Reynolds number; in the range between approximately 1.000 to 500.000, the value of C is constant [6].

3. Materials and Methods

For the experiments (see Fig. 4) an electrodynamic vibration exciter (*LDS Shaker V406*) that oscillates

Vid. 1: Bubble in the vibrating column

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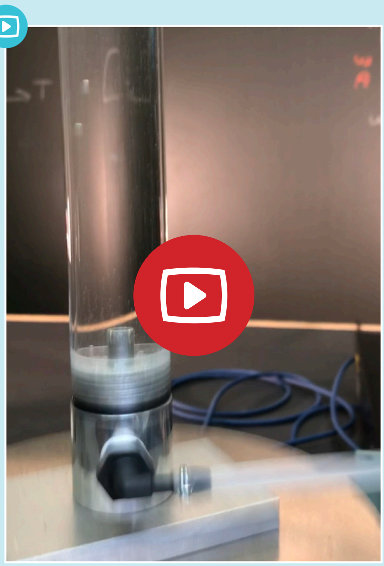
vertically with a frequency gained by a signal generator and amplitude set by the amplifier was used. Furthermore, tubes of different lengths (28.4 cm ≤ l ≤ 57.9 cm) were used, at the bottom of which one could press air through a hose with a syringe. To keep an ambient pressure on top of the tube a hose is attached to the cap and lets the air out. In the main tube one can see a smaller tube (see Fig. 5), it permits the beginning depth to be smaller than the maximal depth which makes it easier to distinguish whether the bubbles are sinking, remaining at the same depth or rising.

The first series of experiments consisted measuring the critical amplitude. That means the amplitude at which bubbles are in a static motion for a given frequency and bubble depth. To do so the set up as shown in Fig. 4 was installed and one started accelerating the harmonic oscillator by going up with the amplitude. Air was pressed with the syringe inside the column. If the bubbles were rising, the amplitude was increased, in the other case, the amplitude was decreased. The idea was to achieve the stationary state, so the state in which the bubbles stay at the same depth. Once this motion was reached, the high-speed video (500 frames per second) of the shaking plate was taken,



Vid. 2: Sinking bubble in real time

to track the amplitude of the oscillation at that moment. In section 4.1 one can find a diagram relating amplitude and frequency compiled out of the measured points.

The second type of experiments were made to follow the development of a bubble in the vibrating column over time (see Video 1). For this series of experiments the inner tube (see Figs 4 and 5) was removed to assure a clearer view on the bubble. The first step was to choose a fixed depth and frequency and then approximately decide with what amplitude the shaker needed to oscillate. Some air was pressed at the lowest point of the tube. An isolated bubble was chosen and its behaviour over time was captured. This was done with the high-speed camera at 500 frames per second. Later on, the bubble's motion was tracked and its diameter measured, to compare the experimental results to the theory.

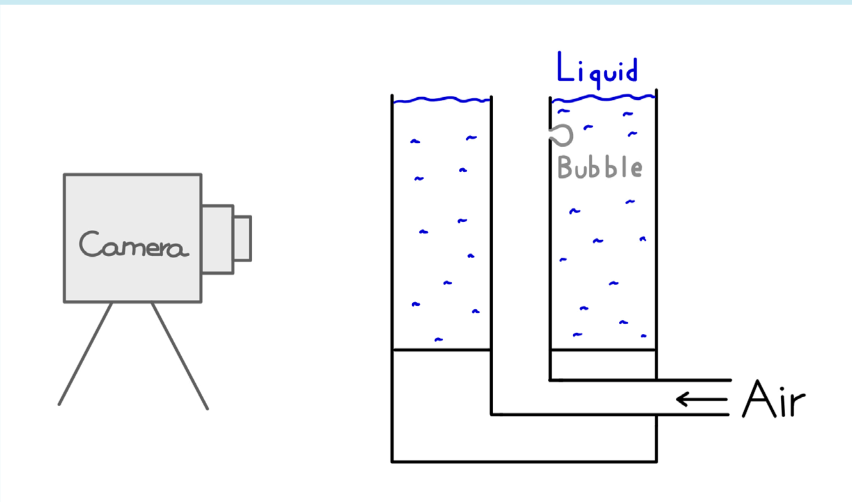


Fig. 5: Sketch of the entry of air with the use of the inner tube.
The sketch shows the cross section of the bottom of the main tube.

In Video 2 one can see a sinking bubble in real time. Note that the bubble appears to be stretched in a vertical direction, this happens because our eyes are not fast enough to see the vertical oscillation of the bubble. Video 1 on the other hand was filmed with a high-speed camera, hence the bubble appears in its normal shape and the oscillations are very clear.

4. The Static Case

4.1 Experimental Results

Please note that all theoretical values are derived from section 2. The following diagrams are based on equation 9 and all error bars are statistical errors.

For a fixed depth of 39.1 cm, Fig. 6 shows the amplitude for stationary bubbles at a given frequency. The blue straight line is a fitted linear function forced through the origin. The error bars represent statistical errors, and the dashed lines are theoretical values with a compressibility factor (see equation 5) $\gamma = 1.6$ for the upper gray line and $\gamma = 1.2$ for the lower orange line.

Many diagrams analog to Fig. 6 have been made for different depth of the bubbles. The slope a of those functions has been plotted as a function of the depth's inverse to validate equation 9 (see Fig. 7). The blue dots represent the experiments while the upper and lower dashed lines represent the theoretical values. The obtained values for the compressibility factor (see equation 5) are $\gamma = 1.2$ for the upper limit (orange line) and $\gamma = 1.6$ for the lower limit (grey

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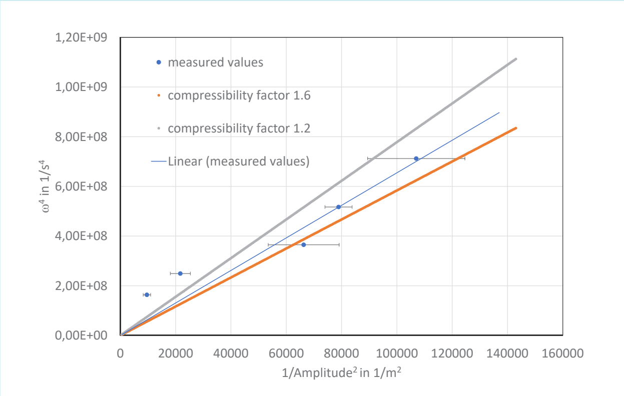

Fig. 6: Diagram of the critical amplitude in stable state.

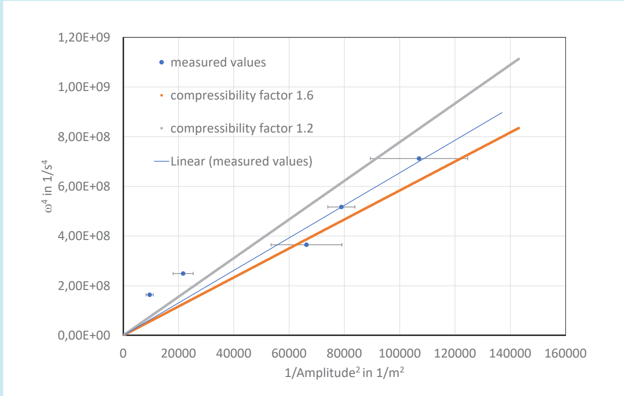

Fig. 7: Variation of depth for validating equation 9.

line). The straight line is the regression.

4.2 Discussion

While doing the first measurements, the shaker's limits were rapidly attained. That means there was only a limited range of frequency in which one could measure. A low frequency speaks for a large displacement amplitude and vice-versa. In both cases — at low and high frequencies — the generated oscillations were insufficient for the experiments. Close to the borders the measurements started to get complicated which explains the points of lower accuracy for the two highest amplitudes in Fig. 6. To optimise the range of measurements the bubbles' depth was increased using longer tubes. By doing that, the system got more stable, which had a positive repercussion on the data. The next encountered issue was the mass of the column that would lower the stability of the set up. To work around the problem and enlarge the range of measurements longer tubes were used.

As the fitted line in Fig. 7 lays in between the calculated limits we can say that the compressibility factor γ is estimated with

$$\gamma = 1.4 \pm 0.2 \,.$$

This speaks for an adiabatic compressibility as assumed in the theory.

Overall, one can conclude that

Tab. 1: Sinking and rising bubbles in water. The parameters amplitude, radius and Reynolds number in Figures 8 to 13.

Figure and motion of bubble	Radius r in mm	Amplitude A in mm	coefficient of added mass in %	Reynolds number
8, rising bubble	1.2	2.2	–25	160
9, rising bubble	3.3	3.2	–17.5	235
10, rising bubble	0.43	1.03	–10	85
11, rising bubble	0.63	1.26	–33	115
12, sinking bubble	0.3	3.4	230	1.9
13, sinking bubble	0.4	4.2	425	16

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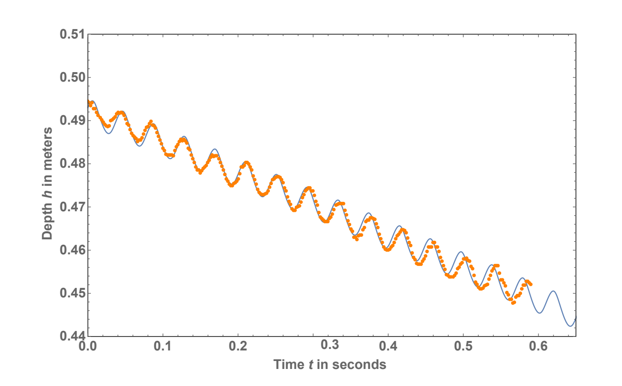

Fig. 8: Motion of a rising bubble of radius r = 1.2 mm in a vertically oscillating column of water. The amplitude chosen for this motion was A = 2.2 mm.

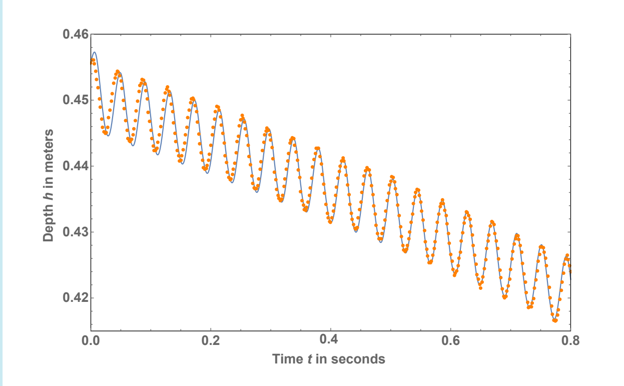

Fig. 9: Motion of a rising bubble of radius r = 3.3 mm in a vertically oscillating column of water. The measured amplitude in this motion was A = 3.2 mm.

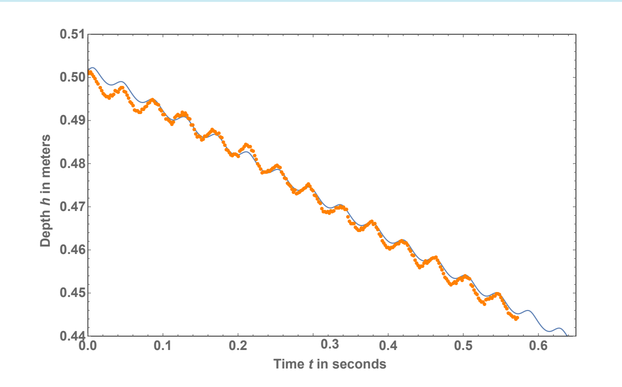

Fig. 10: Motion of a rising bubble of radius r = 0.43 mm in a vertically oscillating column of water. The amplitude chosen for this motion was A = 1.03 mm. The coefficient of added mass was reduced by 10 %.

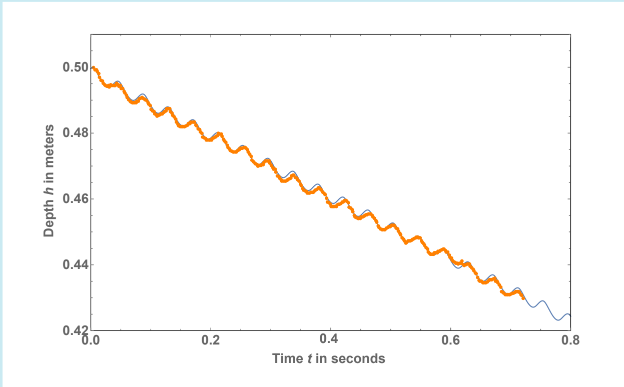

Fig. 11: Motion of a rising bubble of radius r = 0.63 mm in a vertically oscillating column of water. The measured amplitude in this motion was A = 1.26 mm. The coefficient of added mass was reduced by 33 %.

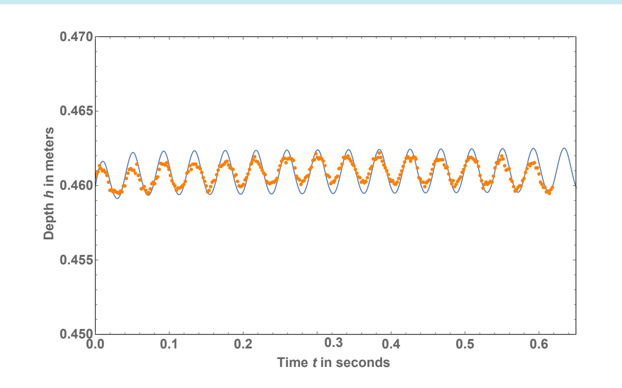

Fig. 12: This diagram shows the development over time of a sinking air bubble in water (r = 0.3 mm). The calculated Reynolds number for this motion is Re = 1.9. The measured amplitude of the oscillator was A = 3.4 mm.

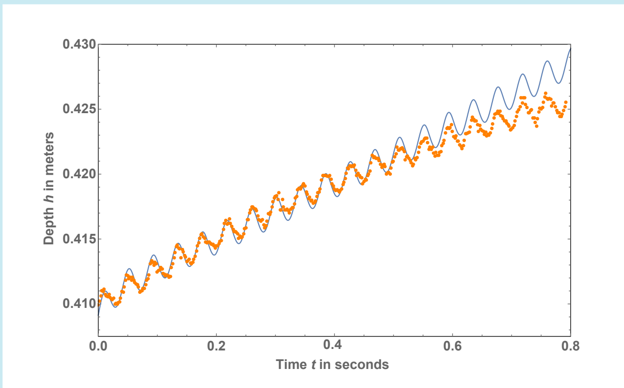

Fig. 13: This diagram shows the development over time of a sinking air bubble in water (r = 0.4 mm). The calculated Reynolds number for this motion is Re = 16. The measured amplitude of the oscillator was A = 4.2 mm.

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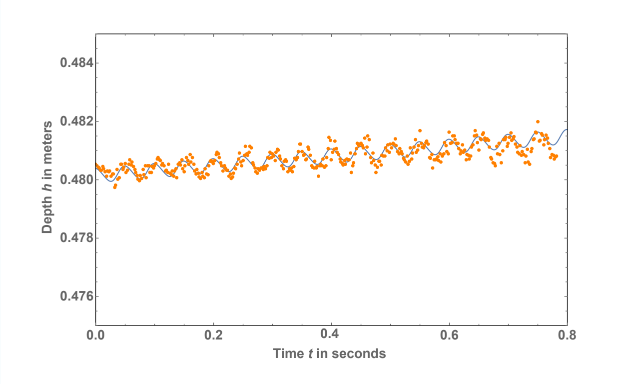

Fig. 14: This diagram shows the development over time of a sinking air bubble, r = 0.4 mm, in oil. The calculated Reynolds number for this motion is Re = 0.02. The amplitude of the oscillator is A = 6.2 mm.

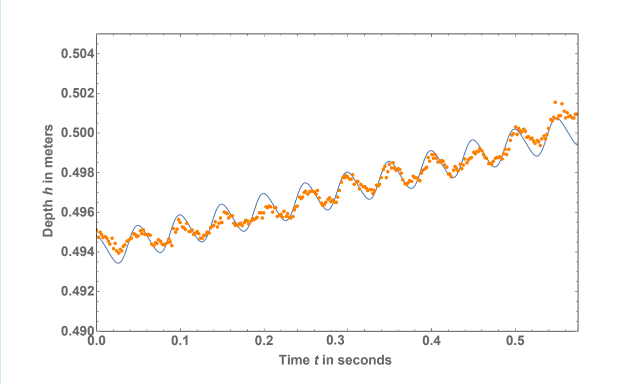

Fig. 15: This diagram shows the development over time of a sinking air bubble, r = 0.7 mm, in oil. The calculated Reynolds number for this motion is Re = 0.25. The amplitude of the oscillator is A = 7 mm.

equation 9 provides a good physical model of the state of the bubble.

5. Dynamics in a Water Column

5.1 Experimental Results

In this section, the orange points in Fig. 8 to 13 represent the experimental values whereas the blue lines are simulations following the equation 10. The simulations were run with the software Mathematica. Error bars were deliberately not included due to an otherwise overloaded diagram. Note that the frequency used for all experiments in this section is $f = 24\ Hz$ and the drag coefficient was kept constant, $C = 0.47$.

5.2 Discussion

One can see comparing Fig. 8 to 11 and Tab. 1, rising bubbles in water, that for smaller amplitudes the added mass must be decreased, to make the amplitude and speed of rising match. Otherwise, the simulated bubble would have a much bigger amplitude of oscillation and its rising speed would be slightly greater. This happens because, for smaller amplitudes, the change in volume of the bubble decreases. Hence, the water volume oscillating with the bubble gets smaller as well which leads to a decrease in added mass. All together, it is problematic to predict the bubble's motion with the equation 10 in a case of low amplitude, as the system is then more stable, and the added mass given by the theory is too big to fit the experiments. This leads to think, that for high Reynolds numbers the formula to calculate the added mass is accurate but for motions with lower Reynolds numbers the computed added mass is too big. It is even shown in section 5.3 and 5.4, that in oil (Re < 1) the added mass must be removed to obtain a good theoretical model.

All in all, the coefficient of added mass must be decreased to describe correctly the behavior of rising bubbles in an oscillating column of water with amplitude below approximately 1.5 mm. Additional research would however be needed to give a quantitative prediction of the change in coefficient for a given Reynolds number. Therefore, in cases of small amplitudes, it is not reasonable to describe the motion of rising bubbles using equation 10.

Comparing Figs 12 and 13 one can see differences in the bubble's radius and the amplitude. The experimental results lead to the conclusion that the motion of the bubbles with smaller radii (e.g. < 1 mm) are described accurately by equation 10 derived in section 2.2. Whereas larger bubbles (e.g. > 1 mm) show a different behavior and derivate from the theory. Regarding the amplitude, for sinking bubbles small amplitudes are favoured since the

Tab. 2: Sinking bubbles in sunflower oil. The parameters amplitude, radius and Reynolds number in Figures 14 and 15.

Fig. and motion of bubble	Radius r in mm	Amplitude A in mm	Reynolds number
14, sinking bubble	0.4	6.2	0.02
15, sinking bubble	0.7	7.0	0.25

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bubbles' speed is then lower.

After studying the results, the observation was made that a "calmer" system was recommended. The idea became to find something comparable to a scale of stability. The Reynolds number of the motions was then calculated and it appeared to be a good indicator since cases of small Reynolds numbers were described more precisely than other cases. To attain even lower Reynolds number it is possible to change the liquid see equation 16. As oil has a smaller density and bigger viscosity than water it was a very suiting alternative, hence further experiments have been made to investigate this new system. The theory was adapted (see section 2.3), compared to experimental data shown in section 6.1 and discussed in section 6.2.

6. Dynamics in an Oil Column

6.1 Experimental Results

In this section, the orange points in the Figures 14 and 15 represent the experimental values whereas the blue line are simulations following the equation 15. The simulations were run with the software Mathematica. Again, the error bars are not included for the same reasons as previously. The frequency as well as the temperature are kept constant, $f = 20\ Hz$ and $\vartheta = 20\ °C$, and the oil used was sunflower oil.

Fig. 14 and 15 show the behavior over time of sinking bubbles in oil, we compare the diameters of bubbles and the Reynolds number of their motion.

6.2 Discussion

Comparing two different measurements (see Tab. 2), one can see a better agreement between theory and experiment in Fig. 14 than in Fig. 15. This can be explained using the same principles as the ones interpreting Figures 12 and 13 (see section 5.2), a small radius, a small amplitude and thereby a small Reynolds number bring stability to the system. Looking at the Reynolds numbers calculated for the motions in oil, one can use Stokes' law. This treat gives larger borders to the validity of the model. One can see that even though smaller amplitudes imply more precision, it is possible to describe accurately motions in oil that experience a rather big amplitude comparing to the ones in the previous section. Altogether, one can say that the range of accuracy of the simulation in oil is greater than in water.

The flow being more stable in the motion in oil than in water, the oscillation of the liquid around the bubble is less significant. It can therefore be neglected. Followingly, the added mass can be removed from the equation of motion, which takes away many insecurities. Equation 15, which has been used to describe sinking bubbles in oil, relies on simpler physical systems one knows how to master. It is as well visible in oil, comparing Figs 14 and 15, that a low Reynolds number speaks for more exactitude. Equation 15 may also be valid for different kinds of fluids which fulfill the stated conditions.

To conclude, one can see in subsection 6.1 that the physical model, described by equation 15 gives a very suitable description of sinking bubbles in oil.

7. Range of Accuracy of the Dynamic Model

A key point to obtain a working experiment is to have a stable system. That is, when the flow is more laminar. Like that, the bubbles will move in a more predictable way. A good measure for the stability of system is the Reynolds number. The lower the Reynolds Number the higher the stability. The first parameter that one can change to alter the Reynolds number is the velocity at low frequencies. As the velocity is proportional to the Reynolds number, one will target low velocities. In addition, if a sinking bubble has a high acceleration, it will move with a high velocity and its added mass will be greater, leading to a less predictable system. Choosing a small radius of the bubble (see Figs 12 and 13 and Figs 14 and 15) reduces the bubble's velocity. Tending towards smaller amplitudes by increasing the frequency and / or the bubble's depth shows to be an efficient and optimal choice as well to make the sinking bubbles move slower. If the simulation of rising bubbles is carried out in water it is recommended to avoid too small amplitudes as explained in section 5.2.

The second parameter that helps gaining stability in the system is the viscosity of the liquid as shown in equation 16. I switched liquids from water to oil which allowed me to use equation 15. It is convenient to do so since a major issue of the equation 10 is the added mass. As previously shown, the coefficient of added mass is dependent on the shape of the bubble which is generally unpredictable. The fact that the added mass is eliminated in equation 15 offers a broader range of accuracy of the simulation.

8. Conclusion

The major part of the work was to confirm experimentally equations 9 and 10. As a result, one can predict how to reach sinking bubbles, and by what means and in what cases one can use the previous equations to describe the bubble's motion.

Even though the shaker's limits were found quickly, equation 9 seemed to be valid, once the optimal experimental parameters were found. Provided that the experimental values match the theoretical ones, it is reasonable to conclude that the physical models were valid to a certain degree.

The dynamic behaviour of the bubble

was investigated more thoroughly, since it is the one that covered the most uncertainties. This paper also provides the understanding of the limits of the given equations and why they even exist.

As the range of use of equation 10 got limited over and over, the aim became to be able to simulate accurately a wider range of motions. Choosing to investigate a system that was more stable (e. g. lower Reynolds numbers) than the one in water made this aim easier to achieve, so experiments were conducted in sunflower oil. The additional theory in the second part of section 2.2, proved to be very satisfying as it matched well the experimental results. Moreover, it uses simplified physical model (see equation 15), which offers a broad accessibility to the understanding of the non-trivial phenomenon of sinking bubbles.

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