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Influence of non-Newtonian gelatinous fluids on bubble collapse dynamics

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Abstract

The present experimental work investigates bubble collapse in gelatins of different concentrations under various driving pressures. Air bubbles are produced in gelatins of distinct mixture ratios and positioned free from boundaries. Pressure impulses with different intensities generated by a shock tube serve to trigger the bubble collapse. The bubble deformation is visualized by a focused shadowgraph system and recorded as continuous images with a high-speed camera. Image processing is conducted to analyze bubble deformation and radius changes. Results indicate that increasing the gelatin concentration tends to weaken the bubble oscillation, with the minimum radius ratio enlarged and the normalized collapse time elongated. Anisotropic bubble deformation appears and is enhanced in dense gelatins. In addition, higher driving pressures result in more rapid and intense bubble oscillations for all gelatin concentrations. By increasing the driving pressure the difference in the collapse time between different gelatins is reduced, but the trend is opposite for the minimum radius.

1 Introduction

Gelatinous fluids have been applied to study bubble dynamics in an amount of previous literature. Dear and Field (1988) and Dear et al. (1988) produced arrays of two-dimensional cavities in gelatin and induced the collapse with a shock wave to investigate the liquid jet development. A similar setup was employed by Bourne and Field (1992) and Bourne and Field (1999) to study the collapse of differently shaped cavities and the associated luminescence. Another work by Swantek and Austin (2010) examined the interaction of voids in gel with a stress wave and measured the surrounding velocity field.

The current project also adopts gelatin as the working liquid, which allows to produce stationary bubbles of defined volumes at desired locations. Investigation of multi-bubble arrangements and bubbles filled with different gases is rendered possible as well. However, as a Bingham fluid, gelatin acts like a rigid solid under low stresses and behaves as a viscous liquid at high stresses. Such a non-Newtonian property could have a significant influence on the bubble dynamics, especially considering the moderate pressure level (less than 1 MPa) in the present study. Polymer chains formed when the gelatin solidifies add further complexities by introducing anisotropy.

To the authors' best knowledge, there are only a limited number of experimental works focusing on the effect of non-Newtonian fluids on the bubble dynamics. Brown and Williams (1999) investigated collapse of bubbles attached to a free surface in water with polyacrylamide additives, and reported reduction in the liquid jet development with the addition of the polymer. Brujan and Matsumoto (2004) and Brujan (2008) used polyacrylamide and carboxymethylcellulose solutions to study bubble collapse near a solid boundary, and concluded that both the velocity of the induced liquid jet and the strength of the emitted shock wave during the first collapse were weakened. Microbubble oscillation in an unbounded polymer liquid was researched by Bazilevskii et al. (2003), where a prolongation of the collapse time was noted. Similar results were obtained by Brujan and Williams (2006) who addressed that the effect of polymer additives only appeared for small bubbles (with the radius less than 0.5 mm).

As shown, the range of non-Newtonian fluids covered in published bubble experiments is extremely narrow, and the influence of the driving pressure is not included. Therefore more experiments are desired to expand the database and to confirm the pronounced observations. Moreover, given the fact that various aspects of the liquid (e.g. viscosity, elasticity and relaxation time) exert effects on bubble dynamics, light needs to be shed upon the role played by individual fluid properties.

Driven by such motivations, the present paper studies the oscillation of single air bubbles in the free field. Experiments are conducted in gelatins of three distinct concentrations under three pressure conditions. Qualitative descriptions of the bubble deformation are presented. The collapse time and the minimum bubble radius of all cases are quantified and compared.

2 Experimental setup

The current experimental research is carried out in a shock tube, which generates an intense pressure impulse by a shock wave to induce bubble collapse. As depicted in fig. 1, the shock tube is composed of a driver section (3 m), a driven section (19.5 m) and a test section (0.4 m) attached to the end. The inner cross section has a diameter of 290 mm, and is transformed to a square with the side length 190 mm by a cookie-cutter in front of the test section. A diaphragm, which initially separates the driver section and the driven section, breaks as a critical pressure is achieved in the driver section. Then a shock wave develops immediately and propagates rapidly towards the downstream test section.

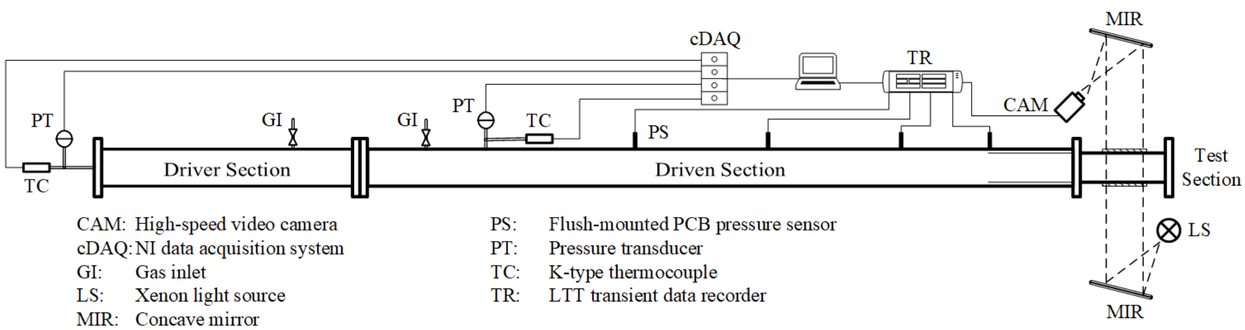

Figure 1: Experimental arrangement of the shock tube for bubble dynamics experiments

As for the measurement system, there are pressure gauges and K-type thermocouples installed to measure the initial experimental conditions, of which the signals are acquired by a NI cDAQ device. The transient pressure changes during the experiments are monitored by PCB Piezotronics ICP® fast-response pressure sensors flush-mounted along the driven section as well as the test section. The pressure data are recorded by a LTT device at a sampling rate up to 4 MHz. To visualize the bubble collapse, a Z-type schlieren system is applied. The light emitted from a 150 W Xenon lamp passes through the high-transparency glass windows at sides of the test section, and casts on the focal plane of a Shimazu Hyper Vision HPV-X ultra-high-speed camera. Several cycles of the bubble oscillation are recorded as 128 continuous images with a resolution of 250×400 pixels at a framing rate up to 5 MHz. In the present experiments, the optical system is simplified to a focused shadowgraph, with no knife edge employed to guarantee the adequacy and the uniformity of the image brightness.

Detailed arrangements in the test section are shown in fig. 2(a). Ideally, the whole test chamber is filled with gelatin, in which a millimeter-sized air bubble is produced with a syringe and positioned free from boundaries. A uniform and stationary flow field under the atmospheric pressure is established initially. Then the incident shock wave followed by high-pressure flows impacts on the air-gelatin interface. Due to the large difference in the acoustic impedance between the two media, the shock wave reflects nearly ideally, which further raises the pressure in the air. To maintain the pressure balance across the interface, a compression wave is induced and travels in the gelatin at the sound speed of around 1500 m/s. The compression wave reflects at the rigid endwall as well as at the air-gelatin interface back and forth during the experiment, causing pressure oscillations in the test section. But a careful choice of the bubble location (e.g. close to the endwall) could find a 0.5 ms time period of constant driving pressures for the bubble collapse.

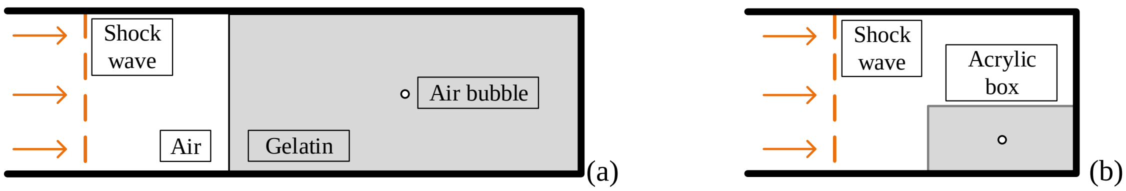

Figure 2: Sketch of the test section in the ideal setup (a), and in the workaround setup (b)

The ideal setup which allows for uniform initial conditions and constant boundary conditions, however, is still under preparation and suffers from problems of slow pressure increase (most likely due to the contraction of trapped air between construction parts) and a bent air-gelatin interface (due to the gravity). A plan to tackle these problems is in progress, but meanwhile a workaround setup as shown in fig. 2(b) is utilized for the present project. Similar ideas to the ideal setup are adopted, but an acrylic box serves as the container for the gelatin. Since the interior of the test section is not occupied by the box completely, wave motion in the air surrounding the box emerges and is captured in some shadowgraph images. Another drawback is that the acrylic plates tend to deform under high pressure, which could significantly alter the pressure field inside the box considering the low compressibility of the gelatin. But the pressure changes caused by the box deformation could be treated as systematic uncertainties, and should not influence the comparison made between cases.

To achieve high transparency, the gelatin is made from a mixture of distilled water, Gelrite™ Gellen gum and magnesium sulfate. Three mass concentrations of the mixture are studied in the current work, with the thinnest of 10000 : 4.2 : 3.5, the moderate of 10000: 6 : 5 and the densest of 10000 : 9.6 : 8. For each gelatin concentration, experiments are conducted under three different pressure conditions, with the pressure in the driver section P_4 equal to 1.5 bar, 3.7 bar and 7.5 bar at the moment of the shock wave formation.

3 Preliminary results

The analysis of the bubble collapse is based on the images recorded from the optical system. Special attentions are paid to the shape changes over the bubble oscillation, the collapse time and the minimum radius of the first contraction.

The deformation of bubbles in different gelatins under the lowest driving pressure P_4 = 1.5 bar is demonstrated in fig. 3. Each row presents images of a specific gelatin concentration, which consists of five selected moments to cover the first collapse, the following rebound and the second collapse.

Bubbles for different gelatin concentrations in fig. 3 behave quite similarly. Due to the low strength of the shock wave, bubbles undergo very slight contractions during the first collapse phase. They recover almost completely to the initial size at the end of the re-expansion and collapse for a second time with even weaker intensities. No significant change of bubble shapes is observed for all gelatin conditions.

Figure 4 shows the bubble deformation driven by a higher pressure P_4 = 3.7 bar. Compared to the previous case, bubbles go through stronger contractions at both the first and the second collapse. The rebounding process ends at a smaller radius than the initial state. Irregular bubble deformation appears after the first collapse for gelatins with 0.096% and 0.060% Gelrite, and the anisotropy of the bubble collapse is stronger for the denser gelatin.

Increasing the driving pressure to 7.5 bar results in the bubble deformation in fig. 5. For all the gelatin conditions, the radius minima at the end of collapse phases are lowered, and the recovery after the re-expansion is further weakened. It is also clearly observed that the bubble oscillation amplitude is dampened as more Gelrite is added to the gelatin. Anisotropic behavior still exists, but whether the irregularity is enhanced or lessened is difficult to judge.

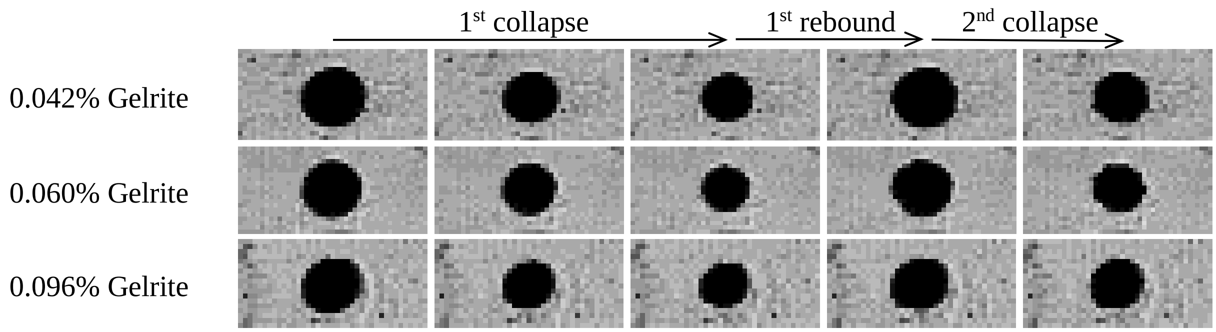

Figure 3: Oscillation of bubbles in different gelatins under P_4 = 1.5 bar
(from top to bottom, the initial bubble radius is: 1.22 mm, 1.20 mm, 1.05 mm)

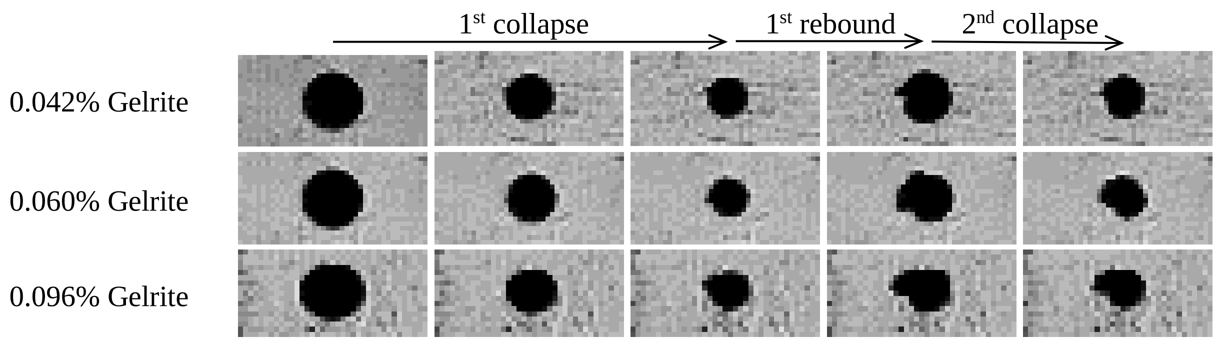

Figure 4: Oscillation of bubbles in different gelatins under P_4 = 3.7 bar
(from top to bottom, the initial bubble radius is: 1.16 mm, 1.13 mm, 1.04 mm)

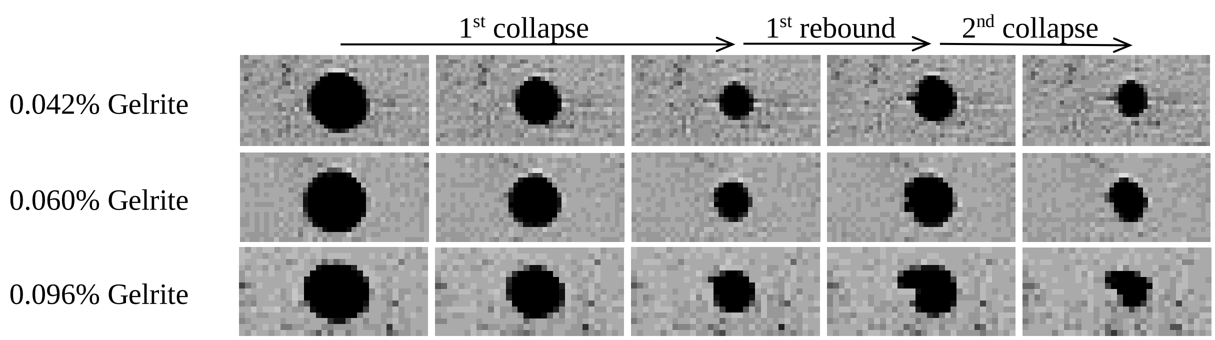

Figure 5: Oscillation of bubbles in different gelatins under P_4 = 7.5 bar
(from top to bottom, the initial bubble radius is: 1.15 mm, 1.13 mm, 0.97 mm)

In summary, the observations of higher driving pressures leading to smaller minimum radii and denser gelatins weakening the collapse strength, conform to the expectations. The explanation is that the inertia of the gelatin is increased in the former case, and the viscous effect is strengthened in the latter. For the appearance of anisotropic bubble deformation, the polymer chains in the gelatin might be held responsible.

But the fact that the anisotropy arises only under the two high-pressure cases (P_4 = 3.7 bar and 7.5 bar), is contrary to the prediction. Since the gelatin behaves more like liquids under high stresses, higher driving pressures are expected to lessen the anisotropy in the gelatin. One possible explanation for the contradiction is that the bubble deformation under P_4 = 1.5 bar is too weak to cause noticeable irregularities, and meanwhile the highest driving pressure is still incapable to fluidize the dense gelatins. More experiments with a wider range of driving pressures and a finer partition of gelatin concentrations will be carried out to make proper assessments.

The quantitative change of the bubble radius is also evaluated, with the equivalent radius R calculated from counting the number of black pixels in the images. A dimensionless radius is defined as $\gamma = R/R_0$, where R_0 is the initial bubble radius. The time T is normalized against the Rayleigh collapse time

$$T_c = 0.915 R_0 \sqrt{\rho/\Delta P} \tag{1}$$

where ρ is the liquid density and ΔP the driving pressure difference between the exterior and the interior of the bubble. In the present study, the exact value of ΔP is unknown because no pressure sensors are mounted on the acrylic box. But to eliminate the influence of the difference in the initial bubble radius, a normalized time variable $\tau = T/T_c$ is still adopted in the following analysis with ΔP chosen as 1 bar. The liquid density is approximated to be 1000 kg/m^3, identical to that of water.

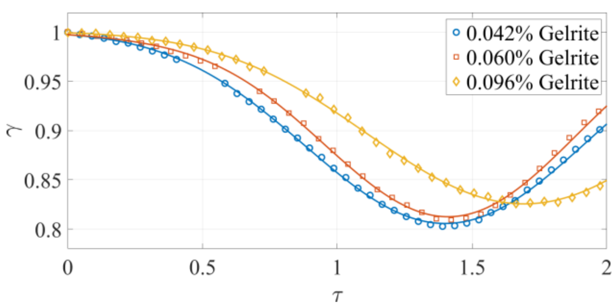

Figure 6: Bubble radius change under P_4 = 1.5 bar

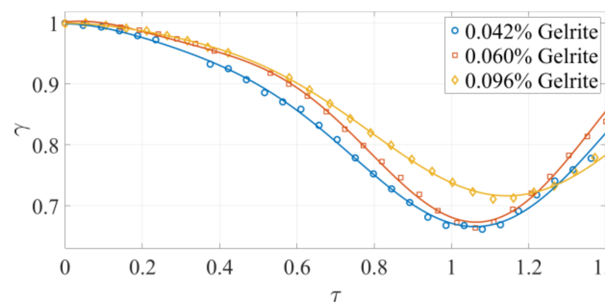

Figure 7: Bubble radius change under P_4 = 3.7 bar

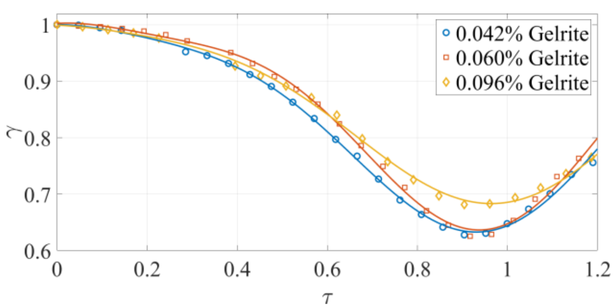

Figure 8: Bubble radius change under P_4 = 7.5 bar

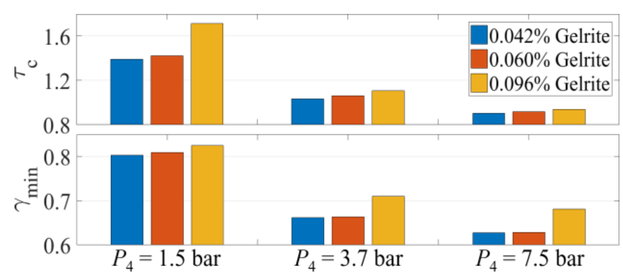

Figure 9: Comparison of the collapse time and the minimum radius between different cases

Figure 6 plots the bubble radius change in different gelatins under the lowest driving pressure P_4 = 1.5 bar. The densest gelatin results in the longest collapse time as well as the highest minimum radius. The difference between the other two gelatins with 0.042% and 0.060% Gelrite is relatively small. Such a trend is consistently observed in fig. 7 and fig. 8, which correspond to the bubble collapse under P_4 = 3.7 bar and P_4 = 7.5 bar respectively. The prolongation of the collapse time by adding Gelrite might be related to the change in liquid relaxation time, and the increase of the minimum radius is most likely caused by enhanced viscosity and elasticity. Detailed study of the gelatin properties is necessary for a thorough understanding of the influence. For all gelatin concentrations, increasing the driving pressure reduces the minimum radius, which agrees with the observations in fig. 3-5.

Figure 9 summarizes the collapse time τ_c and the minimum radius γ_{min} for all cases, and groups the data based on the driving pressure. Apart from the aforementioned findings, another point of interest is that increasing the driving pressure narrows the difference in the collapse time between different gelatin conditions, but enlarges it in the minimum radius. The discussion of this tendency is left open in the present paper, and a further analysis requires supports from more experiments.

4 Conclusion and outlook

This paper investigates the effect of non-Newtonian gelatinous fluids on the single bubble collapse in a free field. The experimental matrix covers three gelatin concentrations and three driving pressures. A workaround setup is employed, of which the repeatability and the uncertainty have not been properly addressed. But some observations are noticed and stated here for future examinations. Adding Gelrite into the liquid tends to prolong the collapse time, increase the minimum radius and introduce anisotropy in the deformation. Increasing the driving pressure consistently accelerates the collapse process and intensifies the collapse strength. Results from single experiments indicate that the collapse time for different gelatin conditions becomes closer under higher driving pressures, while the minimum radius drifts apart. More experiments are desired to testify such interesting effects. The influence of the driving pressure on the anisotropic behavior of the gelatin is still ambiguous and also requires further investigation.

For the future, new experiments will be conducted using the presented ideal setup. Compared to the easily-deformable acrylic box, the new test section is expected to improve the repeatability and reduce uncertainties of the experiments, by establishing more uniform initial conditions and more stable boundary conditions. The pressure information in the liquid would also be obtained, which is of special importance for the quantitative analysis of the bubble dynamics. Mechanical properties of the gelatin are to be examined in detail as well. More outputs are expected in the near future to reveal the underlying physics of the bubble collapse in non-Newtonian gelatinous fluids.

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