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Multiple non-spherical acoustic cavitation bubbles in high-power ultrasonic field

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Abstract: Based on the interaction among non-spherical bubbles, this study investigated the dynamic behavior and internal temperature changes of non-spherical oscillating bubbles in a high-intensity sound field from a theoretical perspective. Under the condition of the same initial parameters, when the sound field frequency approaches megahertz, the research found that in liquids with different viscosities and surface tensions, the temperature inside the bubbles is difficult to reach the high temperature required for sonoluminescence..

Keywords: Non-spherical deformation, High frequency,Temperature, Viscosity,Surface tension.

Background, Motivation and Objective

Ultrasonic waves propagating in liquid media can cause cavities and bubbles within the medium to grow and collapse under their influence. This phenomenon is known as acoustic cavitation [**Azadegan2025**]. Cavitation bubbles exhibit the characteristics of slow expansion and rapid collapse during the oscillation process. This phenomenon can trigger various physical effects, such as microflow, impact waves and shear forces. These acoustic cavitation effects have been widely applied in fields such as biomedicine and sonochemistry [**Wei2023**]. The cavitation phenomenon caused by ultrasonic waves, especially its stable state and inertial state, plays an important role in the sonochemical process. Therefore, by controlling the applied power or adjusting the driving frequency, the expected sonochemical effect can be effectively achieved [**Avramovic2025**].

To date, most analyses on the prediction of cavitation effects have mainly been based on spherical bubble dynamics. However, the shape of the bubbles may deviate from spherical, especially near the interface of different media or in the cavitation bubbles around the bubbles. This deviation in shape can lead to non-spherical oscillations, which in turn may cause the light intensity emitted by sonoluminescent bubbles to be significantly lower than that of spherical bubbles, or form high-speed jets in the liquid[**Liu2025**]. The high temperature generated inside the collapsing bubble (i.e., the "hot spot") is the trigger factor for most sonochemical reactions. Therefore, under different solution compositions and conditions, accurately measuring this temperature is particularly important. At a frequency of 20 kHz, even in the presence of alcohol, the bubble temperature did not show a significant change. The cause of this phenomenon may be related to the transient characteristics of cavitation bubbles [**Rae2005**]. Furthermore, it was observed that at higher frequencies, as the alcohol concentration increased, the average bubble temperature (i.e., the aforementioned chemical temperature) did indeed decrease [**Ashokkumar2011**]. With the increase of alcohol concentration, the measured temperature of cavitation bubbles shows a decreasing trend. In alcohol of the same concentration, the influence of long-chain alcohols is more significant. The reason for the decrease in bubble temperature under high-frequency conditions lies in that the high-temperature environment generated when cavitation bubbles collapse promotes the evaporation and decomposition of volatile solutes, thereby leading to the accumulation of hydrocarbon products [**Ashokkumar1999**]. The above-mentioned research mainly focuses on the variation of bubble temperature with frequency in alcohol solutions, while the mechanism of temperature variation with time within non-spherical oscillating bubbles in high-intensity sound fields is still under further exploration.

The main purpose of this study is to numerically investigate the non-spherical bubble dynamic behavior of three bubbles in left-right symmetrical and asymmetrical environments in a high-intensity sound field, as well as the relationship between the internal temperature of the bubbles and fluid parameters, by applying the published three-bubble model[**Wu12022**, **Wu22022**].

Results

In order to deeply study the oscillation phenomenon of multiple non-spherical bubbles in a high-intensity sound field, this section will adopt the formula (23) of the theoretical model proposed in the previous

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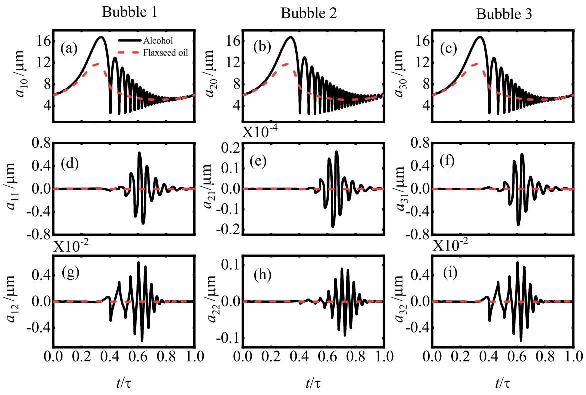

Fig. 1: The evolution of spherical and aspherical components of three identical bubbles at uniform distances in alcohol and flaxseed oil.

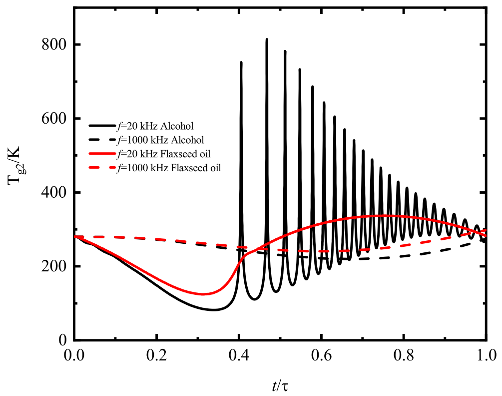

Fig. 2: The temperatures inside the bubbles in alcohol and flaxseed oil liquids at different frequencies.

literature[**Wu12022**, **Wu22022**] to numerically simulate the interaction of non-spherical oscillating bubbles in different liquids of a high-intensity sound field. Previous work on the interaction among three non-spherical bubbles has mainly focused on the interaction of bubbles in water. Based on the study of non-spherical oscillating bubbles in water, this paper further explores the oscillation phenomena of three non-spherical bubbles in alcohol and castor oil, as shown in Fig. 1. Firstly, we set the viscosities of alcohol and castor oil as h=0.0011 Pa·s and h=0.033 Pa·s respectively, with the initial radii and distances of bubbles are $a_{10}(0) = a_{20}(0) = a_{30}(0) = 6\ \mu m$, $D_{12}(0) = D_{23}(0) = 500\ \mu\mathrm{m}$. Other parameters refer to the previous literature. We also set sound waves with a pressure amplitude of 1.1 bar and a frequency of $f = 1/\tau = 20$ kHz to simulate the oscillation behavior of three bubbles. The research results show that when the middle bubble is in the left-right symmetrical mode, the oscillation of its non-spherical even symmetrical mode is more obvious, while the odd symmetrical mode approaches zero (see Fig. 1(e) and (h)), which is consistent with the research results in water. Meanwhile, the study also found that the spherical and non-spherical oscillation patterns of the three bubbles in alcohol were significantly greater than those in castor oil, as shown in Fig. 1. This further indicates that as the viscosity increases, both the volume of the bubbles and the amplitude of the non-spherical oscillation decrease.

Based on the research results in Fig. 1, this study aims to conduct an in-depth analysis of the temperature changes within three non-spherical oscillating bubbles located in a left-right symmetrical environment. The driving frequencies were set to 20 kHz and 1000 kHz respectively to predict the relationship between the internal temperatures and frequencies of the three bubbles immersed in alcohol and flaxseed oil with different viscosities, as shown in Fig. 2. At a driving frequency of 20khz, the temperature of the oscillating bubbles in the alcohol reaches a peak of approximately 800k. Conversely, when the frequency increased to the megahertz range, the temperatures observed in both alcohol and flaxseed oil were close to 280 K. This result indicates that achieving sonoluminescence temperatures in liquids of different viscosities under a megahertz sound field is challenging.

Figure 1 mainly discusses the oscillation phenomena of three non-spherical bubbles in alcohol and flaxseed oil in a 20 kHz sound field. To further investigate the oscillation influence of the megahertz sound field on these three non-spherical bubbles, we analyzed the evolution of the spherical and non-spherical components of the bubbles in alcohol and flaxseed oil over time at a frequency of 1000 kHz, as shown in Fig. 3. The initial distance is set to be consistent with the other parameters in Fig. 1. The research results show that when the three bubbles in alcohol and flaxseed oil are in a left-right asymmetric pattern, the non-spherical component of bubble 3 is the smallest (see Figs. 3(f) and (i)), which is consistent with the relevant research results conducted in water. Compared with Fig. 1, the initial distances and initial radii of bubble 1 and bubble 2 are the same. However, when the frequency approaches megahertz, both the spherical and non-spherical components of the bubbles decrease significantly. This further indicates that as the frequency increases, the oscillation behavior of non-spherical bubbles in alcohol and flaxseed oil becomes increasingly close to a spherical state.

The research results in Fig. 2 indicate that viscos-

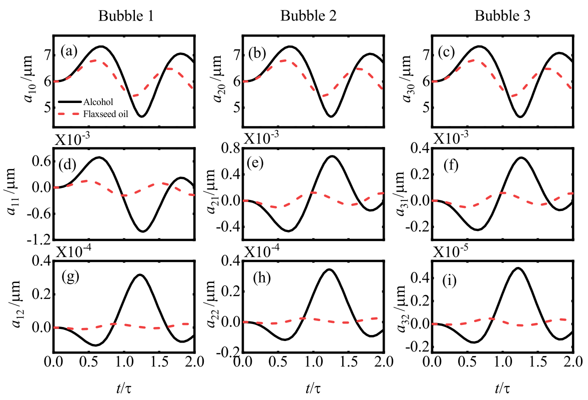

Fig. 3: The influence of megahertz sound fields in alcohol and flaxseed liquids on non-spherical oscillating bubbles.

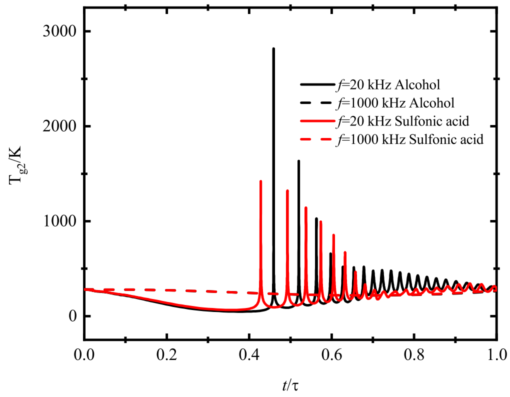

Fig. 4: The influence of surface tension on thetemperature inside the bubble in alcohol and sulfonic acid solutions.

ity has a significant influence on the temperature of non-spherical bubbles. However, fluid parameters are also closely related to surface tension. The temperatures within three non-spherical bubbles in alcohol and sulfonic acid with different surface tensions under a megahertz sound field are shown in Fig. 4. The surface tensions of alcohol and sulfonic acid are $\sigma = 0.022$ N/m and $\sigma = 0.055$ N/m respectively. To better control the variables, we adopted the same viscosity parameters in the experiment, and the other initial parameters were consistent with those in Fig. 3. The research results show that when the driving frequency is 20 kHz, the temperature of the oscillating bubbles in the alcohol reaches the maximum value, approaching 3000 K. When the frequency was raised to megahertz, the temperatures in both alcohol and sulfonic acid were close to 280 K. This result indicates that under the megahertz sound field, it is difficult to achieve the high temperature required for sonoluminescence in liquids with different surface tensions.

Conclusion

In a high-power ultrasonic field, the prediction of the internal temperature of non-spherical bubbles is helpful to achieve the expected sonochemical effect by adjusting the driving frequency. Studies show that in liquids such as alcohol and flaxseed oil, the oscillation trends of non-spherical bubbles are similar to those of spherical and non-spherical bubbles in water. Furthermore, when viscosity and surface tension change, as long as the driving frequency reaches the megahertz level, the internal temperature of the bubble is difficult to reach the high temperature required for sonoluminescence.

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