Enhancement of heat and mass transfer by cavitation

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Abstract. In this paper, a brief summary of effects of cavitation on the heat and mass transfer are given. The fundamental studies of cavitation bubbles, including its nonlinearity, rectified heat and mass diffusion, are initially introduced. Then selected topics of cavitation enhanced heat and mass transfer were discussed in details including whales stranding caused by active sonar activity, pool boiling heat transfer, oscillating heat pipe and high intensity focused ultrasound treatment.

1. Introduction
Cavitation has attracted much attention in the past decades for its unique characteristics, e.g. strong collapse force, generation of high temperature field and oscillating fluid flow around bubbles. Under irradiation of acoustic waves, the bubbles will also oscillate, termed as “acoustic cavitation” [1-6]. Comparing with the traditional hydrodynamic cavitation, acoustic cavitation can be more easily controlled by choosing appropriate acoustic parameters. Based on those principles, new mechanisms and techniques are being investigated intensively.

In this paper, we briefly reviewed of the physical oscillations of cavitation bubbles and several selected topics associated with cavitation enhanced heat and mass transfer. In Sec. 2, a wide range of physical effects relating with cavitation bubbles are introduced; in Sec. 3, recent progress on cavitation enhanced heat and mass transfer are discussed in details with four examples including whale stranding induced by active sonar, pool boiling heat transfer, oscillating heat pipe and high intensity focused ultrasound treatment.

2. Physical oscillations of cavitation bubbles
The basic equation of bubble motion can be described by various kind of models. A Rayleigh-Plesset models or its variants have been developed mainly by Plesset [7], Noltingk and Neppiras [8], Poritsky [9]. A more advanced model was developed by Gilmore [10] by incorporating the effects of sound irradiation for oscillating bubbles. Keller and Miksis [11] further considered the retarded time in the equations. Prosperetti and Lezzi [12,13] explored the connections between various models and built a more sophisticated model for bubble motion. This equation of bubble motion coupled with heat and mass transfer equation around bubbles are the main equations to be solved for bubble dynamics.

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2.1. Nonlinear response

Figure 1 shows the nonlinear response of bubbles to the acoustic excitation. In Figure 1, one can observe five types of nonlinear phenomena:

a. Main resonance (marked as “1/1” in Figure 1);

b. Harmonic resonance (marked as “2/1”, “3/1” etc in Figure 1);

c. Subharmonic resonance (marked as “1/2” in Figure 1);

d. Ultraharmonic resonance (marked as “3/2”, “5/2” etc in Figure 1);

e. Jump phenomenon caused by nonlinear feature of bubble motion equation (marked as dotted line near each resonance).

For more details about definitions of each resonance and jump phenomenon, readers are referred to the classic paper by Lauterborn [14].

![Figure 1](image1)

Figure 1. Frequency response curve of bubble with radius $R_0 = 10\mu m$ under irradiation of acoustic field with different pressure amplitudes (a) 40 kPa; (b) 50 kPa; (c) 60 kPa; (d) 70 kPa; (e) 80 kPa. This figure was adapted from Figure 9 of Lauterborn and Kurz [5].

Other nonlinear response includes bifurcation and even chaos as shown in Figure 2. For review of this topic, readers are referred to Lauterborn and Parlitz [15].

![Figure 2](image2)

Figure 2. Frequency bifurcation diagram and to chaotic oscillations. This figure was adapted from Figure 15 of Lauterborn and Kurz [5].

2.2. Rectified mass diffusion

During bubble oscillations, its surface area and gas concentration inside bubbles change. At the same time, the bubble can generate a (radical) flow field around bubbles, which will influence the mass transfer through convection terms. As a result, a rectified effect exist during bubble oscillations, leading to a small amount of gas diffused into or out of bubbles. After a long duration (e.g. thousands of cycles), this rectified effect will be prominent and changes the bubble radius effectively. This phenomenon is called “rectified (mass) diffusion”. This effect has been studied both experimentally and numerically by numerous researchers [16-22].

Figure 3 shows the variations of bubble radius versus time obtained both by experiments and analytical solution. One can find that there exists a threshold value of pressure amplitude corresponding to the balance of the gas diffused into and out of the bubbles. For higher pressure
amplitude, the bubble will grow gradually; for lower pressure amplitude, the bubble will dissolve. “SW” in Figure 3 refers to the generation of surface wave on the bubbles. A much clear experimental observation was given by Lee et al. [17] as shown in frame 7 of Figure 4.

![Figure 3](image1)

**Figure 3.** Variations of bubble radius versus time through rectified mass diffusion effects. This figure was adapted from Figure 4 of Crum [16].

![Figure 4](image2)

**Figure 4.** Variations of bubble radius versus time through rectified mass diffusion effects with the presence of surfactants. The marked numbers refer to the number of frames. Inter-frame time duration is 30s. This figure was adapted from Figure 1 of Lee et al. [17].

For analytical solution, Zhang and Li [18] developed generalized equations of rectified mass diffusion by incorporating effects of surface tension, non-uniform pressure inside bubbles and liquid compressibility. Zhang and Li [19] further extended the modelling of rectified mass diffusion into the viscoelastic materials (e.g. human tissues).

### 2.3. Rectified heat diffusion

Similar like the rectified effects of gas bubbles shown in Sec 2.2, there also exists rectified heat diffusion of vapor bubbles. The physical process of rectified heat diffusion is quite similar as introduced in Sec 2.2 but it is much more intense as the values of thermal conductivity exceeds those of mass diffusivity by two orders. For review of this topic, readers are referred to Prosperetti and Hao [23].

Figure 5 shows an example of the computation of the process of rectified heat diffusion of a vapor bubble excited by acoustic field. The mean radius shows a quick growth up to the resonance value, which is followed by a much limited growth. Gumerov [24] pointed out that the bubble growth could reach a limited value after the order of hundreds of thousands of cycles. Hao and Prosperetti [25] found that resonance effects only play an important role on the dynamics of vapor bubbles for a few cycles at most and the phase of sound amplitude could influence the behaviour of certain small bubbles (e.g. their collapse or growth).
2.4. Other effects

Due to the limited length of present paper, other important effects are not included in our discussions, e.g. wave scattering effects [26,27], damping mechanisms [29-32], bubble instability [33,34] and wave propagation in bubbly mediums [35,36]. For example, the wave speed in bubbly mediums is a strong function of both frequencies and bubble sizes as shown in Figures 6 and 7. When the bubble are excited by acoustic excitation with multiple frequencies, the problem will be much complex, leading to a lot of new phenomena [37].
3. Cavitation enhanced heat and mass transfer

In this section, several topics including whale stranding by active sonar activity, pool boiling heat transfer, oscillating heat pipe and high intensity focused ultrasound treatment are selected as demonstrating examples for cavitation enhanced heat and mass transfer.

3.1. Whales stranding by active sonar activity

Nowadays, during the marine military training, active sonar is being frequently used to increase the detection range and the accuracy. When those active sonar passing through certain marine mammals (e.g. beaked whales and dolphins), a serious damage will be caused by a rapid process of bubble activity as shown in Figure 8.

Figure 8. Gas-filled cavities in a common stranded dolphin. This figure was adapted from Figure 1 of Jepson et al. [38].

The reason for generations of those damage is possibly due to the rectified mass diffusion process introduced in Sec. 2.2. Although under normal conditions, the process of the rectified mass diffusion of bubbles is slow, it is rather rapid under the oversaturation condition. Crum et al. [39] has proved...
that in ex vitro supersaturated tissues, extensive bubble can be produced under irradiation of short pulses of low frequency sound as those used during active sonar activity (referring to Figure 9). For detailed reviews of this topic, readers are referred to Cox et al. [40].

![Figure 9](image)

**Figure 9.** Supersaturated tissue with and without ultrasound (b and a respectively). This figure was adapted from Figure 3 of Crum et al. [39].

### 3.2. Pool boiling heat transfer

With cavitation generated during pool boiling, it has been observed that the pool boiling heat transfer can significantly promoted, e.g. the improvement of critical heat flux [41-45] and increment of heat transfer coefficient [46]. Various kinds of mechanism for cavitation enhancement of pool boiling heat transfer have been proposed e.g. bubble size reduction and frequency of bubble formation increment [47, 48]. However, the cavitation enhanced pool boiling heat transfer is a quite complex phenomenon because the influential parameters are numerous (e.g. frequency and amplitude of applied acoustic field, heat flux, surface roughness). Hence, in the literature, both negative and positive influences of cavitation on boiling heat transfer have been all reported. Wong and Chon [49] showed that below a critical sound pressure the cavitation effects on heat transfer are negligible. If the pressure is above this threshold, natural convection is significantly enhanced while there is still a negligible effect on nucleate boiling. Kim et al. [50] also found that the enhancement is severely reduced at the initial stage of boiling. Furthermore, the enhancement effects are also influence by the types of pool boiling. Park and Bergles [51] found that for saturated boiling the heat flux decreases with the acoustic fields applied while for subcooled boiling, an improvement with the order of 5–10% is observed.

Figure 10 shows an example of the variations of heat transfer coefficient versus the acoustic pressure amplitude of the applied ultrasonic fields [52]. Krishnan et al. [52] divided the response into three regimes depending on the acoustic pressure amplitudes. In zone I, a slight deterioration effect of pool boiling is observed. After passing a critical pressure amplitude (e.g. about 1.05 bar in Fig.10), it enters into zone II, in which the heat transfer coefficient increases remarkably with the acoustic pressure amplitude. When the acoustic pressure amplitude is larger than 1.7 bar, the enhancement of heat transfer coefficient is limited and enters into saturation zone (zone III). The above behaviour is strongly influenced by acoustic frequency. For example, for frequency 140 kHz, only zones I and II are observed. For frequency 185 kHz, no significant change of heat transfer coefficient is observed over a wide range of values of acoustic pressure amplitude. Krishnan et al. [52] explained the phenomenon based on the hypothesis of liquid-vapor-surface interaction through the process of nucleation and its size density.

Douglas et al. [45] proposed that the contact line interaction with the acoustic field is a possible mechanism for the enhancement of boiling pool heat transfer. Figure 11 shows the capillary wave generation during the detachment of the bubbles with the presence of the acoustic waves. Hence the bubble remove from the surface could be facilitated. Another mechanism for the enhancement of bubble removal is the Bjerknes forces generated with the presence of the acoustic field through the
radiation of the adjacent bubble nearby. According to the rough estimation, comparing with the primary Bjerknes force and buoyance force, the secondary Bjerknes forces plays an important role during bubble detachment process.

![Figure 10](image10.png)

**Figure 10.** Change in heat transfer coefficient versus acoustic pressure amplitude for different heat fluxes. Ultrasonic frequency is 47 kHz. This figure was adapted from Fig.7a of Krishnan et al. [52].

![Figure 11](image11.png)

**Figure 11.** Detachment process of an individual air bubble with the presence of acoustic field. This figure was adapted from Fig.3 of Krishnan et al. [52].

3.3. Oscillating heat pipe

Oscillating heat pipe (OHP) is typically a meandering tube with capillary dimension, which turns in many times between condensation sections and evaporation sections [53-55]. When OHP operated, a self-sustaining oscillatory flow will be generated inside OHP, during the cycles of which the heat is transferred mainly as latent heat. In the past decade, the features of OHP has been intensively studied both experimentally [56-58] and numerically [59-61].

![Figure 12](image12.png)

**Figure 12.** An example of oscillating heat pipes. This figure was adapted from Fig.1 of Khandekar [54].
Recently, the effects of acoustic field on the performance of OHP have attracted much attentions [62, 63]. Generally, the input thermal power for the start-up process of the OHP forming an oscillating motion is relative high. Zhao et al. [62] found that with the presence of an acoustic field with a very small power, the start-up power of can be significantly reduced while the effective thermal conductivity of the OHP can increase (referring to Figure 13). Zhao et al. [63] further found that the presence of acoustic fields can also affect the oscillatory motion inside OHP, enhance the heat transfer performance in a low power input region and reduce the thermal resistance (referring to Figure 14).

3.4. **High intensity focused ultrasound treatment**

High intensity focused ultrasound (HIFU) treatment is rapidly developing modality for the treatment of the deep-seated solid tumors. HIFU generates a high intensity focused ultrasonic beams on the target, leading to the significant rise of the local temperature for killing the tumors. For a comprehensive review, readers are referred Coussios and Roy [64].

Figure 15 shows the temperature rise increment versus pressure amplitude of HIFU. The measurement in Figure 15 was obtained in a tissue-mimicking phantom consisting of a suspension of graphite particles in an agar gel using a fine wire thermocouple positioned near the focal region [65,66]. Initially, for pressure amplitude less than 1.1 MPa, the temperature rise linearly with the pressure amplitude of HIFU. In this region, the prediction (“orange line” in Figure 15) correlates with the experimental measurement well. Then, a large increment of temperature is shown. This is caused by the generation of harmonics in the beam as the energy could be converted from low to high frequencies due to the nonlinearity of the pressure waves. Because the absorption of HIFU energy in the tissue increases with the increase of the frequency [67,68], energy deposition could be enhanced, leading to a sharp increase of temperature. Further increase of the pressure amplitude do not increase the temperature prominently due to saturation effects. For larger pressure amplitude, near-boiling temperature can be attained within a short exposure, leading to appearance of the boiling bubbles. Those boiling bubbles could scatter the HIFU waves and attenuate the waves strongly (called “shielding effects”). Additionally, those bubbles could produce unpredictable and uncontrollable tadpole-type lesions [69,70].

4. **Conclusion**

Cavitation process many unique features. For example, heat and mass can diffused into or out of bubbles during the oscillations of bubbles, termed as “rectified diffusion”. Cavitation enhanced heat or mass transfer not only can promote traditional mechanical and chemical engineering devices (e.g. pool boiling heat transfer, oscillating heat pipe and chemical reactor) but also play an important role during biomedical treatment (e.g. high intensity focused ultrasound treatment). It also further deepens our understanding towards many interesting phenomena (e.g. whales stranding during military training). There are still many problems to be explored, leading to a promising direction for future research.

![Figure 13](image-url). An example of the effects of acoustic field on the oscillating temperature in the oscillating heat pipes. “With PZTs” refers to the presence of acoustic field; “Without PZTs” refers to the absence of acoustic field. This figure was adapted from Fig.4 of Zhao et al. [62].
Figure 14. Thermal resistance of oscillating heat pipe with and without acoustic field. This figure was adapted from Fig.3 of Zhao et al. [63].

Figure 15. Experimentally measurement (blue line) and numerical predictions (orange line) of temperature rise at the HIFU target. This figure was adapted from Fig.2 of Coussios and Roy [64].

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