Acoustics of Two-Phase Fluids and Sonoluminescence

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Abstract: Basic equations for dynamics of two-phase mixtures like gas-particle suspensions and bubbly liquids are presented. Heat and mass exchange phenomena near a drop, particle and gas or vapor bubble are discussed. These phenomena are shown to play an important role in propagation, attenuation and amplification of sound waves and shock waves in gas-liquid systems, sometimes leading to paradoxical effects.

The dynamics of a sonoluminescent bubble is discussed. There are two stages in the bubble oscillation process: the low Mach number stage, when the velocity of the bubble interface is small as compared with sound speed in the liquid, and the stage corresponding to the collapsing bubble’s compression, when the velocity of the interface may be larger than the sound speed. The analytic solution for the low Mach stage is presented. This solution provides the economical boundary condition around the bubble for an effective numerical codes.

ACOUSTICS OF TWO-PHASE FLUIDS

Wave propagation in two-phase fluids is accompanied by a great variety of inter- and intra-phase hydromechanical and thermophysical processes. Among them are the following:

- inertia of the phases, in particular, not only phase flow inertia, but local deformation inertia of compressibility or expansion for the bubbly fluid as well;
- compressibility of the dispersed and carrier phase substances;
- interface force, or momentum interaction, in particular, interface friction because of the viscosity of the phases;
- interfacial heat exchange;
- phase transitions (evaporation and condensation);
- diffusion of the vapor and non-condensable components;
- deformation of drops or bubbles and their fragmentation.

These processes are initiated by a wave and, in turn, influence wave propagation strongly. Specific and anomalous features of the waves are the following:

1. Relaxation non-equilibrium processes mentioned above need some relaxation time \( t_R \) and space (relaxation zone) to transfer one equilibrium state in front of the wave to another equilibrium state behind. That is why the thickness of the wave or its relaxation zone \( L_R \) may be large. For instance, a shock wave in a bubbly liquid with the bubble diameter about \( 10^{-3} \) m may have the relaxation zone \( L_R \sim 1 \) m thick. The time \( t_R \) and distance \( L_R \) required for the wave to become steady many times larger than \( t_R \) and \( L_R \) respectively. In this case the wave after its initiation may be non-steady for a long time and at long distances. For the experiments in usual shock tubes with the length \( L \sim 1 \) m such shock waves cannot be steady in practice.

2. For gas-drop and gas-particle flows the most principal relaxation process is the non-steady friction due to relative motion of the “gas wind” near dispersed particles. For high frequency Basset force and added mass force may influence attenuation of the wave. For bubbly liquid the most principal is the radial micromotion of the liquid near the bubbles with the inertial radial added mass around them and ”elasticity” of the gas into the bubble. The inertia and elasticity lead to oscillation shock waves.

3. Attenuation of the wave is governed by nonlinear dispersion of disturbances and by dissipation because of the viscous friction between the carrier and dispersed phases and thermal dissipation which is strongly dependent on phase transition possibility. In gas-drop or gas-particle mixtures the dissipation is governed mainly by viscous friction between the phases. For bubbly fluids the thermal dissipation determined by thermal properties of the phases is dominant. For “cold” bubbly fluids containing neutral gas without evaporation and condensation the dissipation is determined by thermal properties of the gas. In particular,
changing gas into bubbles (due to changing in thermal conductivity and temperature diffusivity of the gas) one may effectively influence attenuation of the wave. For liquid with vapor bubbles thermal dissipation is determined by thermal conductivity and thermal diffusivity of the liquid that supplies and removes the evaporation heat from the bubble. A tendency to oscillations is more explicit in the liquid with neutral gas.

4. Bubbly liquid may show not only the attenuation, but even amplification of the shock wave after its initiation. This property is conditioned by reflection of the shock wave from the bubbly layer and then from the solid wall (acoustic reflection amplification) and by the property of bubbly liquid to compress itself locally by inertia.

5. For gas-drop mixtures with relatively small drop dimension and small mass fraction with two component carrier gas (non-condensable gas and vapor) it is possible to see an anomalous non-monotonous effect of the mass drop content \( m \) on the attenuation of harmonic forced oscillation wave with the frequency \( \omega \). The attenuation of the wave in the gas-drop suspension is initiated by drops and it is determined by the decrement \( \delta \), or non-dimensional decrement \( \sigma(\omega) = \delta L \), where \( L \) is the wave length. Usually the more drop content \( m \), the more intensive is the attenuation, i.e. the larger is the decrement \( \sigma \). But interaction of phase transitions and friction on the drops may lead to the anomalous non-monotonous effect in the dependence \( \sigma(m) \) for fixed frequency \( \omega \), and fixed radius of the droplets. Namely, when increasing in the droplet content \( m \) decreases the attenuation of the wave \( \sigma \).

6. The breakdown of drops and bubbles has a strong influence on the wave propagation. It intensifies the interface force, heat and mass transfer interactions. Sometimes it may appear as "vapor explosion". This effect is demonstrated for non-steady outflow of boiling water from a high pressure vessel with rarefaction waves observed.

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1. There are two stages in the bubble's oscillation process. The first is a low Mach number stage when the velocity of the bubble's interface is small as compared with sound speed in the liquid. The second stage, bubble implosion, is a stage of very rapid bubble collapse and gas compression, followed by a rebounding expansion when the velocity of the interface may be comparable to or larger than the local liquid sound speed. The low Mach number period takes up almost all the time of the overall process. Moreover, implosion takes place only for the flask acoustic resonant, or near resonant excitation, and takes a very short time (< 10⁻⁸s).

2. Two asymptotic solutions have been derived which are valid for the low Mach number regime. The first one is an asymptotic solution for the field far from the bubble, and it corresponds to a linear hyperbolic wave equation of the second order. The second one is an asymptotic solution for the boundary layer near the bubble and corresponds to the Laplace equation for an incompressible fluid. For numerical codes these asymptotic solutions give the possibility to use an "economical" boundary condition around the bubble during the low Mach number stage that reduces the calculations for this stage by more than three order of magnitude.

3. The low Mach number stage of the forced oscillations of a bubble in a compressible liquid may be described by the Rayleigh equation, where the driving pressure is the pressure at local infinity \( p_\infty \), or the Herring-Gilmore equation, where the driving pressures is the incident pressure \( p_I \). These driving pressures, \( p_\infty \) and \( p_I \), are different from each other and from the pressure on the flask's wall \( p_R(t) \). The driving pressures, \( p_\infty \) and \( p_I \), may be calculated from the flask's wall pressure evolution \( p_R(t) \), or from the flask's wall velocity evolution \( w_R(t) \), using the ordinary difference-differential equation with lagging and leading time presented herein.

4. The analysis of an initial value problem for initiation of bubble oscillations by flask excitation reveals a very strong and curious evolution of the oscillations, and an attempt to obtain the periodic regime using the direct numerical codes based on partial differential equations is not effective because one needs to calculate many evolving oscillations. Indeed, the periodic process should be analyzed analytically.

5. In the case of small harmonic oscillations, the response function, which is equal to the ratio of the relative amplitude of the bubble radius \( a \) to the relative amplitude of the forcing flask pressure \( p_R \) depends on the flask frequency \( \omega \). The maxima of this function determine the resonances of the bubble oscillations, and they are associated with the acoustic flask resonance, when during the time of pressure wave propagation from the flask to the center and back an integer number \( k \) of oscillations takes place (i.e., \( 2R/C = 2\pi k/\omega \)).
It is interesting that outside to the bubble’s Minnaert resonance zone the smaller is the bubble, the higher is the relative response of the bubble to flask excitation. This may explain the fact that sonoluminescence has only been observed for very small bubbles ($a_0 \sim 4 \mu m$).

6. For resonant frequencies it is necessary to use nonlinear solutions. For such frequencies bubble oscillations are not harmonic, and implosions may occur even for oscillations of the flask’s wall having extremely small amplitudes. This is explained by the amplification of the convergent acoustic waves initiated by flask motion.

7. The maximum radius of the bubble for the resonant periodic regime with implosion does not depend on the initial radius of the bubble $a_0$. For small deviation of the frequency $\omega$ from the resonant one $\omega_k$ the influence of $a_0$ may be noticeable.

8. The amplitude of the pressure at the local infinity of the bubble $\Delta p_\infty$ and the incident pressure $\Delta pf$ may be much larger than the amplitude of the pressure on the flask $\Delta pf$. This is an effect of amplification of the acoustic waves from the flask due to their spherical convergence and this amplification is fully or partly compensated by the expansion and compression of the bubble. This compensation is especially strong at resonant frequencies.

9. For calculation of bubble implosion it is necessary to take into account the nonlinear compressibility of the liquid and the shock wave formation, but only in a small sphere within a radius of about ten radii of the bubble.

10. The "catastrophic" collapse of the bubble at implosion causes a superhigh pressure of the bubble gas, the expanding rebound of the bubble and extremely short duration ($< 10^{-8}s$), high pressure shocks wave emitted during the supercompression and propagating from the center of the flask to its wall. According to the linear theory with linear compressibility of the liquid this strong shock wave would attenuate only due to spherical divergence and would have very high amplitude and strongly shock the flask wall. However, due to nonlinear compressibility of the liquid, where the sound speed increases with the pressure, the attenuation of this peak shock wave is very strong, and the shock wave becomes very weak before reaching the flask wall and produces only some additional high frequency "noise".

11. More study of the picosecond processes of shock wave cumulation in the center of the bubble and the resultant high gas temperatures is needed.

REFERENCES


