Research paper

Effect of water depths on the initial bubble dynamic behaviors and acoustic radiation characteristics origin from the high-temperature particles of pyrotechnic mixtures combustion underwater

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Received: May 2, 2017 Accepted: August 17, 2017

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Abstract

The initial bubbling dynamic behavior and acoustic radiation characteristics induced by the high temperature particle, which originate from the combustion of pyrotechnic mixtures underwater, and with different water depths such as 1.0 m, 4.0 m, 7.0 m and 10 m, were studied by theoretical calculation. The results revealed that with the increase of the water depths, the bubbles volume, their change acceleration and the sound pressure level decrease. With the increase of the water depths, the time of bubble volume growth and the acceleration of volume change were extended, which result in the acting time of the sound pressure level prolonged also.

Keywords: pyrotechnic composition, combustion underwater, high−temperature particle, bubble

1. Introduction

In the past, explosives have been used to create underwater sound for ocean acoustics and seismic experiments. Although explosives are an excellent source of acoustic energy, they can be hazardous to use. Alternatives such as air guns, sparkers, and gas combustive sound sources have been developed[1]. Although effective, these devices can be cumbersome and expensive to use at sea. A safe, effective, inexpensive, and reliable low frequency underwater sound source is needed.

Pyrotechnic compositions are usually a combination of several mixed substances, such as an oxidizer, a combustible agent, adhesives etc.[2]. They can be ignited under water even without air being involved. Through continuous and steady combustion underwater, pyrotechnics produce a large amount of high temperature gases and high-temperature particles which form numerous bubbles. The French pyrotechnic company Lacroix Defense Group has developed a “pyrotechnic-acoustic transmitter”, which shows that underwater pyrotechnic combustion has application prospects in underwater acoustic interference[3]. Ouyang et al. have carried out initial research relevant to this subject ; their results show that the bubble formation and the exhausted bubble cloud are the major noise sources[4),5)]. Li et al. have studied the bubble movement characteristics during underwater pyrotechnic combustion with the high speed photography[6].

There are many studies on the bubble noise of explosives and combustion gas, especially the study of Wilson et al.[1),7),8)]. Which were not only studied the bubble dynamics characteristics and the acoustic radiation mechanism due to the combustion, but also did relevant researches on practical application. However, the bubble noise induced by the interaction between high-temperature particles and water was mentioned by literature[9], no relevant research has been reported so far.

The water depth is one of the most important controlling parameters for the onset of the bubbling dynamic behavior and acoustic radiation characteristics. In this research the bubbling behavior induced by the interaction between high-temperature particles and water with the different water depth has been studied. This was done in order to examine the influence of the water depth on the bubble characteristics resulting from the underwater combustion of pyrotechnic mixture. The results of this work should provide valuable information for application of the underwater sound source and designing the pharmaceutical formulations in the underwater combustion of pyrotechnic mixtures.

2. Calculation model

2.1 Bubble dynamic model

When the high temperature particle is injected into the water, because there is a large temperature difference between it and its surrounding water, it will have a dramatic heat transfer effect, as shown in Figure1.

According to the energy conservation equation, the energy change during the cooling process of the high temperature particle can be described by the following formula :

$$m \cdot c_d \frac{\mathrm{d}T_d}{\mathrm{d}t} = Q_d - Q_{rad} \tag{1}$$

Here, m, c_d and T_d is the mass, heat capacity and temperature of the high-temperature particle, respectively. Q_d is the total heat absorbed by the high-temperature particle, which is radiated by the water vapor and water. Q_{rad} is the total heat radiation of the high temperature particle, it can be expressed :

$$Q_{rad} = A \cdot q_d = 4\pi \cdot r_d^2 q_d \tag{2}$$

Where, the r_d is the radius of the high-temperature particles. A and q_d is the surface area and the total heat flux of the high-temperature particles, respectively.

Because the heat radiated by the high-temperature particle is much larger than that of the water vapor and water ($Q_{rad} \gg Q_d$), so Q_d can be ignored ($Q_d \approx 0$). At the same time, we assumed that the high temperature particle is spherical, its mass can be described as follow :

$$m = \frac{4}{3}\pi \cdot r_d^3 \rho_d \tag{3}$$

Here, ρ_d is the density of the high-temperature particles. Equations (2) and (3) are substituted into Equation (1), we can get[10]

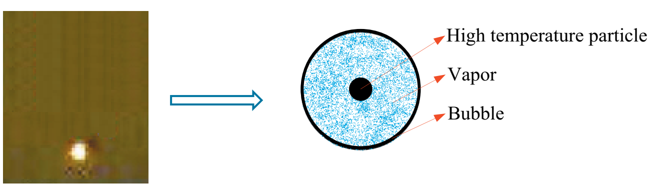

Figure 1 The sample of the bubble formation.

$$\rho_d \cdot c_d \cdot r_d \cdot \frac{\mathrm{d}T_d}{\mathrm{d}t} = -3 \cdot q_d \tag{4}$$

Here, q_d is the density of the total heat flux on its surface, which is

$$q_d = q_c + q_r \tag{5}$$

Here, q_c is the heat flux component related to the thermal conductivity of vapor, which is

$$q_c = -k_v \cdot \frac{\partial T}{\partial r} \tag{6}$$

In which k_v is the thermal conductivity coefficient of vapor, implying that the vapor is treated as a continuous medium, and the effects associated with the finite free path length of molecules are ignored. For the heat transfer in the vapor shell, when the convective transfer, the dynamic and thermal inertia of vapor are disregarded. The heat flux is constant due to the thermal conductivity of vapor, the dependence of the thermal conductivity coefficient of vapor on temperature can be assumed the linear relationship[11]

$$k_v = k_{v0} \cdot \left(1 + \phi \frac{T - T_i}{T_i}\right) \tag{7}$$

Where, T_i=373.15K, k_{v0}=0.025W/(m K), ϕ=1.83. We can assume that the evaporation from the water surface is equilibrium, Equation (7) is substituted into Equation (6), q_c can be described as follow :

$$q_c = k_{v0} \frac{T_d - T_i}{r_d} \cdot \frac{1 + \phi\,(T_d/T_i - 1)/2}{1 - r_d/r_i} \tag{8}$$

The corresponding boundary conditions are

$$T ; T_d \rightarrow T_i, \qquad r ; r_d \rightarrow r_i$$

Here, T_i is the boiling temperature at a pressure p. In order to get T_i, we can assume that the water vapor and water are regarded as pure substances, when the evaporation reaches equilibrium, the pressure inside the bubble and the saturation temperature at its interface can be expressed by the Clausius-Clapeyron equation[12]

$$\frac{\mathrm{d}p}{\mathrm{d}T_i} = \frac{\Delta_{\mathrm{vap}}H}{T_i \cdot \Delta_{\mathrm{vap}}V} = \frac{\Delta_{\mathrm{vap}}H}{T_i \cdot (V_g - V_l)} \tag{9}$$

Where, P is the pressure inside the bubble, $\Delta_{\mathrm{vap}}H$ is the latent heat of vaporization for the water, which is 2.26×10^6 J/kg, V_g and V_l is the specific volume of water vapor and water, respectively.

Due to the $V_g \gg V_l$, when the water vapor is the ideal gas, for the unit mass of gas, we can get :

$$T_i = \frac{\Delta_{\mathrm{vap}}H \cdot M \cdot T_{i0}}{\Delta_{\mathrm{vap}}H \cdot M - R_v \cdot T_{i0} \cdot \ln\frac{p}{p_0}} \tag{10}$$

Where, R_v $\cdot$ is the ideal gas constant, which is 8.314 J·mol^{-1}·K^{-1}, M is the molar mass of water.

In Equation (5), q_r is the thermal radiation flux, according to Stephen - Boltzmann law, we can get :

$$q_r = \varepsilon \cdot \sigma \cdot T_d^4 \tag{11}$$

Here, ε is the thermal emissivity of the high temperature particle ; σ is the radiation constant of the blackbody, which is 5.67×10^{-8} W·m^{-2}·K^{-4}.

Equation (11) substituted into Equation (4), we can get :

$$\frac{dT_d}{dt} = -\frac{3\cdot\left(q_c + \varepsilon\cdot\sigma\cdot T_d^4\right)}{\rho_d\cdot c_d\cdot r_d} \tag{12}$$

The total heat absorbed by the water, which is radiated by the water vapor and high-temperature particle, as follow[11]

$$q_i = (q_c + sq_r)\left(\frac{r_d}{r_i}\right)^2 \tag{13}$$

Here, s includes the fraction of the flux of thermal radiation absorbed in the thin surface layer of water. For an infinite boundary layer, is considered to be a constant in the calculation, which is 0.5[13].

The water absorbs a large amount of heat for evaporation, the evaporation rate of matter is related to the heat exchange intensity, when the heat balance is reached, $\dot{m}$ can be expressed as[11]

$$\frac{dm}{dt} = \dot{m} = -\frac{q_i - p\cdot u_i}{\Delta_{vap}H - p/\rho_w} \tag{14}$$

According to the Equation (13), Equation (14) can be further written as :

$$\frac{dm}{dt} = \frac{\left(q_c + s\cdot\varepsilon\cdot\sigma\cdot T_d^4\right)\cdot(r_d/r_i)^2 - p\cdot u_i}{\Delta_{vap}H - p/\rho_w} \tag{15}$$

The pressure in the bubble may be related to the mass flow rate of the water vapor and the thickness of the bubble. When the equilibrium is reached, we can get[11]

$$pJ = p_\infty\cdot J(0) + R_v\int_0^t \dot{m}\cdot r_i^2 dt \tag{16}$$

Here,

$$J = \int_{r_d}^{r_i}\frac{r_i^2}{T_i}dr_i$$

It is assumed in Equation (16) that, the pressure in the bubble is equal to the pressure (p_∞) away from the high-temperature particle, at the initial moment. One can readily demonstrate that, in the limit of a very small initial thickness of the vapor bubble, the magnitude of the initial vapor pressure has no effect on the solution to the problem. In case the high-temperature particle by the moment of beginning of interaction is already surrounded by a bubble of appreciable thickness, the vapor pressure must be taken to be atmospheric. Note that in calculations it is more convenient to use the respective differential equations for p and J instead of Equation (16). So we obtain the following basic equation :

$$\frac{dp}{dt} = \frac{r_i^2}{J}\cdot\left(R_v\cdot\frac{dm}{dt} - \frac{p\cdot u_i}{T_i}\right) \tag{17}$$

Where, $u_i = \frac{dr_i}{dt}$.

The bubble behavior at its generation phase is complex. A large temperature difference between high temperature particle and its surrounding water gives a heat transfer from the particle to water, which results in the generation of bubble and the increase of the bubble pressure. However, the increase of bubble volume reduces the internal pressure. There is a balance between the two, and it is difficult to model the vapor pressure. In the present study, we simply assumed that the vapor pressure remains constant during the expansion of the bubble in the initial stage. And it is always equal to the hydrostatic pressure, which is

$$\frac{dp}{dt} = \frac{r_i^2}{J}\cdot\left(R_v\cdot\frac{dm}{dt} - \frac{p\cdot u_i}{T_i}\right) = 0 \tag{18}$$

At the same time, since $r_i \neq 0$, and J will not approach infinity, so

$$R_v\cdot\frac{dm}{dt} - \frac{p\cdot u_i}{T_i} = 0 \tag{19}$$

We can get,

$$\frac{dr_i}{dt} = u_i = \frac{R\cdot T_i}{p}\frac{dm}{dt} \tag{20}$$

The aluminite powder (Al) has been widely used as the combustible agent in compositions of pyrotechnics, its combustion production is Al_2O_3 (ρ_d = 4000 kg/m^3, c_d = 1168.1 J·kg^{-1}·K^{-1}, ε = 0.8)[14], so the Al_2O_3 is regarded as the high temperature particle in this paper.

And then, the bubble volumes and the volume change acceleration are calculated by using Equations (12), (15) and (20) with the fourth-order runge-kutta method by the Matlab soft. And the initial conditions are as follows :

$T_d(0) = 1200$K, $r_i(0) = r\cdot r_d$, $u_i(0) = 0$, $p(0) = p_\infty$, $m(0) = 0$

Here, γ is the ratio of the initial bubble radius to the high temperature particle, and $\gamma > 1$.

2.2 Acoustic radiation model induced by the bubble volume deformation

According to literature[15], we get to know that the general equation of acoustic propagation underwater is as following :

$$\nabla^2 p_p - \frac{1}{c_0^2}\ddot{p}_p = -\dot{q} + \nabla\cdot f - \frac{\partial^2\tau_{ij}}{\partial x_i\partial x_j} \tag{21}$$

In this equation, p_p is the sound pressure, Pa ; c_0 is the sound velocity in liquid, m·s^{-1} ; q is the pulsation rate of the mass in unit volume in liquid, kg·m^{-3}·s^{-1} ; f is the pulsation external force effecting on the fluid in unit volume, N·m^{-3} ; τ_{ij} is the stress tensor of fluid, N·m^{-1}.

On the left of the Equation (21) is the passive sound pressure wave equation, those three items on the right side respectively represents the main types of acoustic radiation source. Among them, the first item represents the non-stationary mass flow into the fluid, its function is similar to a monopole. The second item represents the divergence of non-stationary force imposed on some

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interfaces, which is in dipole nature. The third item represents the eddy stress of the fluid itself, which has the nature of quadrupole [15].

If there is no influence of external vibration force, and no considering the effect of sheer stress, then Equation (21) can be simplified as [15]:

$$\nabla^2 p_p - \frac{1}{c_0^2}\ddot{p}_p = -\dot{q} \tag{22}$$

For the bubble in water, it acts as a kind of effective monopole sound source (simple sound source formed by the ups and downs of the volume or the quality), the noise is caused by the processes of growth, deformation, combination and crumbling etc. of the bubble, so the solution of Equation (22) is as following:

$$p_p(r,t) = \frac{\dot{Q}(t-r/c_0)}{4\pi \cdot r} = \frac{\dot{Q}(t')}{4\pi \cdot r} \tag{23}$$

In this formula, $p_p(r,t)$ is the acoustic pressure value at time t, location of r distance to the bubble center, Pa; $\dot{Q}(t-r/c_0)$ is the change rate of mass flux at r distance to the bubble center at t time, kg·m^{-2}·s^{-1}; $t' = t - r/c_0$ is the delay time, s. It is known from literature[15] the following:

$$Q = \int_s q dV = \frac{d}{\mathrm{d}t}(\rho_0 V) \tag{24}$$

Moreover, water can be regarded as incompressible fluid, simplifying Equation (23) and substituting it into Equation (24) to get the Equation (25) as below:

$$p_p(r,t) = \frac{\rho_0 \ddot{V}(t')}{4\pi \cdot r} \tag{25}$$

As r is the distance between the bubble center and the test point, which is 1 m, the influence of r/c_0 can be ignored, then $t' = t$, and the Equation (25) can be written as [15]:

$$p_p(r,t) = \frac{\rho_0 \ddot{V}(t)}{4\pi} \tag{26}$$

In this formula, ρ_0 is the density of the water, which is 1000 kg·m^{-3}; $\ddot{V}(t)$ is the bubble volume change acceleration.

The sound pressure level can be calculated[15]

$$L_p = 20 \cdot \lg \frac{|p_p(r,t)|}{p_{ref}} \tag{27}$$

Where, p_{ref} is the reference sound pressure, which is 1 mPa for the underwater sound source.

3. Result analysis and discussion

3.1 Comparison of numerical and experimental result

With the increase of the water depth, the characteristic parameters of water temperature, salinity and pressure etc. will change accordingly. Among them, the temperature and salinity change slowly, but the pressure changes obviously. Therefore, the water temperature and salinity change with water depth are ignored, the effect of the water depths on the bubble dynamic behaviors and acoustic radiation characteristics was calculated and analyzed. When the high-temperature particle is Al_2O_3 with radius r_d=1.0 mm and γ =1.01, the concluded results are showed Figure 2.

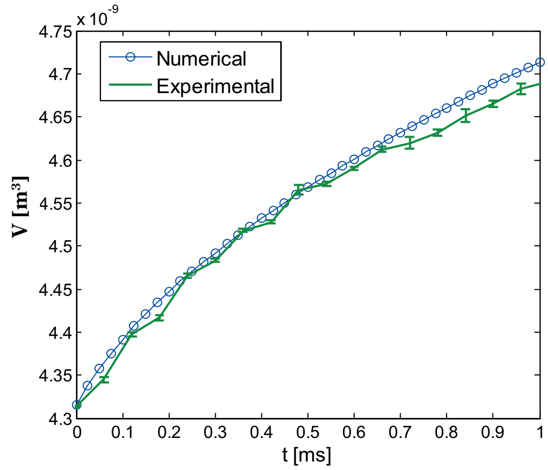

Figure 2 Comparison of experimental and numerical bubble volume versus time (H=1.0 m).

Figure 2 is the bubble volume versus time. It shows the average of the results of the five experiments (the testing process can refer to the reference[16]), on the basis of which the corresponding standard deviation chart is also obtained by Origin soft. Figure 2 is also the comparison of experimental and numerical bubble volume versus time at water depth 1 m (H=1 m). It can be seen from Figure 2 that the mean deviations of bubble volume between the present experimental studies and numerical calculations are −4.6 % for water depth at H=1 m. It is clear from Figure 2 that numerical calculation is in good agreement with experimental studies under the same condition.

3.2 The influence of water depth on the bubble dynamical characteristic

Figure 3 is the bubble volume - time history with the different water depths (1 m, 4 m, 7 m, 10 m) based on the model described above. It can be seen that with the increase of the water depth, the bubble volume decreases. It could be due to effect hydrostatic pressure, when the water depth increases, the corresponding hydrostatic

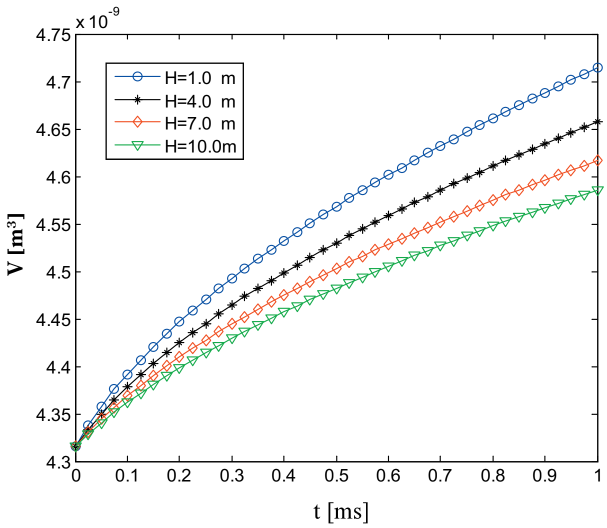

Figure 3 Bubble volume vs time of different water depths.

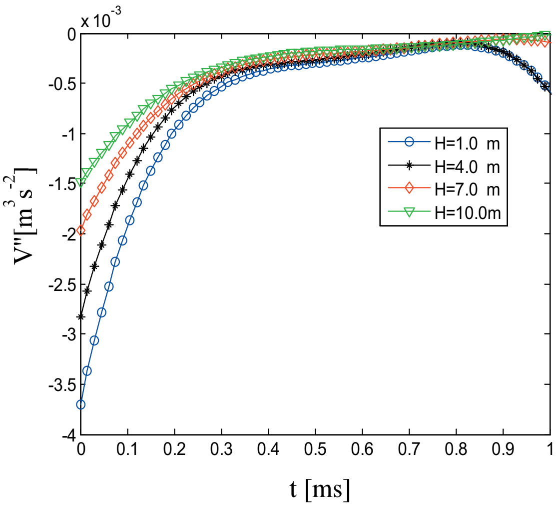

Figure 4 Bubble volume change acceleration vs time of different water depths.

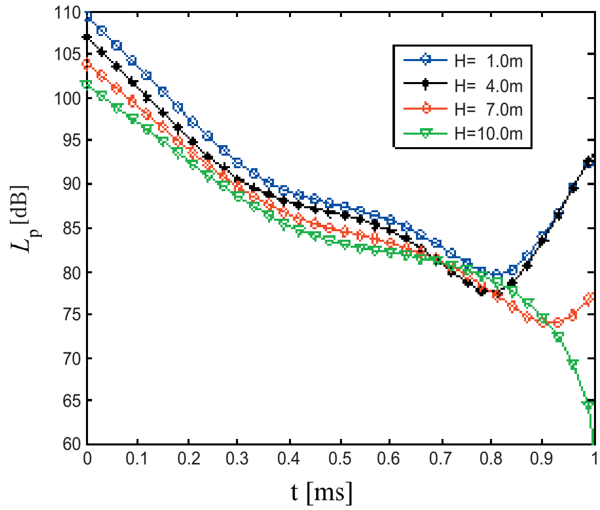

Figure 5 Bubble sound pressure level of bubble vs time of different water depths.

pressure will increase, then the growth of bubble is more and more difficult, which also can be seen from Figure 4.

Figure 4 is the bubble volume change acceleration - time history with the different water depth. They were obtained by getting second-order derivative through the bubble volume - time history. It can be seen that with the increase of the water depth, the bubble volume change acceleration decrease, that is to say the bubble growth becomes slower. This is mainly because that as the increase of water depth, the hydrostatic pressure around the high-temperature particles will gradually increase, at this moment, the bubble must be overcome by the hydrostatic pressure around it to grow, which originating from the interaction of the high-temperature particles and water. Therefore, its growth speed will be reduced. On the other hand, from the Equation (20), we can see that the change velocity of bubble radius is inversely proportional to the hydrostatic pressure around the bubble, so the calculation results appear as shown in Figure 3 and 4.

Besides, the dynamic characteristics of the explosion bubble were studied by theoretical calculation and experiment in literature[17], it was found that the bubble volume, maximum radius and the pulsation period decrease as the water depth increase, which is consistent with the result in this article.

3.3 The influence of water depth on the bubble acoustic radiation characteristics

Figure 5 is the sound pressure level - time history with the different water depth, which was calculated by the Equation (26) and (27). It can be seen from Figure 5 that with the increase of water depth, the sound pressure level decreases.

It can be known from the Equation (26) and (27) that the sound pressure level (L_p) depends on the bubble volume change acceleration ($\ddot{V}(t)$). And $\ddot{V}(t)$ mainly depends on the hydrostatic pressure and the maximum bubble volume, the latter is codetermined by the hydrostatic pressure and the energy of high-temperature particle, and by the increase of the energy of high-temperature particle and the decrease of hydrostatic pressure, which can make the bubble volume grow bigger. Under the premise of the same initial energy of high-temperature particle, the bubble volume can only depends on the hydrostatic pressure, that is to say, the $\ddot{V}(t)$ is determined by hydrostatic pressure.

The increase of hydrostatic pressure has two kinds of effects on the $\ddot{V}(t)$. Firstly, it can cause the bubble inside and outside pressure difference, which can make the bubble become bigger, and quicken the motion status of bubble volume, then $\ddot{V}(t)$ will get bigger. But, on the other hand, it will restrict the expansion of the bubble and make the expanded maximum bubble volume decrease. According to Figure 4, we can know that the latter is the primary effect, so the result appears as shown in Figure 5. This conclusion is consistent with the literature[17], which is that with the increase of water depth, the maximum bubble radius increases, and the peak sound pressure level decreases.

And besides, it can also be known from Figure 5 that with the increase of water depth, the duration of sound pressure level is constantly extended. As shown in Figure 5, for the water depth at 1.0 m and 4.0 m, the sound pressure level keeps declining initially, and begins to rise at about 0.8 ms. For the water depth at 7.0 m, it begins to rise when the sound pressure level declines to be around 0.9 ms, but when the water depth increases to be 10.0 m, lasting to 1.0 ms, its sound pressure level keeps going down without raise. This is consistent with the literature[18], which is that with the increase of water depth, the sound pressure level decreases, but the effect time period is extended.

In order to analyze this phenomenon, we can draw the curve between 0.6 ms to 1.0 ms separately from the Figure 4, as shown in Figure 6. From Figure 6 we can know that when the water depths are 1.0 m and 4.0 m, the acceleration of bubble volume change appears to decline at 0.8 ms ; while when the water depth is 7.0 m, it declines at 0.9 ms ; but when the water depth is 10.0 m, it keeps increasing. That is to say, as the increase of water depth,

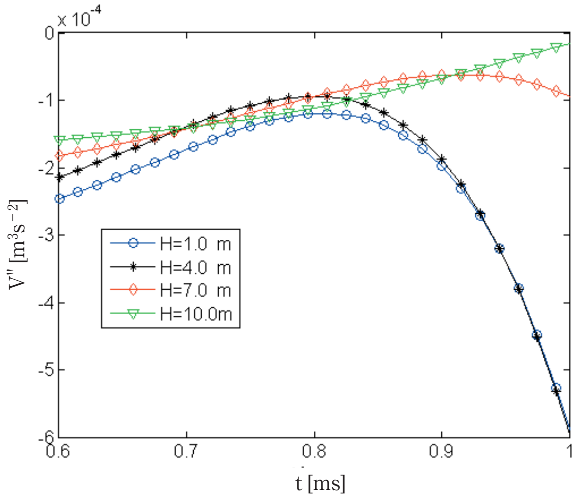

Figure 6 Time-acceleration of bubble volume change at different water depths (at 0.6~1.0 ms).

the acceleration absolute value of bubble volume change decreases, which results in the decline of the sound pressure level.

4. Conclusions

Theoretical investigation of the bubbling dynamic behavior and acoustic radiation characteristics originating from the high-temperature particles at different water depths, were performed to reveal the effects of water depth on the bubbling dynamic behavior and acoustic radiation characteristics. The following conclusions were extracted from the study.

It was concluded that water depth is one of the most important controlling parameters for the bubbling dynamic behavior and acoustic radiation characteristics.

The numerical results revealed that with the increase of the water depth, the volume of the bubbles, volume change of the acceleration and the sound pressure level all decrease. Meanwhile, as the increase of water depth, the time of bubble volume growth and the acceleration of volume change were extended, which result in the acting time of the sound pressure level were prolonged.

Acknowledgments

The authors are grateful to Hua GUAN, Chen-guang ZHU, Xin CHEN and Gong-pei PAN for their help. This work was supported by the National Natural Science Foundation of China (No.51506222) and Natural Science Foundation of Shanxi Province (No.2016JQ5085).

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