Research Article

A Numerical and Experimental Study of Wall Pressure Caused by an Underwater Explosion Bubble

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The bubble dynamics behaviors and the pressure in the wall center are investigated through experimental method and numerical study. In the experiment, the dynamics of an underwater explosion (UNDEX) bubble beneath a rigid wall are captured by high-speed camera and the wall pressure in the wall center is measured by pressure transducer. To reveal the process and mechanism of the pressure on a rigid wall during the first bubble collapse, numerical studies based on boundary element method (BIM) are applied. Numerical results with two different stand-off parameters (\( \gamma = 0.38 \) and \( \gamma = 0.90 \)) show excellent agreement with experiment measurements and observations. According to the experimental and the numerical results, we can conclude that the first peak is caused by the reentrant jet impact and the following splashing effect enlarged the duration of the first jet impact. When \( \gamma = 0.38 \), the splashing jet has a strong impact on the minimum volume bubble, a number of tiny bubbles, formed like bubble ring, are created and collapse more rapidly owing to the surrounding high pressure and emit multi shock waves. When \( \gamma = 0.90 \), the pressure field around the bubble is low enough only a weak rebounding bubble peak occurs.

1. Introduction

Experiment is an useful method to study the bubble dynamics and the mechanism of impulsive pressure generated from a collapsing bubble, including UNDEX bubble [1, 2], laser-induced bubble [3–7], and spark-generated bubble [8–13]. Owing to the small size of the laser-induced bubble (~1 mm) and the low voltage spark-generated bubble (~20 mm), the results obtained from the transducer were only qualitative [8, 14]. The small charge underwater explosion remains the best way to study the bubble dynamics and to measure the pressure by transducer while avoiding undertaking real-scale explosions. Much of the work concerning UNDEX bubble behavior was performed with solid wall boundaries. However, there are rare studies about measuring the pressure on the rigid wall caused by the UNDEX bubble jet impact. Cui [2] conducted the small charge underwater explosion to measure the collision of an annular jet with the wall boundary. It shows a reasonable way to measure the UNDEX bubble jet impact.

Another powerful tool to study bubble dynamics and bubble jet impact is numerical simulation. Boundary integral method (BIM) is widely used to simulate the bubble dynamics [3, 15–23]. Impulsive pressure on the rigid wall caused by the nearby bubble dynamics has been simulated by domain approaches based on the Euler equation or Navier–Stokes equations for axisymmetric configuration [24–26]. This pressure also can be calculated by BIM [13, 18, 27]. In Li’s work [13], by using BIM with incompressive assumption, introducing the vortex ring for the toroidal bubble and combining the auxiliary function in Wu’s work [28], the pressure on the wall can be calculated. The numerical and experimental results of present study would make the quantitative analysis of the bubble jet impact.

The present paper describes both experimental and numerical investigations of the mechanism of impulsive pressure on the rigid wall caused by the nearby UNDEX explosion bubble during the first cycle bubble collapsing. Two typical cases are selected with stand-off parameters \( \gamma = 0.38 \) and \( \gamma = 0.90 \). In this paper, UNDEX bubble is generated by the gunpowder underwater explosion. Compared to TNT, it has a weaker shock wave after detonation which protects the pressure transducer from the strong shock wave. The pressure on the wall surface is numerically studied by BIM with the
auxiliary function method [13, 28]. In this paper, we firstly make comparisons between the experimental measurements and numerical predictions for the impulsive pressure during the first cycle bubble collapsing. The agreements and differences between these two results are discussed and the causes of peaks in pressure profile are clarified.

2. Boundary Integral Method

The liquid contain the bubble is assumed to be incompressible and irrational, and the governing equation is

\[ \nabla^2 \phi = 0 \] (1)

where \( \phi \) is velocity potential.

According to the green function, the velocity potential at any point in the domain \( \Omega \) can be expressed by the velocity potential and its normal outward derivative from the boundary \( S \)

\[ \lambda \phi(p) = \int_S \left( \frac{\partial \phi(q)}{\partial n} G(p, q) - \phi(q) \frac{\partial}{\partial n} G(p, q) \right) dS \] (2)

where \( q \) is the reflected image point of \( p \) across the wall, \( \lambda \) is the solid angle at point \( p \), and \( G(p, q) = \|p - q\|^{-1} \) is Green's function.

The dynamic boundary condition on the bubble surface can be written as

\[ \frac{d\phi}{dt} = \nabla\phi^2 + \frac{p_{\infty}}{\rho} - \frac{p}{\rho} - g z \] (3)

where \( p_{\infty} \) is the ambient pressure of the liquid at the inception point of the bubble, \( p \) is the pressure on the bubble surface, \( \rho \) is the density of the liquid, and \( g \) is the gravity acceleration. The full account of calculation process can be found in Wang [30] and Blake [31]. Assuming the inner gas is adiabatic during bubble motion, the pressure inside the bubble can be described as a function of the volume

\[ p_b = p_0 \left( \frac{V_0}{V} \right)^\gamma + p_c \] (4)

where \( p_b \) and \( p_0 \) are the present and initial inner pressures of the bubble, respectively, \( p_c \) is the saturated vapor pressure of the condensable gas, which can usually be ignored for an underwater explosion bubble, \( V \) and \( V_0 \) are the present and initial volumes of the bubble, respectively, and \( \gamma \) is the specific heat ratio.

To generalize the analysis results, the problem is nondimensionalized with respect to \( p_{\infty}, R_m, \) and \( \rho_i \), where \( R_m \) is the maximum radius of the bubble. Therefore, the initial condition of the bubble motion is given by the strength parameter \( \varepsilon = p_0/p_{\infty} \) and the buoyancy parameter \( \delta^2 = \rho g R_m/p_{\infty} \). Further, the stand-off parameter is \( \gamma = d/R_m \), where \( d \) is the distance between the bubble center to the wall.

By using the Bernoulli equation, the pressure at the structure can be expressed as

\[ P = 1 - \frac{\partial \phi}{\partial t} - \frac{1}{2} |\nabla \phi|^2 - \delta^2 z \] (5)

According to Wu & Hu [28], the auxiliary function \( \Lambda \) is induced to solve \( \partial \phi/\partial t \)

\[ \Lambda = \frac{\partial \phi}{\partial t} \] (6)

In the flow domain, the auxiliary function \( \Lambda \) still satisfies the Laplace function

\[ \nabla^2 \Lambda = 0 \] (7)

The dynamic boundary condition for \( \Lambda \) on the bubble surface can be written as

\[ \Lambda = 1 - \varepsilon \left( \frac{V_0}{V} \right)^\gamma - \frac{1}{2} |\nabla \phi|^2 - \delta^2 z \] (8)

The kinematic boundary condition for \( \Lambda \) on the wall can be written as

\[ \frac{\partial \Lambda}{\partial n} = 0 \] (9)

After the velocity of on the bubble surface \( |\nabla \phi| \) and the velocity potential \( \phi \) are solved by (1)-(3), the right side of (8) will be obtained. With the known boundary condition on the bubble (8) and the wall (9), \( \Lambda \) on the wall and \( \partial \Lambda/\partial n \) on the bubble surface can be solved by (2). Therefore, the pressure on the wall can be calculated by (5). The full account of calculation process can also be found in Li's work [13, 32].

3. Experimental Set up

A schematic of experimental setup used for studying the motion of a UNDEX explosion bubble beneath a rigid wall is shown in Figure 1. Experiments × are conducted in a water tank with dimension 600 mm × 600 mm × 600 mm. An UNDEX bubble is generated beneath a circled steel plate holding by a steel base. The circular steel plate had a diameter of 250 mm. To investigate the mechanism of wall pressure, we set a pressure transducer in the steel plate center, shown in Figure 2. The pressure transducer used in this paper is the piezoelectricity type pressure transducer of SINOCERA PIEZOTRONICS INC (http://www.china-yec.com) together...
with a YE5853 Low noise Charge Amplifier. This pressure transducer (CY-YD-205) had a diameter of 10 mm and was capable of measuring pressure up to 60 MPa, with the sensitivity of 13.68 Pc/10^5 Pa. Its overload capacity is 120% and the natural vibration frequency is over 100 kHz. The bubble dynamics are captured by high-speed camera Phantom VEO-640S. The camera works at 14,000 frames per seconds.

Figure 3 shows the UNDEX bubble dynamics in the free field at different moment. The bubble maximum radius is 78 cm, with 0.2 g gunpowder underwater explosion in the water tank shown in Figure 1. Individual frames were selected to present major stages in bubble dynamics during the first 21 ms which covers the time from detonation to the end of the second cycle of bubble oscillation. According to Figure 4, we obtain the dimensionless time history of equivalent bubble radius of the UNDEX bubble. Generally, the evolution of UNDEX bubble radius has excellent agreement with R-P equation and the numerical results. The period of an explosion bubble is a little bit smaller than Rayleigh oscillation time and the numerical prediction by BIM. The R-P equation and the numerical results are adaptive to describe the first cycle of bubble oscillation. All in all, UNDEX bubble present in this paper can be a way to study the bubble dynamics.
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Rayleigh-Plesset equation
BIM
present experiment

Figure 4: Dimensionless time history of dimensionless equivalent bubble radius.

Figure 5: Quantities used to characterize a collapsing bubble reentrant jet [10, 29] before the bubble jet touchdown the wall.

4. Results and Discussion

It is found that the impulsive pressure is linked directly or indirectly to the behavior of the bubble jet [10, 14, 29]. In this paper, five main geometric quantities used to define jet characteristics were selected as in [10, 29, 33]: jet width, \( W \); jet base radius, \( R_{base} = W/2 \); jet height, \( H \); jet equivalent cylinder radius, \( R_{eq} = \sqrt{V_{jet}/(\pi H)} \), where \( V_{jet} \) is the volume of the liquid jet within the bubble; the minimum radius for the toroidal bubble, \( R_{min} \). The schematic of the jet quantities in different time period is shown in Figures 5 and 6.

To better characterize the reentrant jet, we induce the following three jet velocity selected in [10], \( V_{tip} \), is the velocity of the top tip of the liquid jet. \( V_{avg} \), is the geometric average of the vector velocities in the reentrant jet surface. \( V_{mom} \), is the momentum of reentrant jet velocity based on a computation of momentum of the reentrant jet and has the following definition:

\[
V_{mom} = \frac{1}{V_{jet}} \int_{V} |V| \, dv
\]  

4.1. Bubble Dynamics and Wall Pressure for \( \gamma = 0.90 \). In this case, the bubble maximum radius is 78 cm. The distance from the charge center to the circular plate center is 7 cm. Then the stand-off parameter is chosen as \( \gamma = 0.90 \). The strength parameter is chosen as \( \epsilon = 15 \) in this paper for the initial internal pressure condition.

Figure 7 shows the experimental bubble dynamics observations and the numerical results (cross section of the bubble, the pressure contours on the left side, and velocity contours on the right side). Serial frames (0-x) and (1-x) represent the experimental and numerical results, respectively, and x can be a to h. As shown, the UNDEX bubble expands from frame a and reaches its maximum volume at frame b, and then the bubble collapses and forms a bubble jet toward to the wall (Frame c). In frame c, we can see a high pressure region near the bottom of the bubble and the velocity of bubble jet reaches 120 m/s. Owing to the local high pressure, the liquid jet within the bubble is formed quickly. To characterize the collapsing bubble reentrant jet, we describe the time history of quantities of reentrant jet in Figures 8 and 9. We can observe that \( V_{tip} \) and \( V_{mom} \) firstly increase and then decrease in time as the bubble collapse proceeds. As the jet touchdown, the velocity of \( V_{tip} \), \( V_{avg} \) and \( V_{mom} \) are 103 m/s, 76 m/s, and 74.82 m/s. The jet dimensions of jet Height and Jet Base Radius are 41.92 mm and 12.89 mm. The numerical results in frame (1-f) and frame (1-g) illustrate the effect of the boundary on the generation of a splash. The bubble reentrant jet impacts a thin liquid layer between the bubble and wall producing a radial flow outwards from the jet axis. The splash would propagate radially along the wall. Frame f shows the moment the bubble reaches its minimum bubble volume. Frame g and h show bubble rebounding. Although the period of numerical results is longer than experimental results, they agree greatly with each other about the bubble dynamics during the first cycle of bubble oscillation.

Figure 10 shows the time history of pressure on the wall center, measured by a pressure transducer and predicted by BIM at the first bubble collapse. As we can see, there are two pressure peaks (labeled in Figure 10(a)) in time history during the bubble collapse. Figure 10(b) shows that the numerical results have similar phenomenon and peak values with the experimental measurement. To find more evidence, we find the corresponding time ticks in the experiment observation and numerical prediction in Figure 7. When we come to the first pressure peak, we can refer to frame e in Figure 7. It can be clearly found out the first pressure peak is caused by reentrant jet impact and its numerical prediction for the peak value is 6.213 MPa. One can estimate the impulsive pressure generated by reentrant jet impact using

\[
P_{impulse} \sim 0.6 \rho v_{tip}^2
\]

Owing to splashing effect (frame e ~ frame f), the duration of the first pressure peak is extended. \( \Delta t \), the difference between the impact time of the liquid jet on the rigid wall and the
Figure 7: Comparison between high-speed photographic record of bubble motion and numerical simulation results.

Figure 8: Jet speed as a function of time.

Figure 9: Reentrant jet dimensions as a function of time.
time at minimum bubble volume, lasts 0.85 ms in this case. By checking the variation of the bubble volume, we find that there is local minimum pressure when the bubble reaches its minimum volume. As the bubble volume increases with increasing time, the pressure in the wall center rises. We can conclude the second peak corresponds to the generation of a shock wave coming from the rebound of a toroidal bubble, while it only lasts 0.21 ms (about one-fourth of the $\Delta t_j$).

The variation of pressure on the wall with time and with the radial direction is illustrated in Figure 11. This figure provides a picture of the dynamic evolution of the pressure loading in space and time for the case of $\gamma = 0.90$. The radial pressure distribution at different instants shows that as the bubble collapses the pressure on the axis gradually increases until it reaches the first peak (caused by the reentrant jet impact) and then it gradually decays (extended by splashing effect) until it reaches the second peak (caused by bubble rebounded). The reentrant jet in the radial direction can be describe as $P(r) \sim P_{\text{impulse}} \cdot e^{-\left(\frac{1}{2}\frac{r}{R_{eq}}\right)^2}$; see Figure 11(a). Now we turn to Figure 11(b). As mentioned before, the bubble jet splashing effect may cause the location of the peak pressure to move outward radially as a ring wave. The red dotted line
show the values of $R_{eq}$, when $r < R_{eq}$ and they share the same time history of pressure in this local region. The white line shows that when the ring bubble (frame 1-g) occurs the second peak is achieved.

4.2. Bubble Dynamics and Wall Pressure for $\gamma = 0.38$. In this case, the bubble maximum radius is 78 cm. The distance from the charge center to the circle plate center is 3 cm. According to the experiment case, the stand-off parameter is chosen as $\gamma = 0.38$. The other parameters are the same as those in Section 4.1.

Similar as Figure 7, the typical phenomenon at typical time is shown in both experimental observations and numerical results for stand-off $\gamma = 0.38$. They, respectively, are the expansion of the bubble (frame a), the maximum volume of the bubble (frame b), the formation of the bubble jet (frame c), the moment of the bubble jet impact on the wall (frame d), the moment of the first pressure peak achieve (frame e), the minimum volume of bubble (frame f), the moment of the second pressure peak achieve (frame g), and the second expansion of the bubble (frame h). The behavior of a bubble jet is shown in Figures 13 and 14. Compared with case of $\gamma = 0.9$, the jet tip speed increases to 121 m/s, while the jet Height and Jet Base Radius decrease to 22.2 mm and 11.17 mm. Unlike the case of $\gamma = 0.9$, in this case, the jet speed is larger and its bubble volume during the bubble collapsing is smaller. Owing to the interaction of a contracting bubble surface with the radial flow following reentrant jet impact (jet splash), a number of tiny bubbles are created and they seem to form in the torus-like bubble interior; see frame (0-f) and frame (0-g). When the tiny bubbles in the bubble ring collapse, the shock wave can be produced; see frame (0-g). The numerical results about the toroidal bubble are solved by induced vortex ring, which may have difference with the model of the ring collection of tiny bubbles. In a way, numerical results can predict the macroscopic view of bubble dynamics.

Figure 15 shows the comparisons of experimental and numerical results about the time history of pressure. The time ticks in Figure 15(a) correspond to the time image of frame e and frame f in Figure 12. The first peak in numerical results is larger than the experimental measurements, while the second peak is smaller. However, they show the similar trend in time history during the bubble collapse. The reason can be expressed as follows: when the stand-off parameter is small, the incompressible model can cause the difference in the pressure peak value; to some degree, it still can reveal some details about the mechanism of the wall pressure. More detail can be found in Figure 15(b). The first pressure peak caused by the reentrant jet impact is evident by Figure 12 (frame e). The fluctuation of pressure occurs in numerical results following the reentrant jet impact induced by the splashing effect. In the experimental measurements, multipressure peaks occur after the splash jet impact. As mentioned above, the shock waves
emit from the tiny bubbles collapse and their maximum peak reaches 19.59 MPa while its duration is 0.09 ms.

Figure 16 shows the variation of the pressure at the wall with time and with the radial direction. The radial pressure of the reentrant impact still can be expressed as \( P(r) \sim P_{\text{impulse}} \cdot e^{-(1/2)(r/R_{eq})^2} \). After impact, the splashing jet spreads radially outward along the rigid wall from the axis leading to the outward propagation of pressure. It shows that as bubble collapse proceeds there is a high pressure region that appears near the expanding bubble ring. \( R_{\text{min}} \) almost follows the propagation of the splashing jet, because the accelerated splash produces an expanding bubble with high pressure on the wall. In the local region \((r < R_{eq})\), it still holds the same time history of pressure.

### 5. Conclusion

In this study, the process and mechanism of the pressure on a rigid wall during the UNDEX bubble collapse have been studied both experimentally and numerically.

As to the case of \( \gamma = 0.90 \), the pressure profile on the axis shows that the reentrant jet impact causes the first peak and then is followed by the splash jet impact which makes the duration of the pressure longer. And the second peak occurs owing to the rebounding of the toroidal bubble.

As to the case of \( \gamma = 0.38 \), the reentrant jet and following splashing effect lead to a high pressure region near the bubble ring. After the reentrant jet and following splashing effect, the larger bubble jet and smaller collapsing bubble volume make it easier to become a number of tiny bubbles formed like bubble ring. As the tiny bubble collapses, it causes multishock wave peaks in time.

Finally, very good comparisons between the UNDEX tests and the BIM simulations at two cases confirm again that numerical simulations can be a very useful tool to investigate bubble and wall prediction. From the numerical simulation
of bubble dynamics beneath a wall and the pressure on the wall center, confirmed with experimental observations and measurements, we deduced the pressure at the wall with time and with the radial direction as the function of jet characteristics. The impulsive pressure is generated by reentrant jet impact using \( P_{\text{impulse}} \sim 0.6 \rho V_{\text{tip}}^2 \). The radial pressure of the reentrant impact can be expressed as \( P(r) \sim P_{\text{impulse}} \cdot e^{-(1/2)(r/R_{\text{eq}})^2} \).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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