Research paper

Underwater shock wave induced bubble explosions in water and silicone oil

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Received : November 17, 2011 Accepted : February 14, 2012

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Abstract

Underwater shock wave passing through water and silicone oils is investigated in experimentally and numerically. The present work was conducted to study overpressure history, oscillation cycle and visualization of the collapsing gas bubble in visco-elastic fluids. The gas bubble size and repeated cycle strongly depend on the fluid kinetic viscosity, charge depth and sonic speed in medium. ΔP_{max} in silicone oils decrease to about 41 ~ 47% of water value. Numerical results simulate well the experimental ones in bubble motion and jet in a downward flow.

Keywords : underwater shock wave, shock propagation in visco-elastic fluids, suppression of shock waves, environmental problem

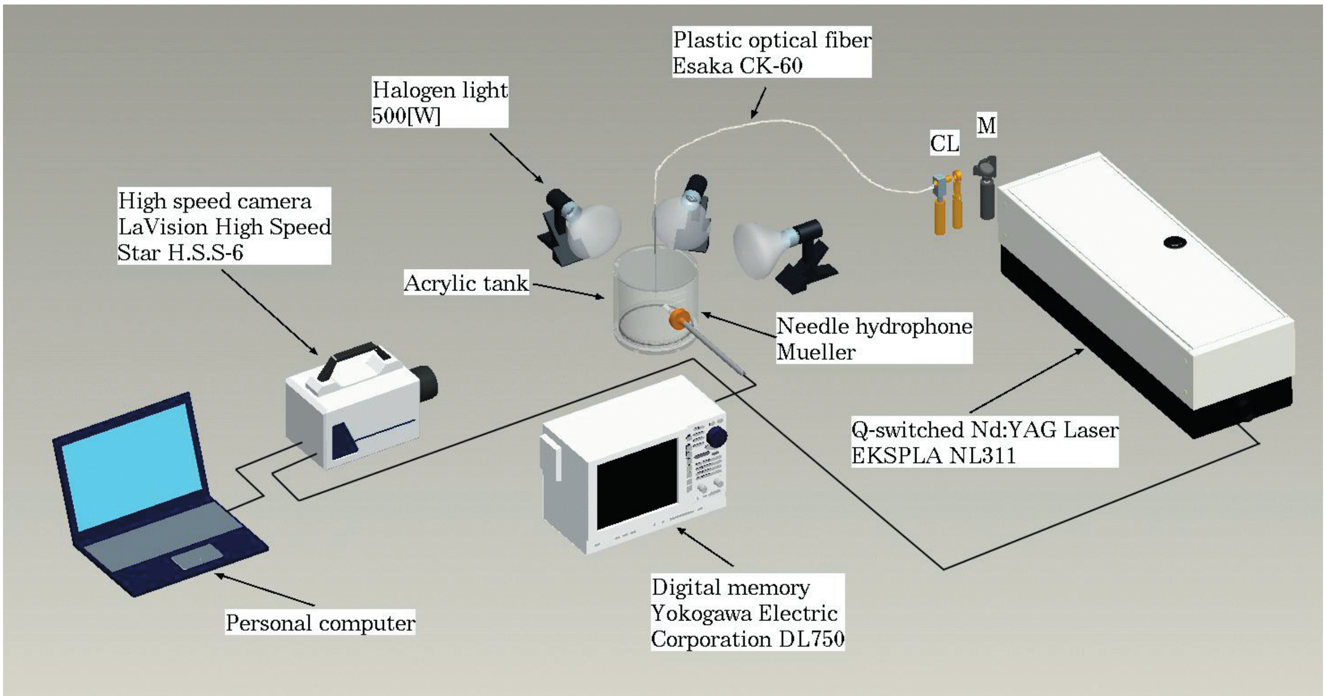
1. Introduction

Underwater shock wave through visco-elastic fluids is one of the research topics related to shock in between human body and complex medias, interaction between shock pressure and structure (oil plat form, offshore platform, ship, submarine and watercraft hull) for safety assessment and prevention from explosion hazards[1)−8)]. The shock wave gives the first damage on a solid structure due to high pressure impingement. The explosive product is generated high pressure gas bubble in the liquid. The gas bubble motion and bubble jet carried out the second damage by inertia effect in its expansion and collapse, and around the fluid flow. Dynamics of underwater explosion bubble in visco-elastic fluid have tended to predict the destructive process and prevention technology in explosion environment from the bubble motion, explosion cavity and bubble jet. The present research aims to investigate the physical phenomena and pressure attenuation effect of underwater shock wave and underwater explosion bubble in visco-elastic fluids.

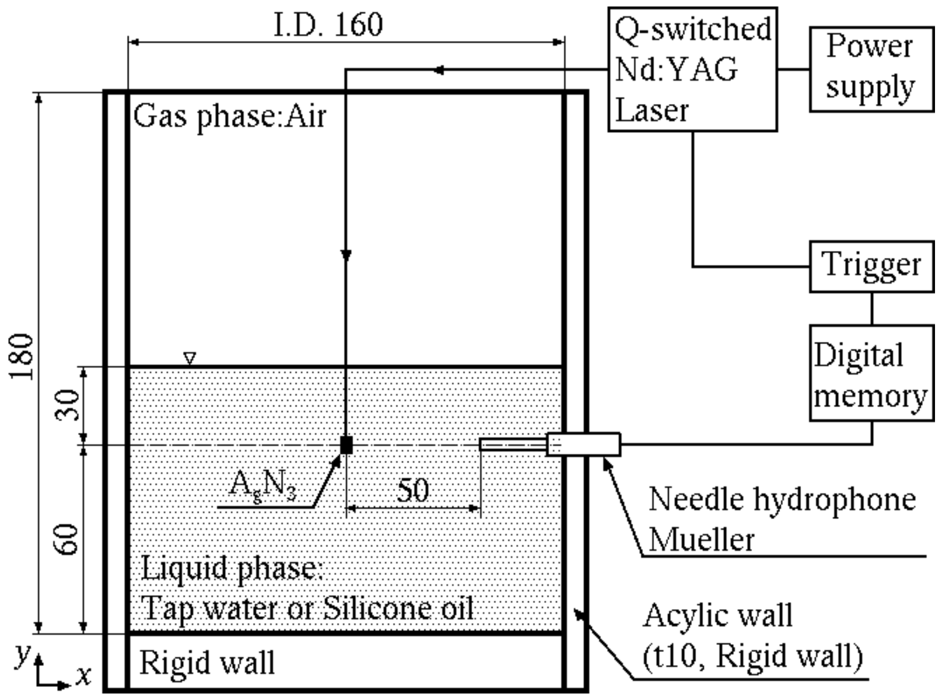
2. Experiments

Underwater shock wave experiments were carried out a detonating micro-explosive in silver azide (A_gN_3) pellet, as shown schematically in Figures 1a and 1b[8)]. The cylindrical acrylic tank has 160 mm i.d. with 180 mm in depth. The silver azide pellet is manufactured by Showa Kinzoku Kogyo Co. Ltd and delivered as cylindrical charge each with its mass of approximately 10 ± 1 mg, since the cylinder with 1.5 mm dia. has aspect ratio (length over diameter) of unity.

The charge is glued to 1.47 mm core dia. plastic optical fiber (Eska CK-60, Mitsubishi Rayon Co. Ltd) and ignited by the Q-switched Nd : YAG laser (532 nm, EKSPLA NL 311) fed to POF. Irradiation condition was operated as 50 mJ/pulse and 5 ns pulse duration. The silver azide pellet was verticality placed at 30 mm in depth from the free surface which the scaled distance is 1.45 m/kg$^{1/3}$, and



a Optical setup



b Pressure measurement

Figure 1 Schematic description of underwater shock wave experimet.

Table 1 Physical properties of tap water and silicone oil.

Material		Kinetic viscosity ν[m²/s]	Kinetic viscosity ratio ν^* [−]	Density ρ[kg/m³]	Sonic speed c_0[m/s]	Surface extension σ[mN/m]
Tap water		1.0038×10^{-6}	1	998.2	1483.0	78.0
Silicone oil	No.1	10^{-5}	$\fallingdotseq 10^1$	935.0	966.5	20.1
	No.2	10^{-4}	$\fallingdotseq 10^2$	965.0	985.2	20.9
	No.3	10^{-3}	$\fallingdotseq 10^3$	970.0	987.3	21.2
	No.4	10^{-2}	$\fallingdotseq 10^4$	975.0	$\fallingdotseq 10^3$	21.3

corresponding to assume intermediate depth explosion ($0.40 < Z < 5.55$)[9]. The overpressure was measured hydraulic shock pressure by piezoelectric polyvinylidenfluorid (PVDF) needle hydrophone (Mueller) at 50 mm from center of charge, as indicated in Figure 1b. The behavior of the collapsing gas bubble was visualized by the back light method with a digital high speed camera (High Speed Star 6, LaVision); the frame rate was operated 30,000 fps with exposure time of 1/119,000 s. Physical properties of tap water and high visco-elastic fluids are given in Table 1. The silicone oils are produced by Shin-Etsu Chemical Co., Ltd. Four kinds of silicone oil have different kinetic viscosity, sonic speed and surface extension.

3. Numerical analysis

A multiple material Eulerian solver is used in hydrocode ANSYS® AUTODYN® to describe material flow which is treated as including multiple material components. Numerical model is used for a two-dimensional asymmetric coordinate system. The boundary condition on the acrylic walls was applied to rigid wall condition. The air region has a 30 mm height from the liquid surface and a flow-out boundary condition was located on the upper side of the air region. Mesh size and the number of cells were set uniformly 0.5 mm and 48000 (x : 300 × y : 160) cells, respectively. Hydrostatic pressure gradient depending on water depth was given to all over region of both liquids. Additional effects of both the atmospheric pressure and gravitational acceleration during jet flow were applied. The EOS of the air was assumed to be ideal gas with a reference density of 1.225 kg/m^3 and specific heat ratio of 1.4. The Hugoniot-based Mie-Grüneisen EOS is defined as $p = p_H + \rho\Gamma(e - e_H)$ for tap water. In the compressed states, the pressure p_H and the specific internal energy e_H on the Hugoniot conditions are obtained from the shock jump conditions and the linear relationship[10]. Linear EOS is applied to silicone oil ($p = K(\rho/\rho_0 - 1)$), because it is very difficult to obtain the Hugoniot data of it, and pressure – specific volume relationship of the Linear EOS is almost identical to those of Hugoniot curve in the pressure region of the experiment. The spall strength is assumed to be identical to the both liquids (=−3MPa). For tap water, the reference density, Grüneisen parameter Γ, c_0 and s denote 1000 kg/m^3, 0.28, 1483 m/s and 1.75, respectively. For silicone oil ($\nu^* = 10^2$), the reference density and bulk modulus K denote 965 kg/m^3 and 0.9363GPa, respectively. The viscosity of the silicone oil was excluded into consideration. The detonation property of the explosive was calculated by using KHT2009[11]. In this study, JWL EOS and programmed 'on-time burning' model were applied for silver azide, and JWL parameters is shown in Table 2.

4. Results and Discussion

Figures 2a and 2b show a comparison of the gas bubble motion in silicone oil ($\nu^* = 10^2$) of experimental (a) results with, numerical (b) simulation for every 0.4 ms up to 6.4 ms. The gas bubble is growth in expanding phase from 0 to about 2.1 ms (Frame 1~5), while the bubble inside pressure drop brings the outward flow to a stop and the boundary of the bubble begins to contract (Frame 7~12). The gravity effects can be neglected when the ratio of the period of the oscillation cycle of the bubble and a square root of ratio of charge depth and maximum bubble diameter is smaller than 1[9]. The ratio in the present experiments are 0.07~0.08, which the gravity effects are approximately negligible. When the explosive is detonated, the explosive produce generated shock wave and a hot gas region in liquid. An incident shock wave is traveling outwardly and its wave attached to the free surface is reflected on the free surface as a reflected wave. The formation of ejection flow on the free surface is started at Frame 3. The upper side of gas bubble is elongated towards the free surface (Frame 4). After reaching the maximum gas bubble size (Frame 6~), the gas bubble inside pressure decrease with the outward flow to a stop and the gas bubble begins to contract. The jet in a downward flow penetrates into the gas bubble, and continues to be seen moving away from the free surface (Frame 7~11). When a bubble diameter becomes the minimum size, bubble pulse is generated with inside gas pressure rises (Frame 11). The gas bubble has little buoyancy and migrates to downward (Frame 12~). In Figure 2b, the numerical computation simulates the experimental results well. The bubble is in contracting its diameter and there found a fall on the free surface. The jet is generated by the bubble motion with the bubbles deformed a concave shape. Figure 3 shows the bubble diameter variation for tap water and silicone oils. The gas bubble in tap water is growth in expanding phase until 2.2 ms, while it is in compressing phase from 2.2 to 4.3 ms. The gas pressure is rise by the contraction of minimum size in bubble and shock wave forcing. The repeated cycles decrease as the fluid kinetic viscosity increase. It is seen from Figure 3 that, as a whole, computed results simulate the experimental bubble motion well. At the repeated cycles, a difference of 10% is observed between the measured and the computed results.

Numerical model of the silver azide was applied for an ideal state explosion, however the experimental condition is in non-ideal state explosion. Figure 4 shows measured overpressure (ΔP) variations under the five kinds of kinetic viscosity coefficients at 50 mm from explosive center. Overpressure histories demonstrated a first peak pressure by impingement of incident underwater shock, after the overpressures decrease quasi-exponentially until the static pressure. Overpressure reaches negative phase

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Table 2 JWL parameters for silver azide.

ρ_0[kg/m^3]	A[GPa]	B[GPa]	R_1[−]	R_2[−]	ω[−]	D[m/s]	e_0[GJ/m^3]	P[GPa]
3770	3520	20.6	6.78	1.58	0.193	5480	8.63	22.1

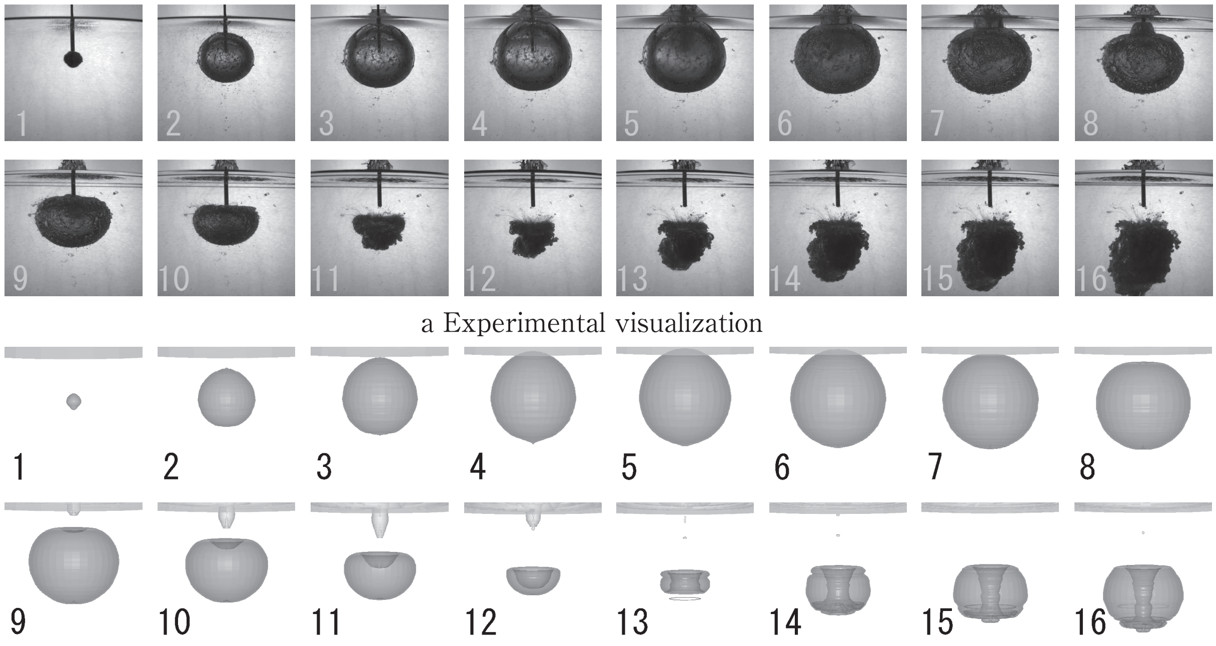

Figure 2 Gas bubble motion in Silicone oil ($\nu^* = 10^2$, $\Delta t = 0.4$ms).

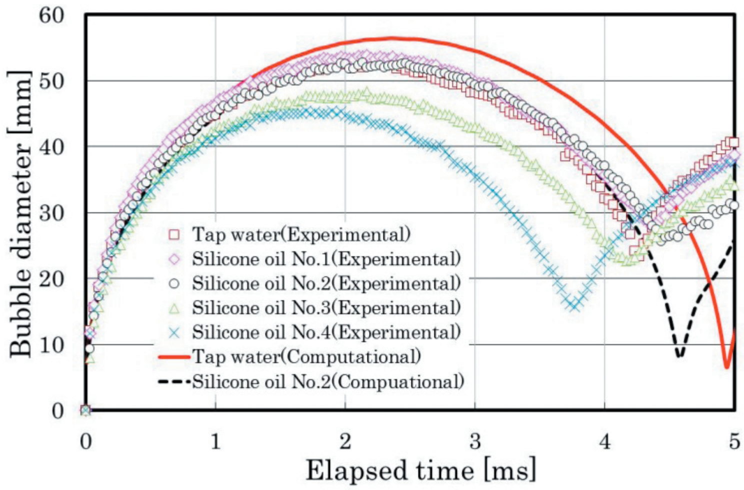

Figure 3 Time variations of gas bubble diameter.

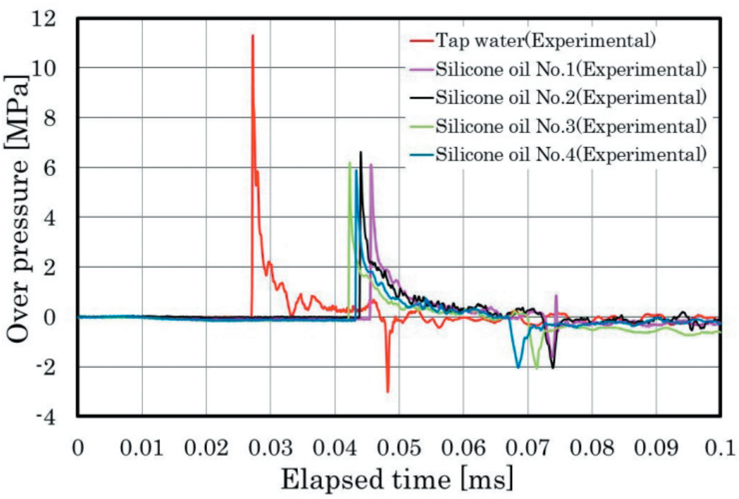

Figure 4 Overpressure histories for tap water and silicone oils.

by the generation of expansion wave due to reflection of shock wave on the free surface. The fluid viscosity increase as ΔP_{max} decrease and ΔP_{max} in silicone oils have about 41~47% of water.

5. Conclusions

Physical phenomena and pressure attenuation effect of underwater shock wave and bubble explosion in visco-elastic fluid were investigated experimentally and numerically. Peak overpressure in silicone oils decrease quasi-exponentially until the pressure reaches static pressure, furthermore pressure reaches negative phase by expansion wave. The repeated cycles fasts as the fluid kinetic viscosity increases. The gas bubble behaves the repeated cycles by the shock pulse, bubble pulse and the jet flow to downward from the free surface. ΔP_{max} decrease as the fluid kinetic viscosity increase. ΔP_{max} in silicone oils have about 41~47% of water value. Numerical simulation was performed the bubble explosion for visco-elastic fluid. Results of numerical computation simulated the experimental findings well.

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水及びシリコーンオイル中での水中衝撃波の伝播機構

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水及びシリコーンオイル中で微少爆薬（アジ化銀）を起爆し，水中衝撃波の圧力計測，ガス球の変形挙動の可視化実験と衝撃解析ソフトウェアANSYS® AUTODYN®を用いた数値解析から水中衝撃波の伝播挙動と圧力減衰効果の差異を調べた。シリコーンオイル中の衝撃波伝播は，水の場合と同様に第一波の過剰圧力，その後，準指数関数的な圧力の減少，膨張波による負圧領域の形成など，水中衝撃波と酷似した現象が確認された。流体の動粘性係数が増加すると過剰圧力の最大値も減少する。シリコーンオイルの最大過剰圧は水と比べ，41から47%へ減衰することがわかった。

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