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Experimental and computational studies of shock wave-to-bubbly water momentum transfer

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ABSTRACT

Momentum transfer from shock waves (SWs) of various intensity (from 0.05 MPa to 0.5 MPa in amplitude) to water containing air bubbles 2.5 to 4 mm of mean diameter is studied both experimentally and by means of numerical simulation. Experiments are performed in a vertical shock tube of a 50 × 100 mm^2 rectangular cross section consisting of a 495-mm long high-pressure section (HPS), 495-mm long low-pressure section (LPS), and 990 mm long test section (TS) equipped with an air bubbler and filled with water. Experiments have shown that as the initial gas volume fraction in water increases from 0 to 0.3 the momentum imparted in bubbly water by SWs increases monotonically, gradually levelling off at an air volume fraction of about 0.30. The experimental data are confirmed by two-dimensional (2D) simulation of SW propagation in bubbly water in terms of the SW velocity versus the air content, pressure profiles, as well as liquid and gas velocity behind the shock front.

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1. Introduction

The thermodynamic cycle with burning in controlled detonation regime (Zel'dovich cycle) is known (Zel'dovich, 1940; Frolov, 2006) to provide a higher thermodynamic efficiency (performance) of fuel chemical energy transformation into the expansion work as compared to deflagration burning at constant volume. Although the use of the Zel'dovich cycle in liquid rocket engines and air breathing jet engines was considered in numerous publications (see review by Roy et al. (2004) and references therein) the feasibility of utilization of this cycle in hydrojet engines was previously discussed solely in our works (Frolov et al., 2013; Avdeev et al., 2015a, b, c). According to Frolov et al. (2013); Avdeev et al. (2015a, b, c), pulsed detonation hydrojet engine consists of a water passage and a generator of detonation waves fed with any suitable fuel mixture. The efficient momentum transfer to the fluid from a shock (or detonation) wave entering the water passage from the generator is the most important problem to be solved when realizing the Zel'dovich cycle in hydrojet engines.

Parameters of shock waves SWs transmitted from a gas to bubbly water were usually studied in vertical shock tubes (see e.g., Mori et al., 1975; Sytchev, 2010; Nakoryakov et al., 1975; Kalra and Zvirin, 1981; Borisov et al., 1983, Gelfand et al., 1973) comprising HPS and LPS separated with a diaphragm, and a TS with water containing air bubbles. After the diaphragm at the top of LPS, filled as a rule with air at atmospheric pressure and room temperature, bursts a SW with known parameters is formed which spreads through LPS and then enters the bubbly water. The velocity and other characteristics of the SWs in bubbly liquid were monitored with pressure gauges mounted in the TS and with high-speed video camera through transparent windows in TS.

HPS and LPS in (Mori et al., 1975) were filled with air at room temperature at 4 and 1 bar, respectively. The 1850 mm high water column was saturated with air bubbles 2 mm in mean diameter; their initial gas volume fraction α_{10} in bubbly liquid varied from 0.01 to 0.2. The SW velocity (D) in bubbly water was determined as a ratio of distance between two pressure gauges to the difference between shock arrival times at them. As follows from the experimental data of Mori et al. (1975), the SW velocity in bubbly water at α_{10} from 0.01 to 0.04 varies from 300 to 100 m/s, which is much less than the velocity of sound in water (1500 m/s) and air (340 m/s), while at α_{10} from 0.08 to 0.2 the SW velocity is virtually independent of the gas content and varies from 70 to 50 m/s. Mori et al. (1975) also measured the velocities of reflected SWs, which exceeded the incident wave velocities because of the lower gas volume fraction in the shocked fluid.

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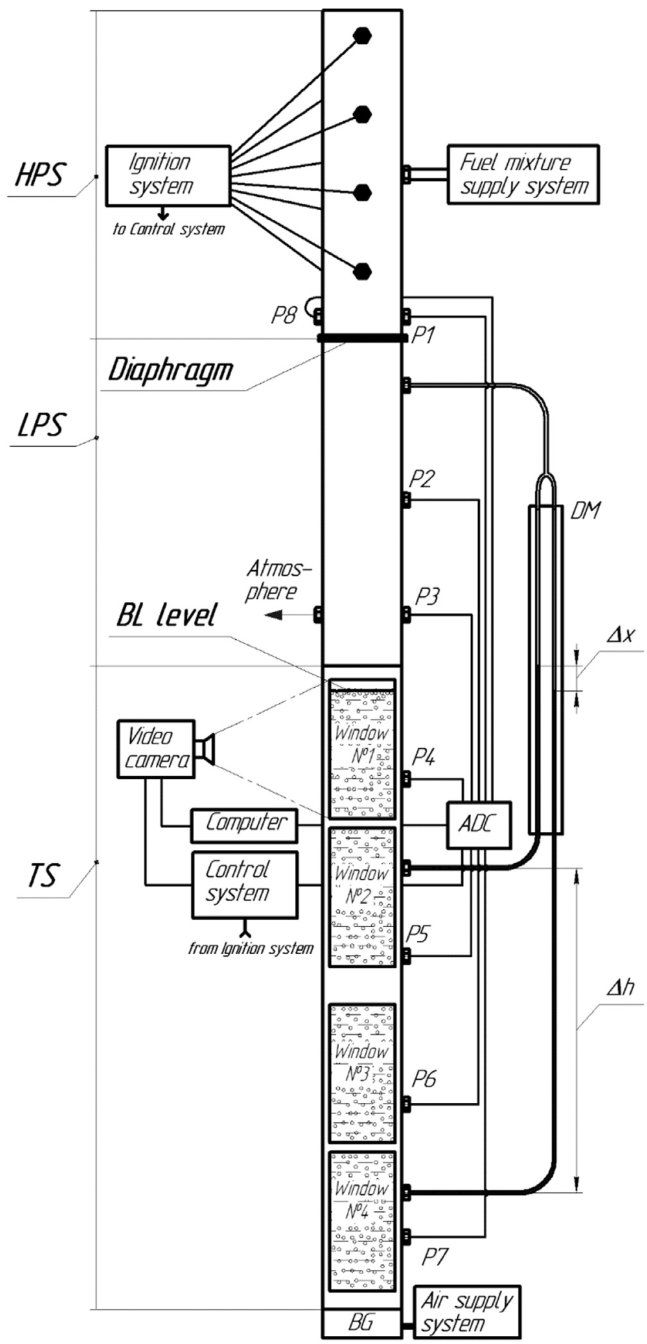

Fig. 1. Schematic of the vertical Hydroshock Tube with four optical windows (Nos. 1 to 4): HPS - high pressure section filled with compressed air or with propane – air mixture enriched with oxygen; LPS – low pressure section; TS – test section; BG – bubble generator; DM – differential manometer; BL – bubbly liquid; P1 – P7 – piezoceramic gauges of overpressure, P8 – absolute pressure transducer.

Experiments by Sytchev (2010) were performed at higher pressures (24 and 36 bar) in HPS where acetylene–oxygen mixture was exploded. LPS was filled with air at atmospheric pressure, TS filled with bubbly water was 3550 mm long, the mean air bubble diameter was 2.5 mm, and the initial gas volume fraction α_{10} varied from 0.005 to 0.06. Both water and air were at room temperature. The SW velocities were measured using pressure traces recorded with three pressure gauges mounted along the TS at a certain distance from each other. The results obtained by Sytchev (2010) show that at a given α_{10} the SW velocities measured between two pairs of gauges differ insignificantly. Because of the higher pressures, the shock velocities measured by Sytchev (2010) were greater than those measured by Mori et al. (1975): 150 m/s in (Mori et al., 1975) and 300 or 400 m/s in Sytchev (2010) at $\alpha_{10} = 0.02$; 100 m/s in (Mori et al., 1975) and 200 or 250 m/s in (Sytchev, 2010) at $\alpha_{10} = 0.05$.

The pressure in HPS in (Nakoryakov et al., 1975) was varied from 1.2 to 4 bar; LPS was filled with air at atmospheric pressure; TS contained a column of aqueous glycerol solution (with kinematic viscosity of $2{\cdot}10^{-6}$ m^2/s) 2000 mm high with air bubbles 2 mm of mean diameter; and the initial gas volume fraction $\alpha_{10} = 0.01$, 0.02, and 0.05. Both air and liquid were at room temperature. Pressure traces recorded with gauges were used to determine the SW velocity in bubbly liquid. It increased as the pressure in HPS rose and the gas content in the liquid decreased; the SW velocity value at moderate gas contents (α_{10}= 0.05) varied in the range of 50–70 m/s.

Optical monitoring of single bubble motion behind a shock front in bubbly water with $\alpha_{10} = 0.0077$ and 0.027 performed by Kalra and Zvirin (1981) showed that at a pressure in HPS of about 2 bar the bubble velocity ranged between 3 and 4 m/s immediately behind the front and decreased as the bubble departed from the front.

Kutateladze and Nakoryakov (1984) measured the acoustic velocity in a liquid containing insoluble gas and its vapour at their various gas volume fractions and performed appropriate calculations. As the gas content in liquid increases from zero to 100% the acoustic velocity passes through a deep minimum. The review article by Wijngaarden (1972) reports that the known relationships for the acoustic velocity in bubbly liquid provide good agreement with experimental findings in a wide range of the characteristic frequencies of the acoustic wave and bubble oscillations (Silberman, 1957).

In a number of works experiments were performed with gases other than air (such as argon, helium, CO_2, etc.) in bubbles and liquids other than water (such as vacuum oil, water – glycerol mixture, boiling water, etc.) rather than water under normal conditions were used as a carrier medium. In some articles (e.g., Kotchetkov and Pinaev, 2012), SWs were initiated by applying high-voltage (about 4–8 kV) to a thin wire submerged in bubbly liquid. Such articles are not mentioned here because have no direct relevance to the main objective of the present paper.

It should be noted that depending on governing parameters of the medium (viscosity, thermal conductivity, bubble size, etc.) SWs in bubbly water can have various pressure profiles (Kutateladze and Nakoryakov, 1984; Burdukov et al., 1973; Noordzij, 1971), namely, with a smooth pressure time history or oscillatory (Campbell, 1958). A condition of the existence of the oscillatory structure of pressure profiles was derived by Kutateladze and Nakoryakov (1984) for a weak SW based on the Korteweg–de Vries and Burgers equation. Experimental pressure traces recorded by Kutateladze and Nakoryakov (1984) in SWs spreading in water containing air bubbles of various size (0.69, 0.48, or 0.1 mm) at a similar initial gas volume fraction ~0.08 show that the oscillation frequency of pressure behind SW decreases for large bubbles (0.69 mm) and increases for small bubbles (0.1 mm).

Kedrinskii and Soloukhin (1961), Kedrinskii (1980), Gelfand et al. (1975), Voinov and Petrov (1971), and Ranjan et al. (2011) studied the interaction of bubbles with SWs in bubbly liquids both experimentally and computationally. It has been found that bubbles are deformed and fragmented behind propagating SWs due to instability of the gas – liquid interface.

The theoretical and computational studies of shock and detonation waves in bubbly liquids are usually based on one-dimensional (1D) partial differential equations of mass, momentum, and energy conservation for two mutually penetrating continua – liquid and

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