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Paper No. 139- 8

An Experimental Study on Shock Waves in Liquid (The Generation of Shock Waves by an Impinging Piston and their Behavior)*

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Onedimensional pressure waves (shock waves) were generated in a liquid (water) column contained in a vertical pipe by the impingement of a piston accelerated by compressed air. The waveforms obtained were sawtooth waves with peak pressures of 100–500kg/cm² and widths of 1 to 2msec. While waves in this pressure range were found to behave essentially as sound waves, the steepening of the wave front with originally a rise time of tens of micro-seconds to a discontinuity over a propagation distance of around 2 meters was observed, which was explainable in terms of the compressibility of the liquid. The density change across the wave front measured with the integrated schlieren technique was found to be proportional to the pressure change in accordance with the relation of adiabatic change of the medium. The motion of the piston following the impingement was observed by means of instantaneous photography, and a fine correspondence of the deceleration process with the generated waveform was evidenced. The displacement velocity of the liquid behind the wave front was also measured with a simple technique.

1. Introduction

Strong shock waves that propagate in a liquid volume are produced when a large amount of energy is released instantaneously at a spot in the medium, or, alternatively, when a violent impact is imposed upon the boundary of the medium. The nature of spherical blast waves produced by underwater explosions was the object of a number of early investigations.(1)–(3) The hydroforming technique that makes use of shock waves in water with pressure rises exceeding 100kg/cm² (0.1kbar) is now popular.(4)–(6) Thus the clarification of the generation/propagation mechanism of shock waves in liquid is of apparent importance from the industrial point of view as well. On the other hand, the measurement of the change of state across plane shock waves in various liquid mediums generated by explosives has constituted a simple and useful means to determine the liquid properties at ultrahigh pressures (1 to 100kbar).(7)–(9)

In the experiment reported here, plane shock waves were generated in the liquid column within a vertical pipe by making a piston accelerated by compressed air impinge upon its free surface, and the behavior of such waves was investigated. Plane shock waves in liquid with pressure rises up to about 30kg/cm² can be produced rather readily by letting gas shock waves or detonation waves hit the free surface. As has already been reported,(10) shock waves in water in this pressure range behave like sound waves (as predicted theoretically (11)), and are

found to propagate in a pipe of constant cross section with no perceptible change in shape (pressure profile). The present study deals with shock waves with 100 to 500kg/cm² pressure rises, observations being made of the pressure waveform, the propagation mode and the change of state across the wave front.

2. Experimental Equipment and Procedure

In Fig.1 is shown the experimental equipment, which consists of a circular-pipe (stainless steel) test section with inner diameter of 25mm and wall thickness of 4.5mm, and a high-pressure tank situated on top of the former with a ball valve separating the two parts. The lower half (630mm) of the test section is filled with the test liquid (distilled water). Prior to the run, the high-pressure tank is filled with compressed air, and a piston, which is a circular cylinder of

Fig.1 Experimental Equipment.

* Received 3rd August, 1974.

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24.8mm diameter equipped with a teflon collar, is fixed at the upper end of the test section (just below the valve). The sudden opening of the valve sets the piston in motion, the latter being accelerated as it travels down the pipe. A 46mm² slit in the side wall of the pipe just above the liquid surface serves as the vent for the air in front of the impinging piston. The piston itself is a permanent magnet, the passage of which is detected at two locations, 90mm and 20mm above the liquid surface, by the voltage signals induced in the coils, the measured time interval determining the final velocity of the piston.

The test section is equipped with three probe ports for pressure recordings (by semiconductor transducers) and a pair of windows for optical density recording (by integrated schlieren method with a laser as the light source) (see Fig.1). The maximum pressure to be measured by the transducers employed is 500kg/cm², and the range of experiment was restricted accordingly. The displacement velocity of the liquid was made, by the method described in the next section, using the window pair for density measurement. Also, the behavior of the piston in its collision with the liquid surface was visualized by a series of instantaneous photographs, whereby the stainless-steel test section had been replaced by an acrylate pipe with the same diameter.

3. Results

3.1 Pressure Waveforms

Fig.2 (a) & (b) show typical pressure waveforms recorded for shock waves in water produced by piston impingement. Of the two traces in the oscillogram (a), the

Fig.2 Pressure Recordings. A: 400mm from downstream end, B: Downstream end, A': 600mm from downstream end, Vertical scale: 120kg/cm²/div., Horizontal scale: 0.2msec/div..

upper is the record at Station A 400mm upstream of the end and the lower is that at Station B (the downstream end). A saw-tooth wave, which exhibits a sharp rise to its peak followed by a gradual fall, is seen to pass A, be reflected at B (the maximum peak pressure is recorded here), proceed upstream past A to be re-reflected at the bottom surface of the piston (below the water surface), and then propagate A → B → A undergoing attenuation. Fig.2 (b) is a simultaneous record of pressure changes at A and at A' (200mm upstream of A). While here again the back-and-forth propagation of the shock wave between the piston and the downstream end is demonstrated, this record shows specifically that the pressure waveform changes little over the distance (A to A' and the other way around). Thus one is led to the inference that a larger portion of the attenuation occurs as the shock wave undergoes reflections. The saw-tooth waveform obtained is apparently related to the behavior of the piston colliding with the water surface. This point will be clarified in 3.5 in connection with photographic observations.

In Fig.3 is shown the relationship between the final velocity of the piston, regulated by varying the driving pressure, and the corresponding peak pressure of the incident shock wave recorded (open circles), exhibiting a linear increase of the latter with the former. Assume that the liquid surface starts to move downward with velocity U at the instant of the piston collision. In an ideal onedimensional situation, one would have as the peak pressure of the pressure wave thus generated:

$$P = P_0 + \rho_0 c_0 U(1 + 0(U/c_0)) \quad (1)$$

where P_0 denotes the initial pressure (atmospheric pressure) and ρ_0 and c_0 the liquid density and sound speed, respectively ($\rho_0 c_0$ is the acoustic impedance of the liquid). The solid line in Fig.3 shows the relation (1) for room-temperature water, a straight-line relation in the present pressure range. The fact that the experimental points lie below this line is considered to reflect the deviation from the onedimensionality of the collision (the distortion of the liquid surface before collision, the splashing of water due to the presence of the piston-wall clearance, etc.).

Also noteworthy in Fig.2 (a), (b) is the fact that, whereas it takes tens of

Fig.3 Relation between Peak Pressure and Piston Velocity.

microseconds for the pressure to reach its peak value in the primary (incident) wave, such rise times become shorter as wave reflections are repeated and the overall propagation distance increases, until the front portion of the wave acquires the feature of a genuine shock wave. This evidently is not the result of reflections at the downstream end and the piston bottom. Also, this was not observed in the experiment in the low-pressure range⁽¹⁰⁾. Such nonlinear effect will be discussed in the next section.

3.2 Propagation Speeds

The propagation speeds of pressure waves can be determined from pressure records like Fig.2 (a) & (b). In Fig.4 is shown the variation of the propagation speed W with the peak pressure. In this pressure range W does not practically change with P , and is equal to the sound speed of water at room temperature, in accordance with the theoretical prediction⁽¹¹⁾. Incidentally, the test-section pipe employed in this experiment had a sufficient wall thickness for the decrease in the propagation speed due to the expansion of the pipe to be disregarded.

Fig.4 Propagation Speed.

Fig.5 Simultaneous Records of Density and Pressure Changes. S: Schlieren Signal, P: Pressure. 120kg/cm²/div., 0.1msec/div..

3.3 Density Change

The density change of water across the incident wave front (from the initial state to the peak-pressure state) was measured by the integrated schlieren method⁽¹⁰⁾. Typical oscillograms representing simultaneous records of schlieren output and pressure waveform are shown in Fig.5 (a) & (b). The schlieren signal S exhibits a waveform roughly representing the time derivative of the pressure P (its sign is reversed for the reflected wave). The integration of S from the initial to the peak-pressure state and multiplication by the calibration constant of the optical system yields the increment in the refractive index of the test medium, from which the density change $\Delta\rho$ or the specific-weight change $\Delta\gamma$ is obtained via the Gladstone-Dale constant. Fig.6 shows a plot of $\Delta\gamma$ against $\Delta P = P - P_0$.

In an adiabatic change of a liquid medium, ΔP and $\Delta\rho$ are connected by the following relation:

$$P = (\partial P / \partial \rho)_s \Delta\rho + (1/2) (\partial^2 P / \partial \rho^2)_s (\Delta\rho)^2 \quad (2)$$

$$= c_0^2 \Delta\rho + (1/2) (\partial^2 P / \partial \rho^2)_s (\Delta\rho)^2$$

where s denotes the entropy, and higher-order terms have been dropped on the assumption that the relative change in the density is small ($<10^{-2}$). Substituting pertinent values for water, we have the relationship between ΔP (kg/cm²) and $\Delta\gamma$ (specific-weight change, g/cm³) as

$$\Delta P = 2.6 \times 10^4 \Delta\gamma + 5 \times 10^1 (\Delta\gamma)^2 \quad (3)$$

The relation (3) is shown in Fig.6 with the solid line, which is practically a straight line because of the smallness of the second term on the right-hand side of the equation in the present range of pressure. The figure inserted on the top right represents the results in lower pressure ranges, those for $\Delta P < 10\text{kg/cm}^2$ and $\Delta P > 10\text{kg/cm}^2$ having been obtained with the incidence of gaseous shock waves (step-function pressure change) and the incidence of detonation waves in the oxygen-acetylene mixture above the water surface (saw-tooth pressure change), respectively, and the solid line representing the theoretical prediction.

Fig.6 Density Change.

3.4 Displacement Velocity of Liquid

Efforts have been made to measure the displacement velocity (flow velocity) of liquid behind shock waves making use of the Doppler effect⁽¹²⁾ or with the electromagnetic flowmeter arrangements*. In this study, a simple method as described below was adopted. The test section was filled with liquid paraffin from the bottom up to the center of the observation window, and ethanol dyed in ink was placed on top of it. The two liquids do not mix with each other, and have almost equal densities and sound speeds. A laser beam was passed through a rectangular slit and then through the observation windows, and the change of the intensity of the transmitted light due to the displacement of the interface was recorded photoelectrically. A typical record is shown in Fig. 7. The pressure P was recorded 200mm downstream from the station where light intensity L was recorded, so that the change in the former lags behind that in the latter for the incident wave, the situation being reversed for the reflected wave proceeding in the reverse direction. A fine correspondence between the two signals are found, demonstrating a downward displacement of the interface by the incident wave (the acceleration is most pronounced at the steepest pressure change)

Fig.7 Simultaneous Record of Interface Displacement and Pressure. L: Transmitted-Light Intensity, P: Pressure. 120kg/cm²/div., 0.2msec/div..

Fig.8 Interface Displacement and Liquid Velocity vs. Time.

and its upward movement by the reflected wave. In Fig.8 (a), (b) are shown the temporal changes of the position of the interface with time (in the incident-wave region) and of the displacement velocity of the interface, i.e. of liquid, which was obtained by differentiating the former curve. The pressure profile and ΔU (Fig. 8 (b)) exhibit very similar shapes, and the calculated value of the liquid velocity peak (closed circle on the vertical axis in Fig.8 (b), calculated with liquid density =0.855, sound speed =1230m/s) corresponding to the pressure peak is found to agree well with the experimental value (curve).

3.5 Piston Motion

Examples of instantaneous photographs that record the motion of the piston near the water surface are shown in Fig.9 (a), (b). A horizontal water jet, evidently induced by the escaping air, is observed before the impingement ((a)), which persists until after the bottom of the piston has penetrated below the water surface ((b)). Fig.10 shows a typical locus of the piston constructed from a series of snapshots with varied delay times for a fixed driving pressure. (Since an acrylate tube was used in place of a steel pipe, the latter was rather low, the peak pressure being around 20kg/cm².) The piston is decelerated after hitting the water surface until it comes to a standstill at a position a few millimeters below, 1 to 2 milliseconds being spent for the process. This time interval corresponds to the duration of the pressure wave, and the saw-tooth waveform of the pressure wave is interpreted as a combination of a front shock wave due to the collision and a rarefaction wave that follows which is emitted in the deceleration process.

4. Discussions

Shock (compression) waves in liquid with the pressure rise up to 500kg/cm² as studied in this experiment are expected to behave practically as waves of infinitesimal amplitudes i.e. sound waves propagating at sound speed, for which the pressure rise is proportional to the density rise and the induced displacement velocity, the proportionality constants being the sound speed squared and the acoustic impedance, respectively. All this has been confirmed by the experimental results described in 3.1 - 3.4. On the other hand, the pressure waveform in the front portion of the wave that initially has a finite rise time was observed to steepen as the wave propagates until the rise time is reduced practically to zero. Such a deformation process occurs very rapidly in a gaseous medium, and is attributable to the non-linearity in the underlying gasdynamics. Generally, in a medium with a finite compressibility, i.e. a finite value of sound speed, it may be shown that the front of a compression wave always has a

tendency to steepen until it develops into a discontinuity after a certain distance of travel (the viscosity of the medium being disregarded). If the initial pressure rise rate is denoted by $(\partial P/\partial t)_i$, this distance is given as⁽¹⁴⁾

$$L = \rho_0 c_0^3 / (1 + (\rho_0/2c_0^2)(\partial^2 P/\partial \rho^2)_s)(\partial P/\partial t)_i \quad (4)$$

Employing a typical value: $(\partial P/\partial t)_i = 300 \text{ kg/cm}^2/40 \mu\text{s}$ and substituting pertinent data for water, we have $L = 185 \text{ cm}$, which explains the observation in the present study. The thickening of the wave front due to viscosity is estimated to be no more than 10^{-4} mm , which is too small to be observed.

The peak value of the pressure wave decreases considerably as it repeats reflections. In general, for the reflection of a plane shock wave in liquid at an infinite solid wall, the pressure rises of incident (suffix i) and reflected (suffix

r) waves are connected by the relation:

$$\Delta P_r/\Delta P_i = (Z_s - Z_l)/(Z_s + Z_l) \quad (5)$$

where $Z_s = \rho_s c_s$ and $Z_l = \rho_l c_l$ are the acoustic impedances of solid and liquid, respectively. Whereas pressure rise ratio (5) is calculated as 0.93 when pertinent numerical data are substituted, this value was obtained in practice only for $\Delta P_i \approx 100 \text{ kg/cm}^2$, the ratio dropping to 0.82 in the higher pressure range. The reflection at the bottom surface of the piston (which is movable) gave a still lower ratios, typically around 0.6.

The temperature increase across the wave front may be estimated from a simple thermodynamic calculation as

$$\Delta T = (\alpha T/\gamma C)\Delta P \quad (6)$$

where α and C are the thermal coefficient of volume expansion and the specific heat of the medium, respectively. Again, substituting $T = 300 \text{ K}$, $\Delta P = 500 \text{ kg/cm}^2$, we have $\Delta T \approx 0.75^\circ \text{C}$, which is small enough for the shock-wave compression in the present range to be regarded as isothermal.

5. Conclusions

- (1) By the impact of a piston accelerated by compressed air at $3 - 5 \text{ kg/cm}^2$, it was possible to generate onedimensional saw-tooth pressure waves with peak pressures up to 500 kg/cm^2 in a vertical column of water.
- (2) The propagation speed of waves in this pressure range was practically constant and equal to be the sound speed. The density change across the wave front in water measured by the integrated schlienen method was proportional to the pressure rise in fair agreement with the equation of state of the medium.
- (3) The front portion of the wave that initially has a rise time of tens of microseconds becomes steepened due to the nonlinearity effects and develops into a discontinuity over a propagation distance of about 2 m .
- (4) A good correlation was observed between the deceleration process of the piston after collision and the shape of the pressure wave generated.

Fig.9 Snapshot Photographs of Piston. (a) Before Collision, (b) After Collision.

Fig.10 Piston Locus.

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