Shock Waves From Vapor Explosion in a Shock Tube

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Abstract

Rapid liquid/vapor phase transitions occurring frequently in industrial accidents may cause catastrophic consequences. For example, such a situation arises in metallurgy when a molten metal suddenly contacts a coolant or a cold liquid falls onto a red-hot interface. In the atomic energy industry, such a rapid-phase transition may occur as a result of water reactor depressurization. Studies of shock and rarefaction waves and condensation jumps are important for the problem of thermal detonation. The present work investigates the properties of planar shock and rarefaction waves generated by sudden expansion of a high-temperature, pressurized, water-saturated vapor system. Experiments were carried out in a vertical shock tube 2-m long and 50-mm in diameter in the range of 380 - 520 K temperatures and 0.1 - 4 MPa pressures. The water-vapor system was put in a high-pressure chamber of the shock tube. After the rupture of a diaphragm separating the high and low pressure chambers, shock and rarefaction waves formed. Parameters of these waves were measured by piezoelectric pressure gauges. The experiments show that condensation and evaporation processes in rarefaction waves affect the shock parameters. Condensation of the saturated vapor in the rarefaction waves leads to a decrease in the shock wave intensity. Explosive boiling results in the formation of a shock wave with compression phases of very long duration. Specific features of the flow generated by expansion of a volume filled with a nonuniformly heated liquid were also studied.
Introduction

For safe exploitation of an apparatus containing a high-pressure and high-temperature vapor/liquid system, simulation of possible catastrophic accidents is needed. The main hazard is associated with sudden depressurization of a superheated liquid. As a result, a rarefaction wave propagates into an expanding volume and rapid phase transition comes into play. The processes inside a depressurized volume have been studied.\textsuperscript{1-3} As a consequence of rupture of a container with superheated liquid, shock waves may form in the surrounding atmosphere. Study of events coming into effect after the depressurization is of great practical importance, since it allows for better understanding of the reasons for the considerable destructive capacity of vapor explosions. Clearly, a decrease in the pressure of an overheated liquid precipitates rapid vaporization, or "flashing." The phenomenon has much in common with molten metal/water explosions.\textsuperscript{4} Hence, investigations of the sudden expansion of a superheated liquid may also shed light on large-scale vapor explosions.

The paper records the investigation of the properties of planar shock and rarefaction waves generated by the sudden expansion of a high-temperature, pressurized and stratified, water-saturated vapor system. The results are

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{Fig. 1 Schematic of the experimental setup.}
\end{figure}
compared with those typical for expansion of a high-pressure gas volume. The experimental measurements were carried out in a specially designed shock tube.

**Experimental**

Experiments were carried out in a vertical shock tube schematically shown in Fig. 1. The low-pressure chamber (LPC) denoted as Sec. I was filled with air (pressure $p_1 = 0.1$ MPa, temperature $T_1 = 293$ K). Sections II and III represent two parts of the high-pressure chamber (HPC). Fragile diaphragm 1 separates the HPC from the LPC. The water-filled Sec. III is equipped with electrical heating bands of power $W = 0.7$ kW. Initially, Sec. II was filled with air at $p_1 = 0.1$ MPa, and $T_1 = 293$ K. Section II was being filled with vapor during heating. The temperature is measured by thermocouple 2. When the pressure in Secs. II and III achieves the value $p_4$, the diaphragm bursts, which causes shock and rarefaction waves to form. The wave parameters are measured by piezoelectric pressure gauges 3 - 10. In addition, photogauge 11 is used for registration of the two-phase flow in the LPC. Section III (length $L = 160$ mm, ID = 80 mm) was used in all the runs. The maximum pressure and temperature values in the HPC are, respectively, 7 MPa and 530 K.
Shock Waves Generated by Expanding Saturated Vapor

Studies of the expansion of saturated vapor/air mixture were carried out in a shock tube with a 40 x 40 mm\(^2\) square cross section. Section I was 1-m long, Sec. II 0.5-m long. Section III was filled with a certain amount of water, typically 600 ml. Gauge 7 was used to trigger the oscilloscopes. Gauges 8 and 6 are positioned, respectively, at 320 mm and 135 mm from the bursting diaphragm. The distance between gauges 8 and 9 is 255 mm and between gauges 5 and 6 is 200 mm. Figure 2a shows pressure histories behind a shock wave as registered by gauges 8 and 9 and Fig. 2b shows those in a rarefaction wave as registered by gauges 5 and 6. The diaphragm bursts at \(p_4 = 3.05\) MPa \((T_4 = 506\) K\).

It is obvious that the shock wave intensity depends on the characteristics of an expanding saturated vapor/air medium. The shock wave Mach number \(M\) relates to the initial pressure ratio by the following well-known expression:

\[
\frac{p_4}{p_1} = \frac{2\gamma_1}{\gamma_1 + 1}M^2 - \frac{\gamma_1}{\gamma_1 + 1}\left(1 - \frac{\gamma_4 - 1}{\gamma_1 + 1}a_4\left(M - \frac{1}{M}\right)\right)^{\frac{-2\gamma_4}{\gamma_1 + 1}}
\]  

(1)

Here \(\gamma_4\) is the ratio of the specific heats, \(a_4\) is the sound velocity in the driver medium; quantities \(\gamma_1\), \(a_1\) are those in the air. Figure 3a presents the dependence of \(M\) on \(p_4/p_1(T_3/T_1)\). Curve 1 corresponds to Eq. (1) with quantities \(a_4\), \(\gamma_4\) pertaining to the saturated vapor/air mixture in the HPC. Curve 1 in Fig. 3b is the theoretical prediction for \(a_4\). For the specific heat ratio of the mixture, the value \(\gamma_4 = 1.3\) was assumed.\(^3\) As seen from Fig. 3b, the measured velocity of a rarefaction wave head (point 2) is in good agreement with the theoretical prediction. The calculated curve 4 and experimental data 3 in Fig. 3b present the velocity of the rarefaction wave head in nitrogen at \(T_4 = 293\) K. As seen from Fig. 3a, the experimental values of the shock Mach number (point 2) are quite low. Probably as a result of sudden expansion, vapor condensation comes into play and the growth of water droplets in the driver medium leads to shock wave attenuation. It is known that the sound velocity in a two-phase mixture is lower than that in a pure gas. It was found recently\(^6\) that the bursting of a pressurized vessel filled with a particle-laden gas generates shock waves that are characterized by a longer compression phase and a lower intensity, compared with the case of a vessel filled with a pure gas. One may suggest a simple explanation of the effects produced by an expanding vapor/air system, using the "equilibrium" flow hypothesis. The suspension of small liquid particles in the HPC may be treated as an "equivalent gas," characterized by the following well-known parameters:

\[
a_0^2 = \frac{a^2}{\gamma(1 + \eta)}
\]  

(2)

\[
\Gamma = \frac{1 + \eta\hat{\eta}}{1 + \gamma\eta^2}
\]  

(3)
Here η is the particle-to-gas mass ratio; \( a_s, \gamma \) are the thermodynamic parameters of the gas and \( a_4, \Gamma \) are those of the "equivalent gas"; and \( \delta \) is the ratio of the specific heat of the particles to that of the gas (at a constant pressure). The experimental results plotted in Fig. 3a are in good agreement with curve 3 drawn for \( a_4 = a_s, \gamma_4 = \Gamma, \eta = 4, \delta = 2 \). Hence, the bursting of vessels filled with a saturated vapor/air mixture results in the generation of shock waves of lower intensity than one calculated without phase transition. Thermodynamic parameters of the equivalent driver gas may be used to obtain the upper bound of shock intensities.

**Shock Waves Generated by Sudden Expansion of a Superheated Liquid**

The other situation can be realized when the HPC is filled with water at \( T_4 > 373 \) K. After diaphragm rupture, water becomes superheated relative to the conditions in the LP (\( p_1 = 0.1 \) MPa, \( T_1 = 253 \) K); and because of this, intense vaporization occurs. Sudden expansion of the vapor can lead to the onset of shock waves. Mass addition to the vapor phase exists in the rarefaction wave, which exerts essential influence on the intensity and duration of the shock wave.

The experimental setup for this case is also represented in Fig. 1. Section III is now directly attached to Sec. I (LPC) and separated from it by a diaphragm. The length of the LPC is 2 m and its inner diameter is \( d_0 = 50 \)
mm. The values of $T_4$, $p_4$ in the HPC depend on the diaphragm thickness. To compensate for heat expansion of the liquid, a water-free volume between the diaphragm and water surface have been provided. At the moment of diaphragm rupture the vapor/air mixture occupied a volume of about 30 ml.

Typical pressure records are presented in Fig. 4a, which shows pressure records at the position of gauge 8 (upper trace) and gauge 9 (bottom trace). The distances from each gauge to the diaphragm are, respectively, 0.57 and 0.81 m, the pressure $p_1 = 0.68$ MPa, and the temperature $T_4 = 427$ K. As seen from these records, the pressure profile consists of a leading shock of triangular shape and a section of monotonic pressure increase followed by a pressure plateau. We shall characterize such wave structure by the following coefficients: $\alpha = \Delta p_1 / p_1$ and $\beta = \Delta p_2 / p_1$. Here, $\Delta p_1$ is the overpressure at the wave front and $\Delta p_2$ is that on the “plateau.” The leading wave is formed as a result of vapor/air volume expansion. The monotonic pressure increase is due to nonstationary evaporation. The pressure rise time correlates with the data on the time of vapor bubble growth in boiling water. Parameter $\beta$ is independent of the water-free volume and depends primarily on the water temperature. The dependence of $\beta$ on $T_4$ is shown in Fig. 5.

As is known, expansion of a boiling vapor/liquid system generates a two-phase flow. This was confirmed by our experiments. It is shown that there exists a heterogeneous vapor-droplet flow behind the contact surface between the air and vapor. Under the conditions of the experiment represented by Fig. 4a, the contact surface arrives at gauge 9 later than the shock front by more than 7 ms. Figure 4b (bottom trace) shows the pressure record produced by gauge 9. Figure 4b (upper trace) shows the light absorption signal from the photodiode at the same position. As seen from Fig. 4b, the photocurrent begins to decrease 4 - 7 ms after the shock front arrival. This effect seems to be due to the existence of the vapor/droplet flow far behind the shock wave front.

One may calculate the rate of vapor generation on the basis of Fig. 5. The pressure at the contact surface is $p_v = p_1 + \Delta p_2$. If the saturated vapor is assumed to obey the ideal gas law, one has $p_v = p_v / R_v T_v$, where $R_v$ is the gas constant of the vapor and $T_v$ is the temperature of the saturated vapor at pressure $p_v$. According to the shock tube theory, the flow velocity of a vapor/air mixture is given by the following expression:

$$v_v = \frac{a_1}{\gamma_1} \beta \left(1 + \frac{\gamma_1 + 1}{2\gamma_1} \beta \right)^{-0.5}$$

Thus, one obtains for the specific vapor discharge

$$p_v v_v = \frac{a_1}{\gamma_1} \frac{\Delta p_2}{R_v T_v} \left(1 + \beta \right) \left(1 + \frac{\gamma_1 + 1}{2\gamma_1} \beta \right)^{-0.5}$$

(4)
Fig. 4 Pressure records for expansion of a hot liquid. Divisions of the time scale in ms are: 0.5 (a,d,e), 1 (b,c), 10 (f). Divisions of the pressure scale in MPa are: 0.05 (c), 0.03 (a,d,e,f-upper traces), 0.12 (f-upper trace), 0.028 (a,d,e-bottom traces), 0.056 (b-bottom trace).

The pressure vs temperature dependence at the saturation line far from the critical point may be written as

\[ p_v = p_0 \exp\left[ \frac{q}{R_v} (T_o^{-1} - T_v^{-1}) \right] \]  \hspace{1cm} (5)

Here \( q \) is the heat of vaporization and \( T_o \) is the saturation temperature at pressure \( p_o \). If one takes into account that \( T_o = 373 \text{ K} \), \( p_o = p_1 = 0.1 \text{ MPa} \), and \( p_v/p_1 = 1 + \beta \), then

\[ T_v^{-1} = T_o^{-1} - \frac{R_v}{q} \ln (1 + \beta) \]  \hspace{1cm} (6)

Thus, from Eq. (4) and Eq. (6) one has

\[ p_v v_v = \frac{a_1}{r_1 R_v T_v} \Delta p_2 \left[ 1 - \frac{R_v T_o}{q} \ln (1 + \beta) \right] (1 + \beta) \left( 1 + \frac{n+1}{2\gamma_1} \beta \right)^{-0.5} \]  \hspace{1cm} (7)
Equation (7) determines the intensity of vaporization in a volume with boiling water (HPC). At \( T_4 = 427 \) K one has \( \beta = 0.42 \) and thus \( \rho_0 v_0 = 73 \) kg/m s \( (R_0 = 461.7 \) J/kg k, \( q = 2.26 \) MJ/kg). Vapor flow rate through the tube cross section is \( G = \rho_0 v_0 \pi d_0^2 / 4 = 0.14 \) kg/s. If \( T_4 = 506 \) K and \( \beta = 1.79 \), one obtains \( G = 0.8 \) kg/s. The vapor flow rate increases with the initial temperature \( T_4 \). Note that the vapor flow rate under normal boiling conditions is \( G = W / q = 0.0003 \) kg/s, which is much lower than that under nonstationary conditions at issue.

For weak shock waves \( (\beta < 0.3) \) the formula in Eq. (7) may be simplified to

\[
\rho_0 v_0 = A a_4 \gamma_1^{-1} \Delta p_2, \quad A^{-1} = R_0 T_0 = \text{const}
\]

(8)

If the vaporization intensity is independent of the thermophysical parameters of the LPC gas and is determined only by the initial temperature of the liquid, one may observe the dependence of the shock intensity on the nature of a test gas in the LPC. For example, as is obvious from Eq. (8), the use of helium instead of air at the same temperature \( T_1 \) leads to a decrease in the shock overpressure \( \Delta p_2 \) by about 2.5 times.

Destructive capacity of a shock wave is known to be determined not only by the overpressure at the wave front, but also by the impulse and duration of the compression phase \( \tau_4 \). The parameter \( \tau_4 \) depends on the motion history of the rarefaction wave during the depressurization of hot water. It is shown\(^2\) that the transient depressurization process consists of three phases. At the beginning, the rarefaction wave propagates into the single-phase liquid medium at a typical sound velocity. The pressure decreases to a certain value \( p_{\text{min}} \), and spontaneous evaporation starts. So at the second phase of the process the pressure increases to a constant value that is lower
than the initial pressure $p_i$. At the end of the process, mass losses due to expansion are larger than vapor generation and pressure falls off. Figure 4c shows a rarefaction wave record produced by gauge 3 at $p_i = 1.23$ MPa and $T_i = 456$ K. The registered pressure variation is the same as reported.\textsuperscript{1,2} The onset of evaporation corresponds to appearance of "oscillations" at the pressure trace.

The influence of explosive boiling on the shock wave duration and impulse is illustrated by the pressure and impulse records shown in Fig. 6. Figure 6a is obtained without heating the water. The required pressure $p_i$ was achieved using high-pressure nitrogen, which occupied the space between the water surface and the diaphragm. Figure 6b is obtained under the same conditions but by heating the water. As seen from the records, a sudden expansion of the hot liquid generates shock waves of a longer duration and higher impulse, compared to those without heating. This effect may be explained on the basis of the considerations suggested.\textsuperscript{2} According to that, the reflected rarefaction wave propagates into the two-phase mixture at velocity $c$, which is lower than the sound velocity in the single-phase liquid. One estimates the duration of a compression phase as $\tau_c > 2L/c$, where $L$ is the HPC length. As seen from Fig. 6b, the measured $\tau_c$ is longer than $7 \cdot 0$ ms. Further measurements become difficult because of the reflected shock wave arrival. Calculations of the $c$ values were performed in Ref. 7. For the present experiments one has

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{fig6}
\caption{The influence of explosive boiling on the shock wave parameters. Expansion of gas (a) and hot water (b). The time scale is 1 ms per division. The pressure scale (bottom traces) is 0.018 MPa per division. The impulse scale (upper traces) is 110 Pa s per division.}
\end{figure}
$c = 20 \text{ m/s}$ and thus $\tau_+ > 16 \text{ ms}$. This result is well in accord with the experimental pressure records. Hence the bursting of vessels filled with hot liquid generates longer waves than those filled with gas. Such shock waves evidently may produce severe destruction.

It was of interest to study a nonstationary flow of boiling water through discharge rings with an orifice diameter less than the tube diameter. We studied the effect of a decrease in the orifice area on shock wave parameters. The experimental setup (Fig. 1) consists of a short Sec. II separated by a diaphragm from the LPC. A ring with the orifice diameter $d$ was mounted at the joint of Secs. II and III. Sections II and III were filled, respectively, with a vapor/air mixture and hot water. Figures 4c and 4d show, respectively, pressure records for experiments with $d = 30 \text{ mm}$ and $5 \text{ mm}$. Here $p_4 = 0.68 \text{ MPa}$ and $T_4 = 426 \text{ K}$. The leading pressure wave corresponds to expansion of the vapor/air volume in Sec. II. The pressure level behind the leading wave depends on the orifice diameter. Figure 7 presents the influence of the ring permeability, $d/d_o$, on the shock wave intensity at $p_4 = 0.6 \text{ MPa}$ ($T_4 = 426 \text{ K}$). The values $\beta = \Delta p_4/p_1$ were measured 3 ms after shock front arrival.

**Sudden Expansion of a Nonuniformly Heated Liquid**

In real technological systems with hot water there exist large temperature gradients. Expansion of nonuniformly heated water was also simulated in our experiments. Section III (HPC) in these experiments was placed above Sec. I (LPC). Thus, the distance between the heating bands and the diaphragm was about $40 \text{ mm}$. The water that occupies the space below the heating bands was heated more slowly than in the previous shock tube configuration. When pressure in the HPC attains the value $p_4$ corresponding to temperature $T_4$, the temperature $T_3$ of the water located near the diaphragm is lower than
$T_4$. The temperature gradient may be sufficiently large. For example, at a
pressure $p_4 = 0.68$ MPa ($T_4 = 426$ K) the temperature of the water near the
diaphragm was $T_3 = 320 - 330$ K.

Figure 4f presents the experimental records at $p_4 = 1.23$ MPa. The upper
trace is a pressure recorded by gauge 9 and the bottom trace is a signal of the
photogauge. The process may be interpreted as follows. After the
diaphragm rupture the “hot” liquid at the upper part of the HPC evaporates.
Vaporization will maintain the pressure at a level of about $p_4$. The “cold”
water below the heating band represents a liquid piston, which is accelerated
by the pressure difference $p_4 - p_1$ at its opposite sides. The accelerated piston
generates a weak acoustic wave in front of it without a sharp pressure rise
(Fig. 4f, upper trace). The pressure increases to $p_{\text{max}}$ behind the piston.
The pressure $p_{\text{max}}$ is higher than that in a shock corresponding to the same
initial pressure $p_4$. We call such a flow pattern a “rocket regime.” It may
be characterized by the velocity of the vapor-water piston. At a distance
of 0.7 m from a diaphragm the measured piston velocities were, respectively,
80 m/s and 40 m/s at $p_4 = 1.23$ MPa and 0.68 MPa. The maximum pressures
were, respectively, $p_{\text{max}} = 0.36$ MPa and 0.22 MPa. In spite of a relatively
small piston velocity, the “rocket regime” may be highly detrimental since
it is characterized by large impulse and pressure (temperature).

Conclusion

The use of a shock tube for simulation of the sudden expansion of high
temperature and high pressure vapor/water systems reveals some peculiar-
ities of vapor explosion action. Sudden expansion of a volume filled with
a saturated vapor/air mixture generates shock waves of a lower intensity,
compared to the case without condensation in the rarefaction wave. The
bursting of vessels filled with hot liquid generates waves of a longer duration
than the waves generated by gaseous explosion at the same initial pressure
of the explosion products. Shock intensities increase with increasing water
temperature. It was found that sudden expansion of a nonuniformly heated
liquid leads to development of a flow regime characterized by high values of
pressure, temperature, and impulse.

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