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EXPERIMENTAL STUDY ON VAPOR EXPLOSION INDUCED BY PRESSURE PULSE IN COARSE MIXING OF HOT MOLTEN METAL AND WATER

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ABSTRACT

An experimental study was done to investigate characteristics of metal-water interaction, when a mount of hot liquid metal is injected into the water. The test section is a vertical shock tube of 60mm in inner diameter and 1200mm in length .
A special injector which is designed to inject hot metal of controlled volume and flow rate is attached at the top of the tube. When the hot metal is injected in the water and comes down at a position of the test vessel ,a trigger pressure pulse is generated at the bottom of the test tube. Local transient pressures along the tube are measured by piezo pressure transducers. The following items were investigated in the experiment; 1)The criteria to cause a vapor explosion, 2)Transient behaviors and propagation characteristicsof pressure wave in the mixing region. 3) Effects of triggering pulse, injection temperature and mass of hot molten metal on the peak pressure. The probability of the vapor explosion jumped when the interface temperature at the molten metal-water direct contact is higher than the homogeneous nucleation temperature of water and the triggering pulse becomes larger than 0.9MPa. Two types of the pressure propagation modes are observed, one is the detonative mode with a sharp rise and other is usual pressure mode with a mild rise.

INTRODUCTION

In the various industries, we have experienced many vapor explosions which are caused by the mixing of hot liquid with low volatile liquid such as molten metal or slag-water, mineral oil-water and sea water-LNG etc. It is reported that some of volcanic explosions under sea water are related to vapor explosions. In the nuclear reactor, especially LWR, when a severe accident led to core melt occurs , it is supposed that two sequences of the accident followed by a vapor explosion may jeopardise safeties of reactor vessel or reactor container. One is a large scale liquid-liquid mixing, when a mount of molten fuel in the core region is dropped into the stagnant water of the bottom plenum in the reactor vessel, as experienced in the TMI accident and another is the case when the molten fuel penetrates bottom wall of a reactor vessel and is dropped into a sump of the container filled with water.

Many small scale vapor explosions in which single molten drop is poured into cold volatile liquid have been studied [1], [2], [3]. Nelson et.al. [4], observed the explosion of single iron oxide drop by a high speed movie which was initiated by a pressure pulse generated by a wire explosion. They found that the metal drop was expanded and burst immediately after collapse of vapor film. Iida et.al. [5] observed that an explosion of a molten salt drop in alcohol liquid caused another explosion of a drop nearby. The meaning of these drop tests are to know the detail mechanism and behaviors of the explosion by its simplified configuration.

According to large scale experiments, the explosion front propagates with the explosive pressure pulse. Therefore, local mechanisms or behaviors of large scale explosion in the corse mixing state may be similar to that of single drop under a pressure pulse. However,the propagation and the escalation behaviors of the pressure pulse generated by the vapor explosion must be affected by the mixing situation and the vapor void fraction. Thermal detonation model proposed initially by Board et.al. [6], was an attractive model to explain the vapor explosion in the large scale mixing. However, mechanisms of fragmentation and transient heat transfer under a shock pressure have not been enough clear in the model. Sharon & Bankoff [7], and Schwabe [8], proposed fragmentation models based on the Taylor instability and the boundary layer stripping caused by the intensive slip flow between drops and cold liquid which was caused by an explosive shock wave travelling in two phase mixture. There have been reported other analysis based on the transient detonation model for the escalation phase [9][10][11]. One dimensional propagation in the uniform corse mixing were postulated in almost all of these detonation models.

On the other hands, many experiments for large scale tests were performed at nuclear research laboratories to know the criteria of generation of vapor explosion and potential of the mechanical energy [12][13] [14]. These tests were performed in the conditions that a large mount of liquid was dropped into cold volatile liquid and was disintegrated spontaneously by the fluid dynamic and/or thermal effects. Therefore, the initial corse mixing conditions were not clearly set. One of the efforts in this experiment was how to realize one dimensional uniform mixing condition.

The purposes of this experiment are to investigate following items for the vapor explosion in the corse mixing mixture.

1) Criteria of the vapor explosion,
2) Effect of magnitudes of the triggering pulse on the peak pressure,
3) Effects of conditions of temperature and mass of mixing fluids,on the peak generative pressure, and
4) Propagation characteristics of pressure wave in one dimensional mixing region.

EXPERIMENTAL DEVICE

The device is composed of a vertical shock tube type, an injector of hot liquid metal and a circulation loop of water with a heater, a preheater and a pump as described in the Fig.1. The tube is made of stainless steel of 60mm in inner diameter and 1200mm in length with 6 pairs of windows to observe transient behaviors. At the position of 55cm from bottom end of the tube, a pair of arc electrodes are installed to generate a triggering pulse by an electrical discharge. At the 3 positions (PT1, Pt2, and Pt3) of the 85mm, 350mm and 460 mm from the electrodes respectively, the piezo type pressure transducers are installed to measure the generative pressure along the tube. At the center of window between PT1 and PT2, a photo sensor is attached to detect the front of the metal-water mixing region. The test duct is initially filled with water. The water in the tube is circulated slowly to keep constant temperature. However, the circulation lines connected to the tube are shut ist before the test and the test is done in the stationary water.

A special injector described in the Fig.2 is attached at the top of the test duct. It is designed so as to control the temperature , the injection rate and the injection volume of the molten metal. After evacuation by the vacuum pump, the injector is charged with molten metal. When

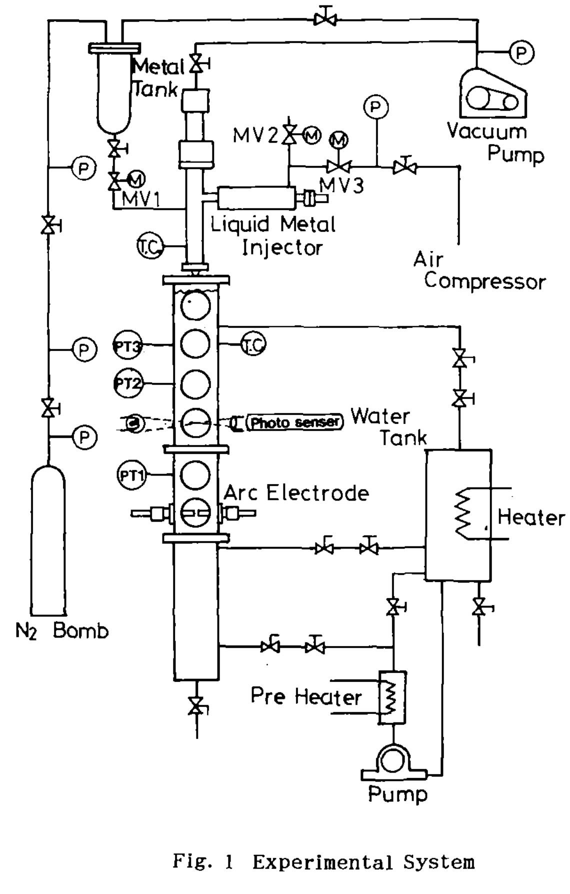

Fig. 1 Experimental System

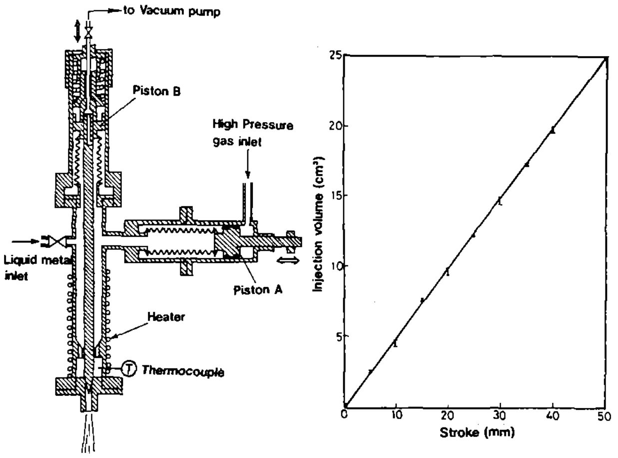

Fig. 2 Metal injector(a) and its injection characteristics (b)

the liquid metal is heated up to a certain temperature, high pressure gas is introduced to the piston A and then the pressure in the injector increases. The piston B moves to upward automatically by the pressure and then the molten metal is discharged. The discharged mass and rate of the metal are controlled by stroke of the piston A and the spring at the piston B.

Figures 2(a)(b) is a relation between the stroke of the piston B and the discharged mass. The molten metal is injected into water through a nozzle of 6mm in diameter. The trigger pressure pulse is generated by the electric discharge between a pair of copper electrodes set with less than 1mm gap in the water. The magnitude of the pulse is controlled by the discharged voltage.

The time behaviors of the trigger pulse and the relation between the peak pressure and the discharge voltage are shown in the Figs.3(a) and (b) respectively. The average duration time of the pulse is about 0.1ms. The peak pressure is lineally proportional to the discharge voltage.

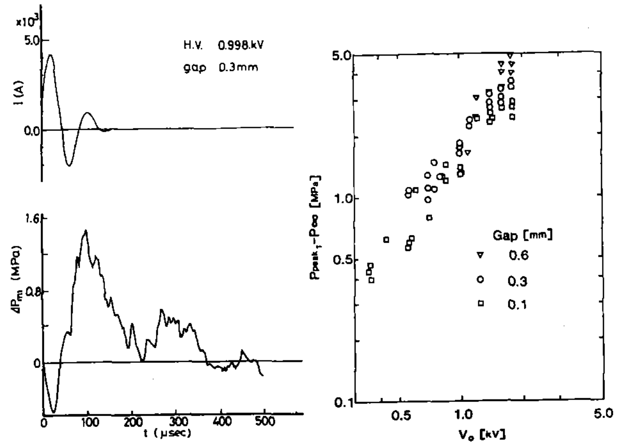

Fig. 3 Pressure pulse generated by electric discharge (a) and relation between the peak pulse and discharge voltage (b)

EXPERIMENTAL METHOD

Subcooling temperature of water in the test duct is kept at constant value of 70℃. Metal alloy (Bi:48%, Pb:26%, Cd:13%, Sn:13%) which melting temperature is 70℃ is used as hot metal. Initial temperature and injection mass of the hot metal are changed from 330℃ to 550℃ and from 25g to 95g respectively.However, the injection volume is set at 10cc (correspond to 95g of the metal alloy) in the standard case , because upper whole region from the photo sensor is just filled with uniform metal-water corse mixture in this case. The trigger pulse travels in the water from a pair of arc electrodes to the photo sensor and then penetrates into the corse mixing two-phase region. The injection rate is kept at 40 cc/sec by control of the spring strength and the pressure at the piston A. This value is correspond to 1.4 m/s of the metal injection velocity at the outlet of the nozzle. A jet of the molten metal is injected into the water in the many droplets and fallen down through the water with uniform dispersion. When the front of the mixing region comes across the photo beam, a triggering pressure pulse is generated. When the drops are dispersed uniformly in the water column, volumetric percentage of the metal is estimated about 1%. The transient phenomena of the metal -water interaction in the mixing region was observed through the window by a high speed movie camera.

EXPERIMENTAL RESULTS

A. Pressure Behaviors and Observation During Metal-Water Interaction

Behaviors of the trigger pulse at the 3 locations of PT1, PT2 and PT3 when it propagates in the water column is shown in Fig. 4. In the water without any vapor bubble, the pulses travels without significant attenuation in the tube. However, it is much attenuated during travelling through two-phase mixing region of hot metal droplets with vapor blanket and water as shown in the following figures.

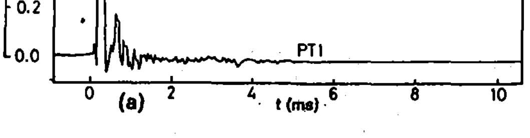

Fig. 4 Propagation of a trigger pulse in the water column

According to detail observation by a high speed camera in the injection experiment, the molten metal is disintegrated into small drops which average diameteris about 5 mm and dispersed into the water. The falling velocity of the drops in the water is almost the same value as the injection velocity due to balance of gravitaional force with resistance force.

The high speed movies and the corresponding pressure behaviors at three points along the test duct are shown in the Figs. 5 and 6.

In the case that the vapor explosion is not caused, the pressures at PT2 and PT3 of the mixing region have mild rise and rather long duration time as shown in the Fig. 5. The metal drops mixture with vapor film falls down without any change of the mixing mode. The light beam can transmit through the corse mixture. The generative pressure is rather small.

On the other hands, in the case that the vapor explosion takes place, the light beam becomes not to be transmitted through the interaction region after 3ms due to fine fragmented particles and their dispersion.
In this case, the pressures with a sharp rise but different duration time from the trigger pulse are obtained (Fig.7) The pressure travels without significant attenuation in the two-phase mixing region from PT2 to PT3. At the same time , an explosive sound is detected. It is considered that these aspects denotes generation of the vapor explosion.

B. Criteria of Vapor Explosion

According to single drop test, generation of vapor explosion is influenced by the several parameters of the temperatures of hot and cold fluids and system pressure. The experiment was done in the water of the subcooling 70K at atmospheric pressure which is the most suitable temperature to cause the vapor explosion.

Figure 7 shows the generating conditions of vapor explosion about various hot liquid temperatures and magnitudes of the trigger pulse. The "spattering" means that the hot molten metal is spattered on the surface when it contacted with the water. Generation of vapor explosion is probability process. However, it is plausible that it has some criteria for the hot metal temperature and the magnitude of trigger pulse. In the figure, T_I and T_{HN} indicate the interface temperature at the metal-water direct contact and the homogeneous nucleation temperature of water respectively . It is plausible that the temperature criteria of the vapor explosion is that the interface temperature is over the homogeneous temperature of water.

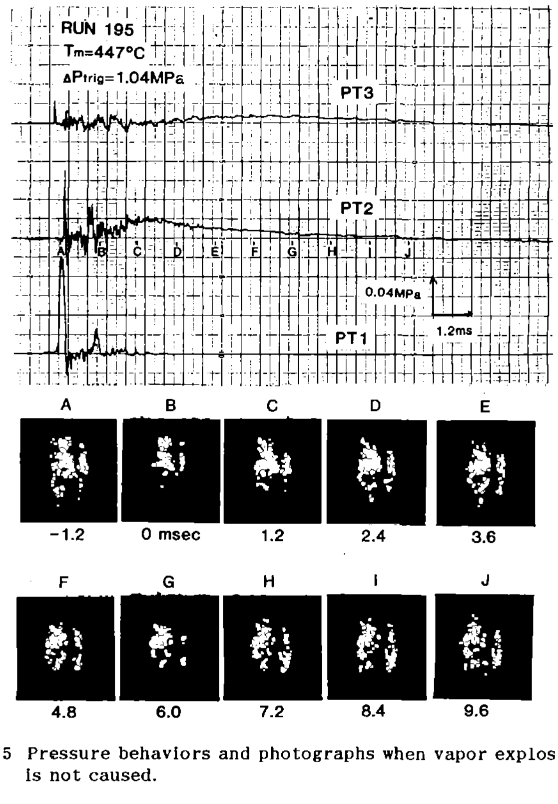

Fig.5 Pressure behaviors and photographs when vapor explosion is not caused.

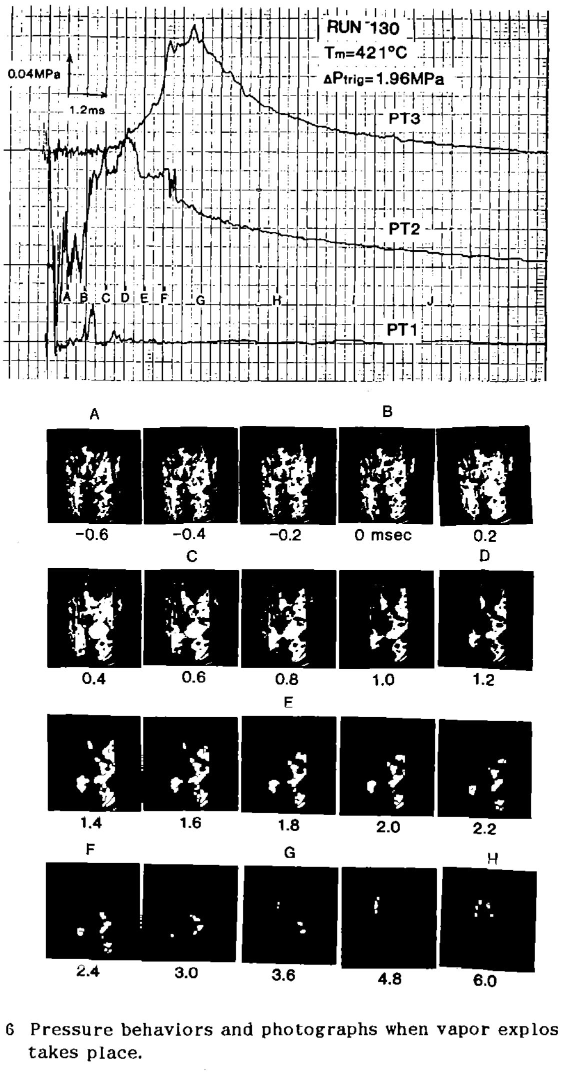

Fig. 6 Pressure behaviors and photographs when vapor explosion takes place.

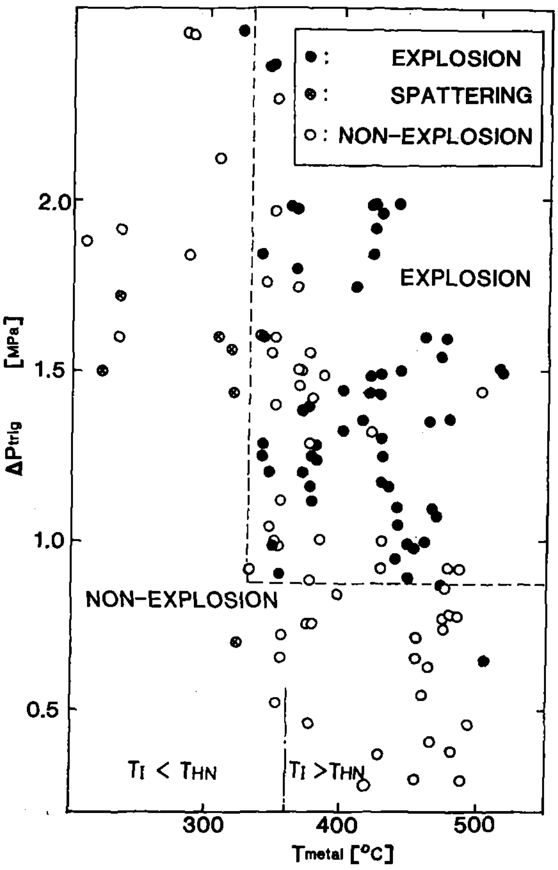

Fig. 7 Criteria of trigger pressure and metal temperature to cause vapor explosion

For magnitude of the triggering pressure, the criteria is about 0.9 MPa, where △Prig denotes over pressure. It is considered that the pressure criteria means necessary condition of metal-liquid direct contact. In the higher triggering pressure more than this value, the vapor film is perfectly collapsed and direct contact of both liquids is taken place.

According to our previous study about transient film boiling on the platinum foil under a shock pressure, it need more than 0.55MPa to collapse the vapor film under these conditions [15]. The initial wall temperature is not sensitive for the collapse of vapor film. The criteria of the triggering pressure in this experiment is a little larger than this value. It may be considered that the triggering pressure decreases about 10% in the water region before it reaches the mixing region. If vapor bubbles are mixed in the region, the pressure pulse is much attenuated in the region.

C. Peak Pressure Caused by Vapor Explosion

1. Effect of trigger pressure

As mentioned above, magnitude of the trigger pulse affects to the collapse of vapor film and fragmentation rate of the liquid metal drop. More stronger pulse promotes collapse of the vapor film and fragmentation of the hot metal drop. These effects enhances the generating pressure due to higher heat transfer rate from hot metal to water. Relations between the measured over pressures at PT2 and PT3 and the magnitude of trigger pulse are shown in Fig.8(a) and (b). Though the data disperse in wide range, it seems that the stronger trigger pulse generates larger pressure at the vapor explosion . Generally the pressure pulse especially sharp rise pulse decreases in the two-phase region as indicated in the Fig.6(b). However, the peak pressures (a) and (b) at PT2 and PT3 respectively keep the same pressure values with each other. It is clear from these figures that the peak pressures in the vapor explosion are kept constant through the interaction zone.

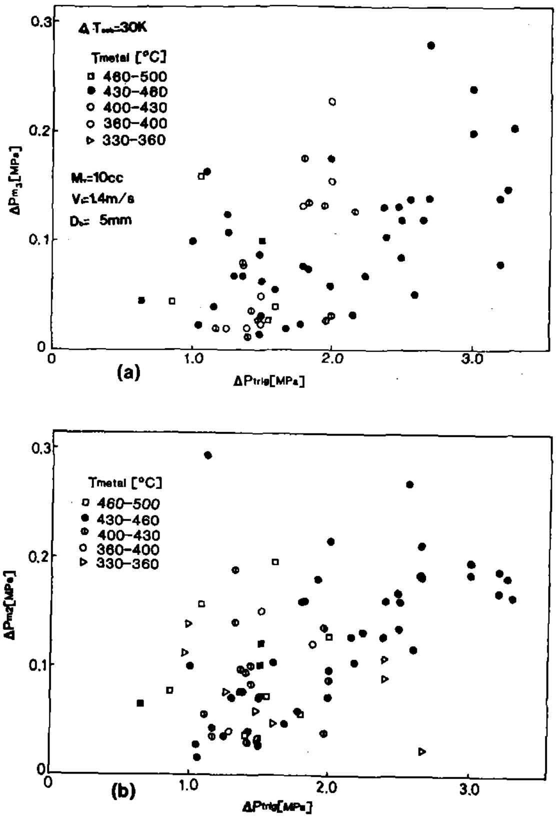

Fig. 8 Relation between generated peak pressure and trigger pressure at (a)PT2 ,(b) PT3.

2. Effect of initial metal temperature

Relations between the peak pressures and the initial temperature of the hot metal are shown in the Figure 9(a) and (b). Though it may look that the maximum pressure appears at near 470 ℃ , as a whole, the initial metal temperature is not sensitive to the peak pressure at the vapor explosion.

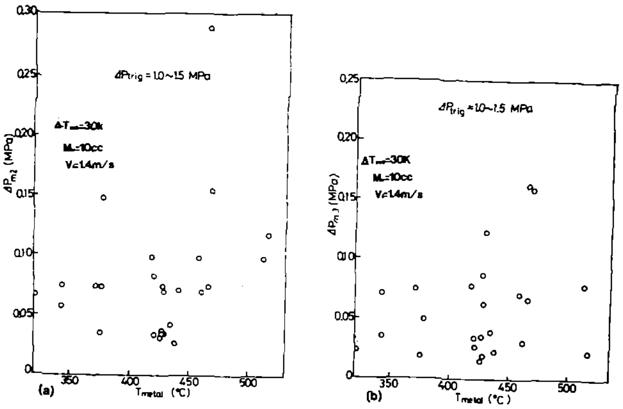

Fig. 9 Relation between generated peak pressure *and metal temperature at (a)PT2 ,(b) PT3.*

3. Effect of metal injection volume(mass)

Figure 10 indicates the effect of metal injection volume on the peak pressure . The pressure slightly increases with the injection volume . When the injection volume of liquid metal is less than 10cc , the peak pressures at PT3 are much less than those at PT2. When the injection volume is more than 10cc, metal-water mixture region occupies a whole region from the photo sensor position till upper free surface of water as shown in Fig.11. However, When the volume is less then 7.5cc, the mixture region becomes shorter and the upper region is occupied by vapor bubble water mixture. The pressure with sharp peak decays violently in the vapor water mixture zone.

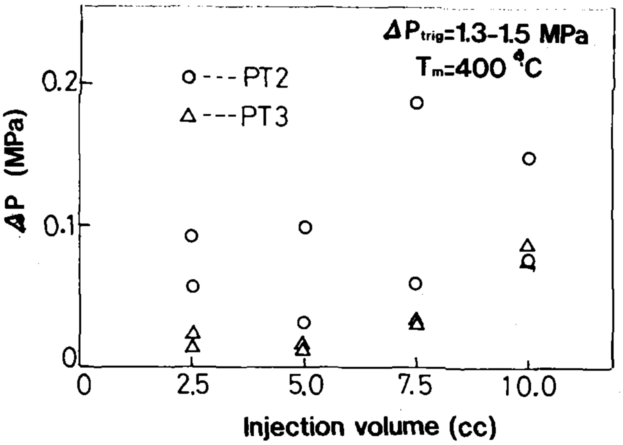

Fig. 10 Relation between generated peak pressure and injection volume of metal.

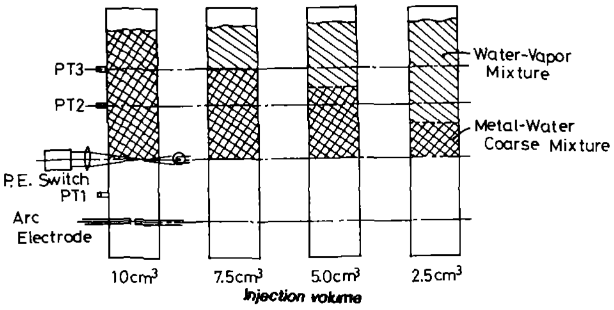

Fig. 11 Distribution of metal-water mixture and injection volume.

D. Characteristics of Propagation Pressure in Mixing Region.

When the vapor explosion is taken place, two kinds of propagation modes are clearly observed in the corse mixture region. In the followings, the characteristics of these propagation modes are investigated.

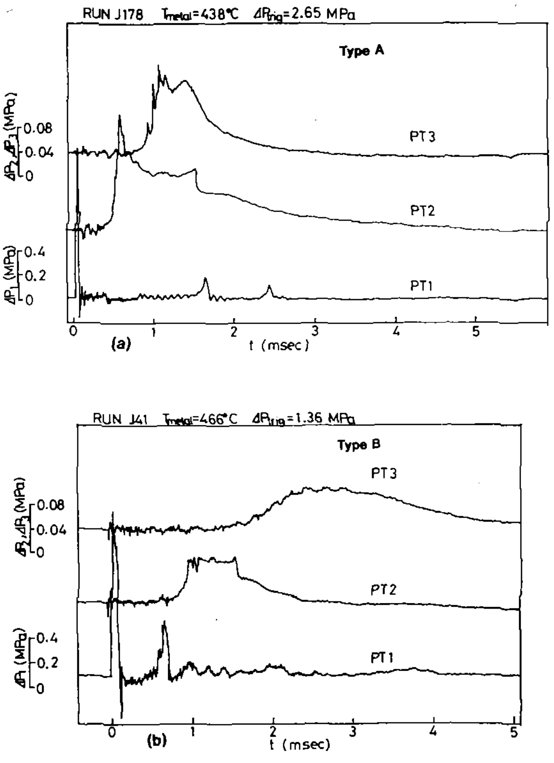

Fig.12 Pressure behaviors when (a) detonation pressure travels (b) detonation pressure disappears between PT2 and PT3.

These characteristics are shown in the Fig.13, where τ_i is the duration time of the over pressure at PTi. The type A is almost discriminated from the type B by both ratios of I_3/I_2 and τ_3/τ_2. When both ratios are nearly or less than unity, the pressure propagation mode is detonative, that is, the type A. However, when they become larger than unity, the propagation mode becomes mild, that is, the type B. This means that a mechanical work by the mild rise pressure at PT3 is generally larger than that by a sharp rise pressure due to longer duration time period. The relation between the ratio of I3/I2, and the trigger pressure, ΔP_{trig}, is shown in the Fig. 14. The type A appears almost when the trigger pressure becomes more than 2MPa. At the smaller trigger pressure, the propagation mode changes to the type B. When the vapor explosions are observed, the measured pressure at PT2 are always detonative with a sharp rise time.

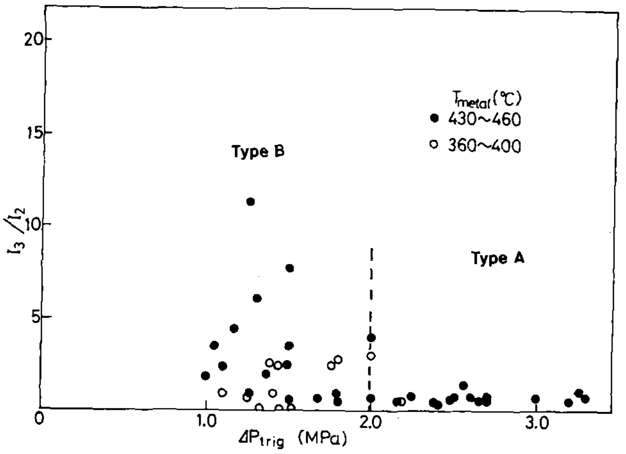

Fig. 14 Relation between I3/I2 and magnitude of trigger pulse

Finally it made clear that the ratios of I3/I2 have good correlations with the I2 as shown in the Fig.15. When I2 is large enough, that is, large momentum is given to the mixture at the PT2, the propagation mode becomes detonative.

DISCUSSIONS

According to the previous study for the transient film boiling on the platinum foil under a shock pressure[15], the collapse of vapor film was taken place at the higher shock pressure than 0.55MPa. The criteria did not sensitive initial wall temperature when its contact temperature at direct solid-liquid contact was higher than the critical temperature of water.

In this experiment, generation of the vapor explosion was occurred when the trigger pulse is higher than 0.9MPa. However, considering the decay of the trigger pulse in the water from PT1

Two typical behaviors of the propagation pressure are shown in Fig.12(a) and (b) respectively. One is the pressure behaviors with shape rise time at both PT2 and PT3 along the duct as shown in the figure (a). The shape rise of the pressure pulse is likely with the detonation wave. The other shown in the figure (b), where the sharp rise pressure pulse is observed at PT2 but it change to the pressure wave with slow rise time but longer duration time at PT3. The interesting point in this type is that value of the peak pressure at PT3 do not decay so much compared with that at the PT2. The pressure propagation in the type means the change from the propagation of the detonation wave to the normal one. The former is named type A and the latter type B respectively. The propagation velocity of the pressure front is about 250m/s in the type A but about 130m/s in the type B respectively.

To investigate the difference of two types, the following parameter, Ii is examined.

$$I_i = \int_0^{\infty} (P_i(t) - P_i(0))\, dt$$

This parameter means the momentum change acted on the stationary fluid in the test duct. In this experiment, the generated mechanical energy can not be measured but Ii is the parameter related to the fluid mechanical energy too. The i denotes the value at PTi position.

Due to the pressure propagation behaviors that the peak pressure at the PT3 do not decay so much compared with that at the PT2 and has longer duration time in the type B compared with type A, I3 becomes generally larger than I2 for the type B but almost same value for the type A.

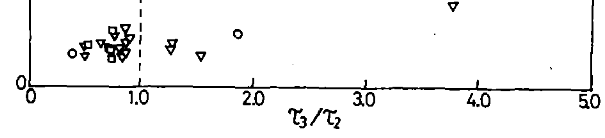

Fig. 13 Ratios of pressure time integration, I3/I2, and pressure duration time, τ_3/τ_2, at PT3 to PT2.

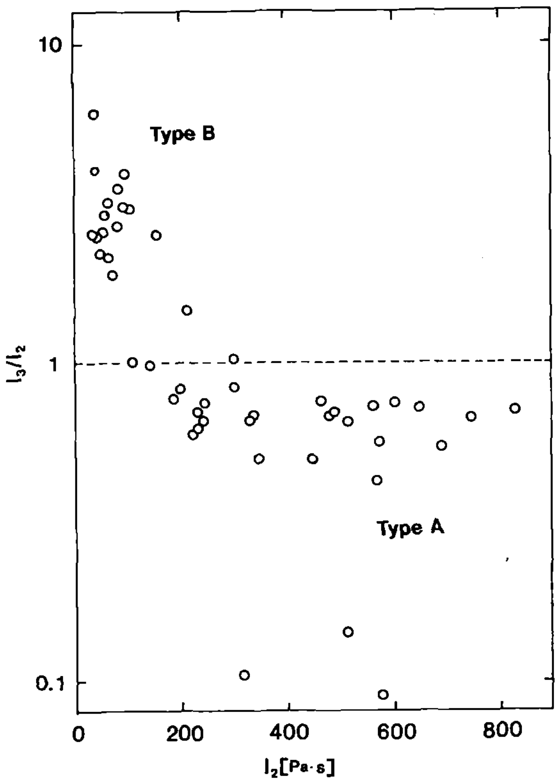

Fig. 15 Relation between I3/I2 and I2

to PT2 which is estimated about 10% and difference of inertia force at the collapse which is influenced by the shape of the initial liquid metal, the measured criteria to cause the vapor explosion means the triggering pressure to be needed to collapse perfectly the vapor film and then to cause the liquid-liquid direct contact.

In the condition that the pressure pulse is higher than the criteria, the vapor explosion is caused at the front of the corse mixture region and the detonative pressure pulse is propagated inward the mixture zone. However, in the mixing region, as the decay rate of shock pressure is significant due to two-phase mixture, the large trigger pulse is necessary to keep the detonative interaction throughout the mixing region and then forces to generate enough large detonative pressure at the front of the mixing region.

At the lower trigger pulse , the detonation pulse at the front of the mixing region changes to a mild pressure pulse during propagation in the mixture region. These characteristics of the propagation pressure have already discussed by the detonation analysis in the previous studies [16]. Therefore, this study means one of an experimental verification of the thermal detonation theory.

However, the big difference from the analysis results due to the detonation theory is that the detonative propagation mode is caused by much weaker trigger pulse about 2MPa. It looks that this value is almost one order smaller than that obtained by the steady state detonation analysis. However, Burger et.al.[17] was reported that they obtained about 5MPa of the detonation pressure in the experiment which 7.5Kg tin at 1350K in the vertical shock tube filled with water and the peak pressure is good agreement with the transient analysis code.

Another significant result obtained in this study is that total generated mechanical work during the interaction will become larger for the mild pressure propagation mode of the type B, because I3 becomes much larger than I2 for the type B. That is, the mild pressure propagation mode has to be concerned for the safety point of view as well as the detonative mode with a sharp rise time.

CONCLUSIONS

In this experiment, one dimensional corse mixture state of hot metal drops and water is investigated in a vertical shock tube by a special injector of hot metal and obtained following results.

1) Whether the vapor explosion is occurred or not, was able to be discriminated by the pressure behaviors and the observation of high speed movie.
2) Generation probability of the vapor explosion highly jumps when the interface temperature at the liquid-liquid direct contact becomes higher than the homogeneous nucleation temperature of water and the trigger pulse is higher than 0.9 MPa.
3) When the trigger pressure pulse increases, the pressure generated by the vapor explosion increases.
4) When a vapor explosion is caused at the front of the mixture region, two types of pressure propagation mode are observed. One is a detonative pressure propagation with a sharp rise. This mode is occurred when the initial trigger pulse is larger than about 2MPa. In the another type, the detonative pressure at the front of the mixture region changes to a mild pressure pulse as it propagates through the mixing region. This mode is occurred in the condition that the trigger pulse is lower than 2MPa.
5) These characteristics of the propagation pressure in the mixture region may offers the experimental verification of the thermal detonation theory, through the trigger pulse to cause the detonative interaction is one order lower than analytical result.

6) Generative mechanical work by another mode with the mild pressure pulse surpasses those in detonative mode due to the longer duration time of elevated pressure. Therefore, this propagation mode will be important for the safety view point as well as the detonation wave.

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