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A study on the effect of non-condensible gas in the vapor film on vapor explosion

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Abstract—The effect of the non-condensible gas contained in the vapor film during vapor explosion is investigated. Vapor explosion, on a small scale, is initiated by dropping a globule of molten tin into water. Quite different phenomena are observed when the space above the pool of water is filled with steam instead of an air–steam mixture, indicating that the non-condensible gas mixed in the vapor film affects vapor explosion greatly and makes the process stochastic.

INTRODUCTION

VAPOR explosion phenomena have been experienced in accidents in metal and paper factories for a long time. Recently this phenomenon has been investigated extensively with relation to nuclear reactor safety [1–25]. It has been recognized that the necessary conditions for a vapor explosion to occur are coarse mixing of high temperature liquid and low temperature liquid, with film boiling, followed by collapse of the vapor film at a temperature higher than the melting point of the high temperature liquid. Nevertheless no theory explains the mechanisms well enough because vapor explosions are very fast and complicated phenomena.

For example, it was reported that vapor explosions occurred stochastically even if the types of and the conditions of the high temperature liquid and the low temperature liquid were specified [8–10]. However, it is not clear whether these phenomena are stochastic essentially. According to former studies, the probability of the vapor explosion occurring increases if the vapor film, created during film boiling, condenses more rapidly. Also it has been shown experimentally that the probability of the explosion increases [11–15], the thermal interaction becomes more violent [16] and very high heat fluxes occur [17], if pressure waves are applied to the vapor film of film boiling, with the high temperature liquid drop/low temperature liquid system. Furthermore, it has been found that the temperature range in which explosions occur broaden [18] and the probability of the explosion increases [10] for experiments in which molten metal globules are dropped into thermally stratified water. Analyses of experiments [10, 19–21] have shown that more rapid condensation of the vapor film causes increased condensation pressure pulses and heat fluxes. For example, this occurs when the applied pressure wave is strong enough, when the subcooling of the low temperature liquid is large or when the thermal boundary layer in the subcooled liquid is thin.

When a high temperature drop comes into the free surface of a low temperature liquid through air, air mixes in the formed vapor film. When subcooling is large, air remains in the vapor film as no gas bubbles separate from it. This mixed air in the vapor film seems to suppress the rapid condensation of the vapor film. Buchanan and Dullforce [22], and Inoue [8] have indicated that the existence of non-condensible gas suppresses the thermal interaction, because it retards the condensation of the vapor film. Corradini [21] has considered that the non-condensible gas is generated by the oxidation of the molten metal. He found that the vapor explosion is suppressed because the pressure of the non-condensible gas within the vapor film reduced its condensation. Furthermore, Kim and Corradini [23] have analyzed vibrations of the vapor film by condensation as air mixes in the vapor film, and indicted that non-condensible gas suppresses the vibration.

Thus it is suggested that non-condensible gas in the vapor film suppresses the condensation of the vapor film, which is an essential process for the vapor explosion to occur, thus reducing the probability of the occurrence of the vapor explosion. The probability of inclusion of non-condensible gas in the vapor film is unknown. This probability is important as it may determine the chance of a vapor explosion occurring. Previously no experiment has reported the effects of non-condensible gas in the vapor film. The present authors have studied vapor explosions with and without the inclusion of non-condensible gas in the vapor film.

EXPERIMENTAL APPARATUS AND THE METHOD

A schematic of the experimental apparatus is shown in Fig. 1. Experiments were performed by dropping molten tin globules, about 1.5 g in mass and 7.4 mm in equivalent diameter, into the water. First, solid tin

NOMENCLATURE

a	thermal diffusivity [$m^2 s^{-1}$]
H	enthalpy [$J kg^{-1}$]
h	heat transfer coefficient [$W m^{-2} K^{-1}$]
M	molecular weight [$kg mol^{-1}$]
m	weight of steam [kg]
n	number of particles of fragmented tin
P	pressure [Pa]
R	gas constant [$J mol^{-1} K^{-1}$]
r	radius [m]
T	temperature [K]
ΔT_{sat}	superheat [K]
ΔT_{sub}	degree of subcooling [K]
t	time [s]
u	velocity [$m s^{-1}$]
w	weight of a fragmented tin particle [mg].

Greek symbols

α_M	condensation coefficient
α_T	accommodation coefficient
δ	vapor film thickness
δ_l	thermal boundary layer thickness in low temperature liquid
λ	thermal conductivity [$W m^{-1} K^{-1}$]
μ	dynamic viscosity [Pa s]
ρ	density [$kg m^{-3}$]
σ	surface tension at bubble interface [$N m^{-1}$].

Subscripts

air	air
b	bubble interface
g	gas in vapor film
h	high temperature drop
i	initial
l	low temperature liquid
max	maximum
min	minimum
s	surface of high temperature drop
sat	saturation
s.s.	steady state
v	vapor in vapor film
∞	infinite.

was heated in a stainless steel nozzle (2) (6 mm i.d.) in an electric heater (4) (1 kW). After the molten tin was heated up to a fixed temperature, the shutter in the nozzle was opened. Thus the molten tin dropped into the water as a droplet, causing film boiling and thermal interaction. The distance between the shutter and the water surface was about 400 mm. The container (7) (530 × 88 × 17 mm) was made of PMMA (polymethyl methacrylate). The phenomena were photographed by a high speed camera (12) or a high speed video. Pressure fluctuations were sensed by a pressure transducer (5) installed at one side of the wall of the container, and recorded with a wave memorizer.

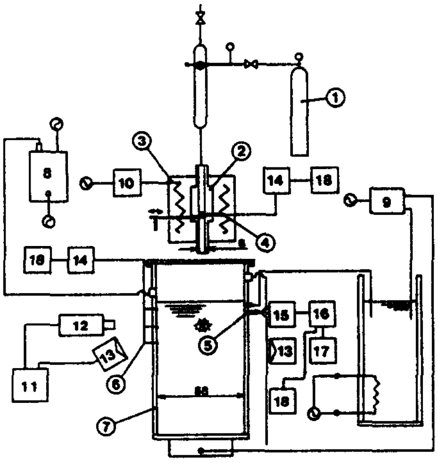

FIG. 1. Experimental apparatus: 1, Ar gas; 2, nozzle; 3, chromel–alumel (CA) thermocouple; 4, heater; 5, pressure transducer; 6, CA thermocouple; 7, water bath; 8, boiler; 9, pump; 10, temperature controller; 11, controller; 12, high speed camera; 13, stroboscope; 14, CA thermocouple; 15, amplifier; 16, wave memorizer; 17, oscilloscope; 18, pen recorder.

The space above the water surface in the container (height 21 cm) was made either an air atmosphere or steam atmosphere, and the conditions that the non-condensible gas mixed or did not mix in the vapor film were thus realized. In order to make the space over the water surface a steam atmosphere, steam was fed in from the side of the container above the water surface, and the surplus steam flowed out from the opposite side. When the molten tin was dropped, a cover on the container was opened. In order to prevent air from flowing into the container at this time, excess steam was applied to the space above the surface. In order to prevent the water temperature rising due to the condensation, water from a constant temperature bath was fed in from the bottom of the container, and the surplus water flowed out from the side several centimeters below the surface. Thus the temperature at the water surface was about the saturation temperature at atmospheric pressure, but the thickness of the thermal boundary layer was several millimeters. It was confirmed that the water temperature around the depth at which thermal interaction occurred was uniform, by measurements with thermocouples installed at three positions in the vertical direction. The initial temperatures of the molten tin drops, T_h, were 400, 600, 800°C, and the water temperatures, T_l, were 20, 40, 60°C.

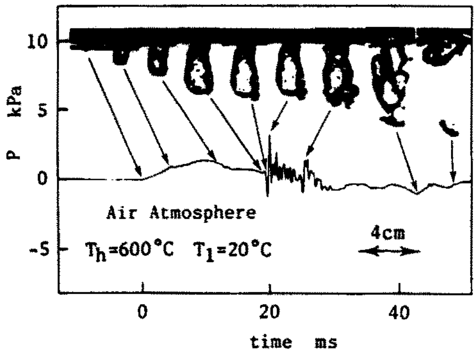

FIG. 2. Typical aspects of thermal interaction (a) (atmosphere above the water surface is air).

EXPERIMENTAL RESULTS

Typical aspects of phenomena and pressure fluctuations

Figure 2 shows typical aspects of the thermal interaction in the air atmosphere and the resulting pressure fluctuations. A molten tin drop comes into contact with the water surface (0 ms), where film boiling occurs. After that rapid evaporation is observed at 20 ms (at the bottom right-hand side of the vapor film), at 21 ms (same position) and at 25.5 ms (at the bottom of the vapor film). However, the pressure generated is weak compared to the case of the steam atmosphere as mentioned later. Further it is clear that fragmentation at these times is partial, due to the appearance of a lump of tin after the bubble departs, and the shape and size of the fragmented tin as mentioned later. A departure of the bubble is not observed before fragmentation for this experimental condition, therefore it seems that much air mixes in the vapor film when fragmentation occurs.

Figure 3 shows typical aspects of thermal interaction in the steam atmosphere and pressure fluctuations at this time. A molten tin drop comes into contact with the water surface (−3 ms), upon which film boiling occurs. But the film boiling differs from the case of the air atmosphere remarkably. It is recognized that the effect of atmosphere on film boiling around a molten tin drop is not negligible. Such a difference appears in the thermal interaction later. After the first pressure peak at 0 ms the steam bubble repeatedly expands and contracts corresponding to the pressure fluctuations. The pressure peak reaches a maximum after several fluctuations [24, 25] (the fourth fluctuation in this example). Further the maximum pressure is one order of magnitude greater than that for the case of an air atmosphere.

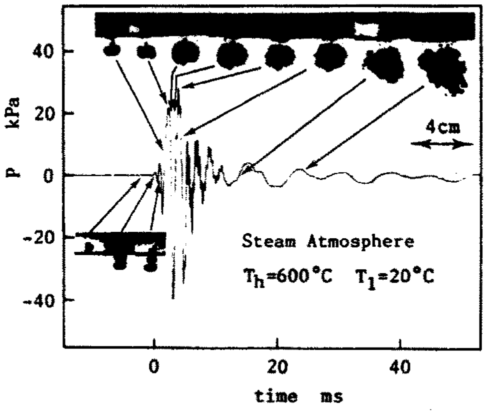

FIG. 3. Typical aspects of thermal interaction (b) (atmosphere above the water surface is steam).

Generated pressure

Figure 4 shows the maximum values of the generated pressure, P_{max}, due to thermal interaction. The number of trials where the pressure fluctuation is less than the trigger level of the wave memorizer, used to measure the pressure fluctuation, is indicated below the temperature axis in Fig. 4. From Fig. 4 it is seen that P_{max} can vary by more than one order of magnitude. In general P_{max} with an air atmosphere is less than that for a steam atmosphere. Therefore, it seems evident that the non-condensible gas in the vapor film suppresses the pressure pulse. Further, as can be seen clearly in the case of $T_h = 800°C$ and $T_l = 40°C$, the spread of P_{max} for an air atmosphere is much greater than that for a steam atmosphere. This shows that the thermal interaction with an air atmosphere is less consistent than the one with a steam atmosphere. At $T_l = 80°C$ no fragmentation nor pressure peak is observed, in either atmosphere, confirming former studies [9, 10].

Fragmentation

Figure 5 shows photographs of the fragmented tin, and Fig. 6 shows the weight distribution of the fragmented particles. As mentioned above, in the air atmosphere, only part of the tin drop (10 wt%) fragments. On the other hand, in steam atmosphere, the whole of the tin drop fragments to several 10 mg pieces, further 38 wt% of the tin fragments to finer than 1 mg. Furthermore, those particles the weight of which are comparatively great are formed by chains of smaller particles. Consequently it is certain that non-condensible gas in the vapor film suppresses fragmentation. Besides, in a steam atmosphere, tin fragments comparatively well, even if P_{max} is less than 1 kPa as shown in Fig. 4. Therefore, in a steam atmosphere, the uniformity of fragmentation by thermal interaction is likely to increase compared to an air atmosphere. That is to say, non-condensible gas in the vapor film suppresses the occurrence of the vapor explosion and production of uniform fragments. This seems to be a reason why the vapor explosion appeared to be a stochastic phenomenon in former studies.

MODEL CALCULATION

Model

As mentioned, many model calculations consider the generated pressure pulse from the vapor explosion

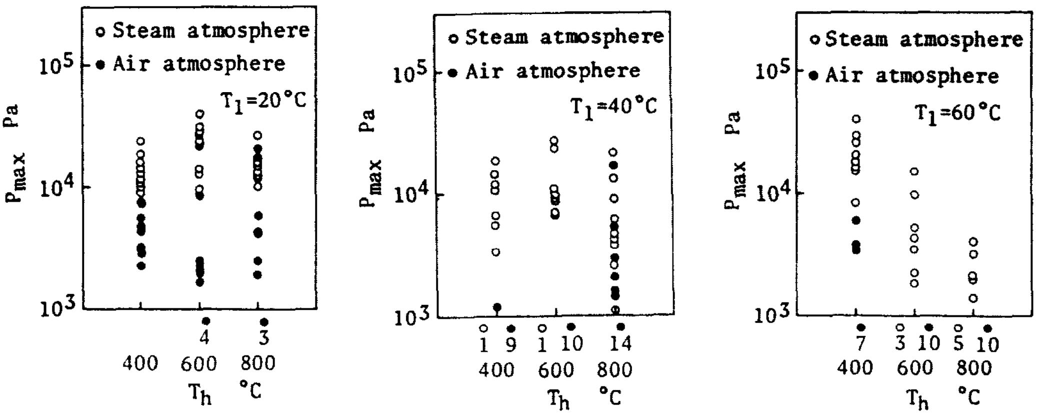

FIG. 4. Peak pressure generated by thermal interaction.

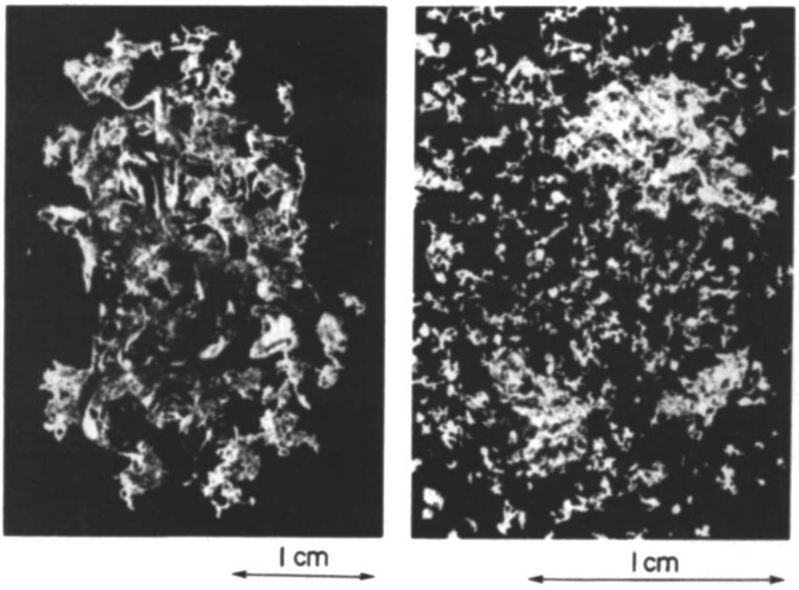

FIG. 5. Photographs of fragmented tin.

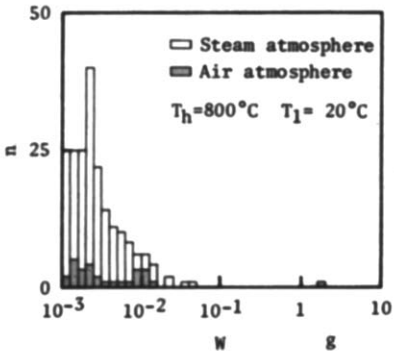

FIG. 6. Distribution of weight of fragmented particles.

to be the condensation pulse. Here the same model is used for the case when a mixed gas of low temperature liquid (water) vapor and non-condensible gas (air) occurs in the vapor film. Figure 7 shows the model.

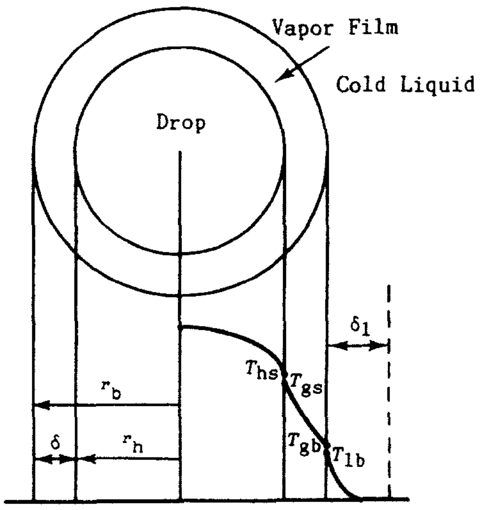

FIG. 7. Model for calculation.

There is an equilibrium bubble in the spherical symmetric system, and no body forces are assumed to exist. The liquid phase is assumed to be infinite and incompressible. In the gas phase, the heat capacity and the viscosity are neglected, and the thermal conductivity is assumed uniform. When the surrounding liquid is suddenly subcooled, the following equations are valid for this system. First, the equation of motion of the bubble interface is

$$r_b \frac{du_{lb}}{dt} + \frac{3}{2} u_{lb}^2 + \frac{u_{lb}}{4\pi r_b^2 \rho_l} \frac{dm}{dt} = \frac{P_{lb} - P_{l\infty}}{\rho_l}. \quad (1)$$

The equation of continuity concerning the velocity at the bubble interface is

$$u_{lb} = \frac{dr_b}{dt} - \frac{1}{4\pi r_b^2 \rho_l} \frac{dm}{dt}. \quad (2)$$

The heat conduction equation in a high temperature drop is

$$\frac{\partial T_h}{\partial t} = \alpha_l \left[\frac{\partial^2 T_h}{\partial r^2} + \frac{2}{r} \frac{\partial T_h}{\partial r} \right]. \quad (3)$$

The heat conduction equation in the low temperature liquid is

$$\frac{\partial T_l}{\partial t} = \alpha_l \left[\frac{\partial^2 T_l}{\partial r^2} + \frac{2}{r} \frac{\partial T_l}{\partial r} \right] + \frac{(r^2 - r_b^2) u_{lb}}{r^2} \frac{\partial T_l}{\partial r}. \quad (4)$$

The boundary condition concerned with the pressure at the bubble interface is

$$P_{lb} = P_g \frac{2\sigma}{r_b} - \frac{4\mu u_{lb}}{r_b} + \left[\frac{1}{4\pi r_b^2} \frac{dm}{dt} \right]^2 \left[\frac{1}{\rho_{gb}} - \frac{1}{\rho_l} \right] \quad (5)$$

where it is assumed that $P_{l\infty} = 1$ atm.

The rate of mass transfer at the bubble interface [26] is given by

$$\frac{dm}{dt} = \frac{2\alpha_M}{2 - \alpha_M} \frac{1}{\sqrt{(2\pi R/M_V)}} \left[\frac{P_{sat}}{\sqrt{T_{lb}}} - \frac{P_V}{\sqrt{T_{gb}}} \right]. \quad (6)$$

At the surface of a high temperature drop

$$-\lambda_h \frac{\partial T_h}{\partial r}\bigg|_s = -\lambda_g \frac{\partial T_g}{\partial r}\bigg|_s. \quad (7)$$

The temperature jump at the surface [27] of a high temperature drop is

$$T_{gs} - T_{hs} = \frac{2 - 0\ 827\alpha_T}{4\alpha_T} \left[\frac{2\pi}{(R/M_g)^3 T_{hs}} \right]^{1/2} \frac{\lambda_g}{\rho_{gs}} \frac{\partial T_g}{\partial r}\bigg|_s. \quad (8)$$

The temperature gradient in the vapor film is given by

$$r_h^2 \lambda_g \frac{\partial T_g}{\partial r}\bigg|_s = r_b^2 \lambda_g \frac{\partial T_g}{\partial r}\bigg|_b = r_b r_h \lambda_g \frac{T_{gb} - T_{gs}}{r_b - r_h}. \quad (9)$$

The temperature jump at the bubble interface is given by

$$T_{lb} - T_{gb} = \frac{2 - 0.827\alpha_T}{4\alpha_T} \left[\frac{2\pi}{(R/M_g)^3 T_{lb}} \right]^{1/2} \frac{\lambda_g}{\rho_{gb}} \frac{\partial T_g}{\partial r}\bigg|_b. \quad (10)$$

At the bubble interface

$$-\lambda_g \frac{\partial T_g}{\partial r}\bigg|_b = -\lambda_l \frac{\partial T_g}{\partial r}\bigg|_b + \frac{1}{H_{vb} - H_{lb}} \frac{1}{4\pi r_b} \frac{dm}{dt}. \quad (11)$$

Outside the thermal boundary layer in the low temperature liquid

$$T_l = T_{l\infty} \quad (\text{at } r = r_b + \delta_l). \quad (12)$$

The thickness of the thermal boundary layer, δ_l, is defined as [10]

$$\delta_l = c\delta_{ls.s.} (0 < c \leqslant 1) \quad (13)$$

$c = 0.5$ in this calculation, where $\delta_{ls.s.}$ is the thickness of the steady-state thermal boundary layer

$$h \Delta T_{sat} = \lambda_l \frac{\Delta T_{sub}}{\delta_{ls.s.}}. \quad (14)$$

The heat transfer coefficient of film boiling, h, is obtained from the equation of ref. [28] for water.

As initial conditions, it is assumed that the velocity, the acceleration and the evaporation rate at the bubble interface are zero, the temperature in the high temperature drop is uniform, and the temperature in the thermal boundary layer in the low temperature liquid is a linear function of radius.

About physical properties

It was assumed that the high temperature liquid was molten tin, and the low temperature liquid was water. For the physical properties of both water and steam, the library program in the University of Tokyo Computer Center, STMTLK, based on the steam table [29] was used. Air was assumed to be an ideal gas, and for the thermophysical properties of air, *JSME Data Book*: *Thermophysical Properties of Fluids* [30] was referred to. For the steam–air mixture, Dalton's law was assumed to be applicable and the thermal conductivity was obtained by the method of *JSME Data Book*: *Heat Transfer* [31]. Further, the accommodation coefficients α_T and α_M were assumed to be unity.

Calculation results

Figure 8 shows the effects of the initial partial pressure of the air in the vapor film $(P_{air}/P_g)_i$ on P_{max} and δ_{min}. Initial conditions are assumed to be $T_h = 600$°C, $T_l = 60$°C, $\delta_i = 100$ μm. When $(P_{air}/P_g)_i$ is small, P_{max} is great and δ_{min} is small. This is due to the air in the vapor film suppressing the condensation at the bubble interface. Further, if $(P_{air}/P_g)_i$ is less than about 1%, the pressure fluctuation is the same as for the case where the air is not mixed.

It is noticed that the maximum pressures predicted in this calculation are a few orders of magnitude

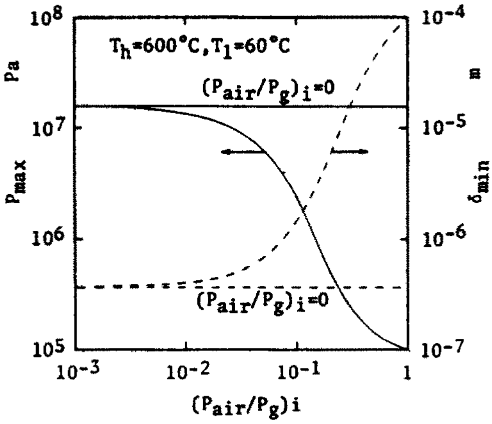

FIG. 8. Effects of initial partial pressure of air in vapor film on peak pressure and minimum thickness of vapor film.

greater than those obtained experimentally. The main reason for such a difference is as follows. An assumption made in the calculation is that most of the heat is transferred from the molten metal globule to the surrounding water only while the vapor film is thin. Actually the process of heat transfer takes a longer time, which reduces the peak value of the generated pressure. However, the tendency that the amount of air mixed in the steam influences the maximum pressure is evident from this calculation.

CONCLUSION

Experiments have been performed to determine the effects of non-condensible gas in the vapor film on the thermal interaction of the molten tin drop/water system. Non-condensible gas in the vapor film suppresses the occurrence of the vapor explosion and reduces the uniformity of the fragments. This seems to explain why vapor explosions are considered to be stochastic phenomena in former studies. Further it is shown by a theoretical model that if non-condensible gas is included in the vapor film the maximum pressure generated is reduced.

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ETUDE DE L'EFFET, SUR L'EXPLOSION DE VAPEUR, D'UN GAZ INCONDENSABLE DANS LE FILM DE VAPEUR

Résumé—On étudie l'effet d'un gaz incondensable, contenu dans un film de vapeur, pendant l'explosion de vapeur. Celle-ci, à petite échelle, est initiée en plongeant un globule d'étain fondu dans la vapeur. Des phénomènes très différents sont observés lorsque l'espace au dessus du bain d'eau est rempli de vapeur d'eau au lieu du mélange air–vapeur d'eau, ce qui indique que le gaz incondensable mêlé au film de vapeur affecte fortement l'explosion de la vapeur et rend le mécanisme stochastique.

UNTERSUCHUNG DES EINFLUSSES VON NICHT-KONDENSIERBAREM GAS IM DAMPFFILM AUF EINE DAMPFEXPLOSION

Zusammenfassung—Es wird der Einfluß von nicht-kondensierbarem Gas, das sich bei einer Dampfexplosion im Dampffilm befindet, untersucht. Ein Tropfen flüssigen Zinns, der ins Wasser fällt, erzeugt eine kleine Dampfexplosion. Andersartige Phänomene treten auf, wenn der Raum über dem Wasser mit Dampf anstatt mit einem Luft/Dampf-Gemisch gefüllt ist. Das nicht-kondensierbare Gas im Dampffilm spielt daher bei Dampfexplosionen eine große Rolle und macht den Prozeß stochastisch.

ИССЛЕДОВАНИЕ ВЛИЯНИЯ НЕКОНДЕНСИРУЮЩЕГОСЯ ГАЗА В ПАРОВОЙ ПЛЕНКЕ НА ПАРОВОЙ ВЗРЫВ

Аннотация—Исследуется эффект неконденсирующегося газа, содержащегося в паровой пленке, при паровом взрыве. Паровой взрыв малого масштаба вызывался опусканием в воду шарика расплавленного олова. При заполнении пространства над объемом воды паром, а не воздушно-паровой смесью, наблюдаются принципиально отличные явления, свидетельствующие о том, что неконденсирующийся газ в паровой пленке оказывает значительное влияние на паровой взрыв и делает процесс стохастическим.