Available online at www.sciencedirect.com
ScienceDirect

NUCLEAR SCIENCE AND TECHNIQUES

Nuclear Science and Techniques, Vol.18, No.6 (2007) 376–380

Experimental investigation on the bursting of single molten droplet in coolant

LI Tianshu* YANG Yanhua YUAN Minghao HU Zhihua

(School of Mechanical Power Engineering, Shanghai Jiaotong University, Shanghai 200030, China)

Abstract An experiment facility for observing low-temperature molten tin alloy droplet into water was established to investigate mechanisms of vapor explosion occurring in severe accidents of a fission nuclear reactor. The vapor explosion behaviors of the molten material were observed by a high-speed video camera and the vapor explosion pressures were recorded by a pressure transducer mounted under the water surface. The results showed that the pressure reached a peak value when the molten metal temperature was 600℃–650℃, and the coolant temperature had an obvious decreasing effect on the droplet breakups. A model for single droplet fuel/coolant interaction is proposed. It considers that in the case of Rayleigh-Taylor instability, the coolant that jets from opposite direction penetrates into the fuel and the vapor explosion occurs because of the rapid evaporation. This model explained the effect of metal droplet temperature and coolant temperature on vapor explosion.

Key words Vapor explosion, FCI, Observable experimental equipment

CLC number TK12

1 Introduction

A vapor explosion can occur when a hot molten metal contacts the low boiling temperature cold liquid [1]. The rapid vaporization of the coolant results in melt fragments of less than 1 mm in diameter. They transfer their heat to the coolant mush more efficiently, resulting in high-pressure vapor and worsening the situation even further [2]. Such an event is postulated to occur with severe accidents of a fission nuclear reactor, and is a subject of study by many scientists and engineers[3].

A number of experimental and theoretical works [4,5] have been performed to study the process and the explosive behavior of fuel and coolant interaction (FCI). Subsequently, a number of mechanisms for fuel fragmentation have been developed. Although a small scale FCI is not representative of real scale situations [6], experimental observations [7] indicate that a small scale FCI may be the unit cell of a large scale FCI of vapor explosions.

Kim [6] has proposed a coolant jet model, in which film boiling occurs around a molten fuel droplet on entry into an infinite coolant pool. The film collapse and coolant jet formation occur due to some triggering mechanism. During the collapse and regrowth of the vapor film, the coolant vapor/liquid interface becomes unstable. These interfacial instabilities generate an array of coolant jets directed toward the fuel surface. Therefore, jet penetration and entrapment occur. Under certain conditions, the jets grow so quickly that they contact the fuel surface and even penetrate the fuel. As a result the needle-like jet penetrates, numerous tiny coolant drops are entrained in the fuel near the surface, which forms a mixture of vapor and coolant drops entrapped in the fuel. Rapid evaporation of entrained coolant occurs, causing fuel fragmentation and vapor explosion.

Supported by the National Natural Science Foundation of China (No.50376036).

* E-mail: tsli@sjtu.edu.cn

Received date: 2007-06-30

Buchanan [8] considered that because the asymmetric coolant vapor bubble around the molten fuel surface collapses so as to form a high-velocity jet that penetrates the fuel, the turbulent mixing occurs. So the rapid increase of heat transfer area leads to the vapor explosion.

Henry[9] has proposed a spontaneous nucleation model. When the coolant is heated to the spontaneous nucleation, the rapid vaporization brings about shock waves, which leads to the fuel fragmentation and vapor explosion.

The purpose of the present study is to experimentally clarify vapor explosion of the molten fuel in the coolant of a reactor vessel. In order to achieve this purpose, a simulative experimental apparatus was designed. The molten material vapor explosion was observed using a high-speed video camera. The pressure transducer on the water tank wall measured the pressure of vapor explosion. This paper studied the effect of experimental conditions, molten material temperature and coolant temperature on the behaviors and pressure of the vapor explosion.

2 Experiment

The schematic diagram of experimental apparatus is shown in Fig.1.

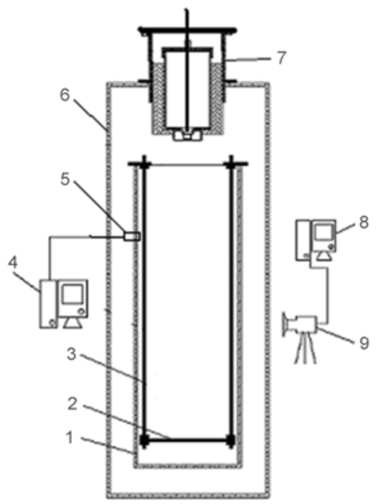


Fig.1 Schematic diagram of experimental apparatus.
1. Water tank; 2. Melt-collect board; 3. Screw bolt; 4. Computer; 5. Pressure transducer; 6. Support frame; 7. Metal-melt furnace; 8. Computer; 9. High-speed video.

It mainly consists of a furnace, a water tank, a high- speed video camera and measuring devices. A stainless steel water tank in 0.3m×0.3m×2m is used for observing the molten metal droplet. The furnace is placed on a frame, with which the distance between the furnace and water surface can be adjusted.

The front and back walls of the water tank and the framework are made of stalinite for seeing the explosion. The back stalinite is lined with scale paper. The melt-collect board reads the breakup diameter at different distance from the water surface by regulating the screw bolt. Visualization can be performed at 100 fps with the video system.

A pressure transducer is placed under water at about 10 cm, where vapor explosions take place.

Fig.2 is a schematic diagram of the furnace to melt metal and send single molten droplet into the coolant. It has a stainless-steel crucible, with a funnel of *Φ*35 mm in its bottom. Minimal diameter of the funnel cone is *Φ*5 mm to form a spherical metal droplet. The lower side of the funnel is *Φ*25 mm to keep the metal droplet from adhering to inner wall of the funnel. The distance from the funnel outlet to water surface is 3 mm, short enough to avoid collisions between the droplet and water surface. By screwing the bolt of the funnel, a molten metal droplet drops. While observing the droplet explosion in water with the camera, the pressure impulses are recorded by the transducer. Diameter distribution of the solidified fragment was measured.

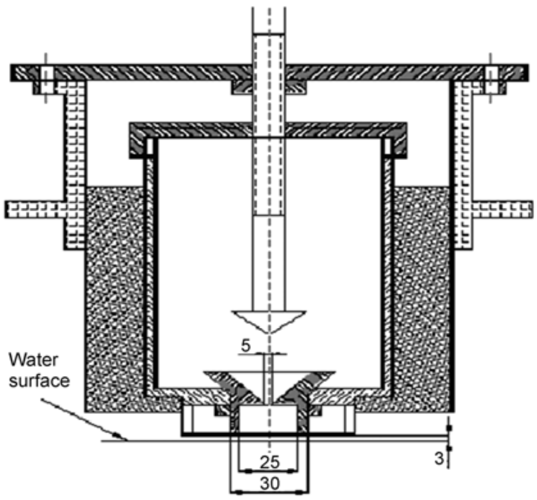


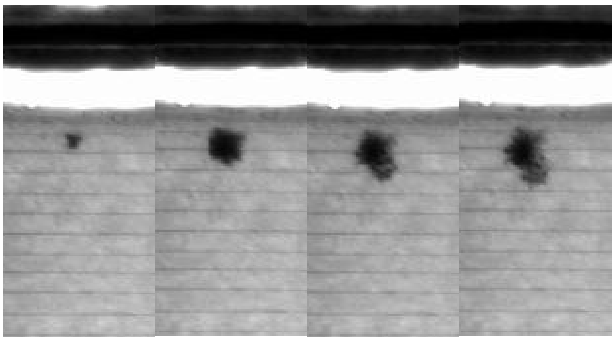
Fig.2 Schematic diagram of heating furnace for single tin droplet bursting.

In the present experiment, tin alloy $ZSnSb_8$-Cu_4 was used as the simulate material. It contains Sb (7.0%–8.0%), Cu (5.5% –6.5%), Pb (0.35%), As (0.3%), Cd (≤0.15%), Fe (0.1%), Bi (0.03%), Zn (0.01%) and Al (0.01%).

3 Experimental results

3.1 Effect of metal temperature on single droplet burst

The molten alloy droplets of 350℃, 400℃, 450℃, 500℃, 550℃, 600℃, 650℃, 700℃, 750℃ and 800℃ were dropped into room temperature (20℃) coolant. Fig.3 is the side view of a 600℃ single droplet dropping into coolant.



0s 0.0075s 0.015s 0.0225s

Fig.3 Side view of 600°C single droplet dropping into the room temperature coolant.

When the coolant was at room temperature, most droplets burst. The maximum pressure impulses recorded are shown in Fig.4.

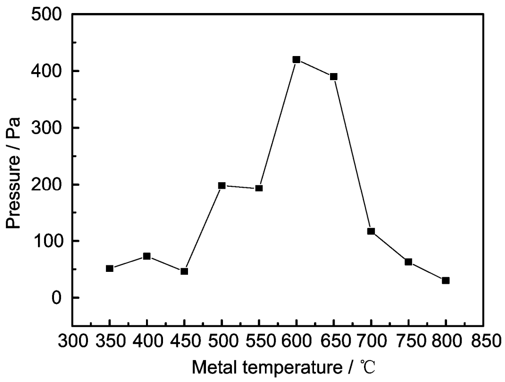


Fig.4 Maximum pressure peak at different temperatures of the tin drops into the coolant of room temperature.

The results showed that the maximal pressure pulse peak increased with the metal temperature at 350℃ to 600℃, but decreased with increasing metal temperature at 650℃ to 800℃, reaching a peak value at 600℃ to 650℃.

It is believed that the Rayleigh-Taylor instability has an important effect on the vapor explosion. When the molten tin droplet contacted with coolant surface, some coolant micro-jet could get into the molten material in liquid-phase, the coolant in molten material was heated, vaporized and vapor explosion occurred.

Behaviors of the pressure at different metal temperatures can be explained as follows. When the 350℃ molten tin droplet dropped into the water surface, the front end of droplet contacted directly with the low temperature coolant. When the metal temperature is not high, the explosion is not violent. With increasing metal temperature, the liquid in the molten metal expands fiercely and the explosion is violent accordingly. However, when the molten tin droplet temperature is above 650℃, the front end of droplet contacted with the vapor and coolant mass in the molten metal decreases. Therefore, the vapor explosion pressure peak decreases rapidly.

3.2 Effect of coolant temperature on single droplet burst

The tin alloy heated to 600℃ was dropped into coolant at 50℃, 70℃ and 90℃ respectively. When the molten metal droplet dropped into 50℃ coolant, the droplet cracked into several pieces and no burst (explosion) took place (Fig.5). When the coolant was at 70℃, only a concave was formed at the bottom of the droplet. It should be noticed that the pits were downward. This phenomenon illustrated the effect of Rayleigh- Taylor instability. With a 90℃ coolant, however, no change was observed from the side view of single droplet interaction. Only from the debris can the pit be observed.

It is believed that in a hotter coolant, more vapor was evaporated at the front of metal droplet and less liquid coolant entered the molten metal. The vapor and liquid acted jointly on the droplet. The higher the coolant temperature is, the more vapor is generated and the less effect the coolant has.

Fig.6 is the picture of the breakup debris under different temperature coolant. The tin droplet had the same diameter (5mm) before penetrating into the coolant. The debris in 90℃ water was the smallest, thickest and there were no burrs on the debris edge. The debris in 50℃ water was the biggest and thinnest. The shape became irregular. Apparently, in a lower temperature coolant, the droplet contacted more liquid, hence less vapor. With a stronger force acting on the droplet, the droplet would burst. When the coolant is hotter, the force acted weakly on the droplet; the pit on the droplet is shallow.

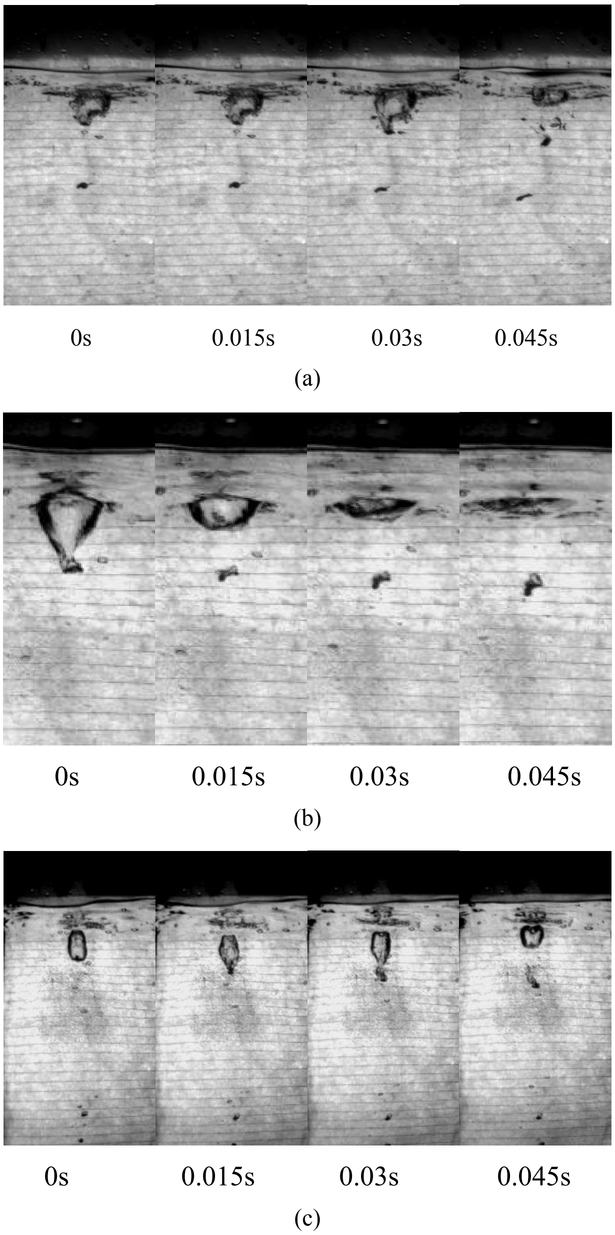


Fig.5 Side view of 600°C single droplet dropping into coolant at (a) 50℃, (b) 70℃ and (c) 90℃.

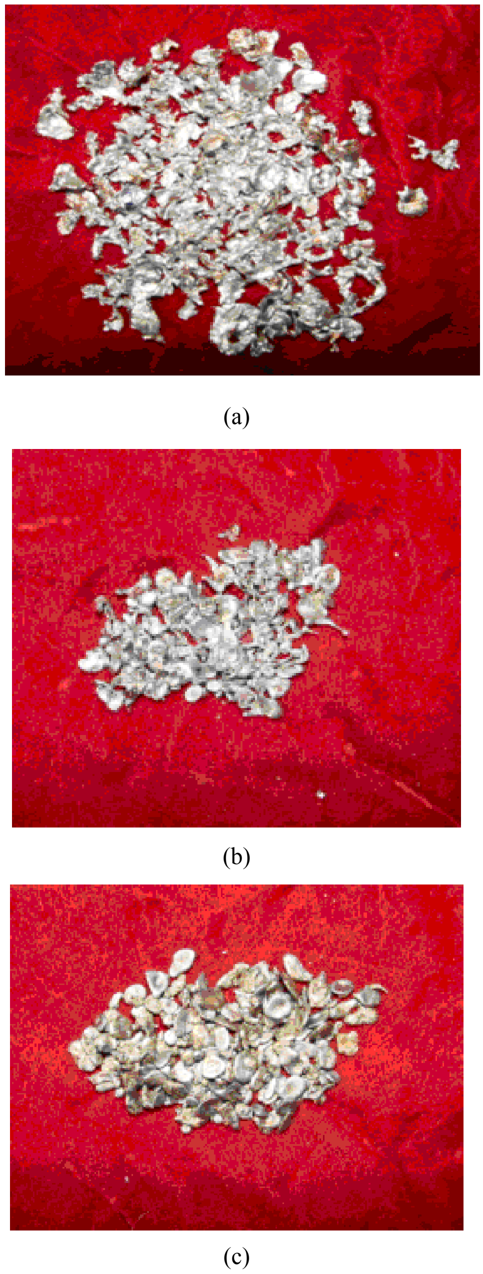


Fig.6 The breakup debris under coolant at (a)50℃, (b) 60℃ and (c) 90℃.

4 Conclusions

In the experiment, the vapor explosion behaviors of the molten material were observed using a high-speed video camera and the vapor explosion pressures were recorded by the pressure transducer. The following conclusions can be reached.

(1) The pressure of vapor explosion increases with the molten metal temperature below 600℃, but decreases with the increasing molten metal temperature above 600℃.

(2) The coolant temperature has an obvious decreasing effect on the droplet breakups.

(3) A physical mechanism that describes the process of vapor explosion was developed. In low temperature region (less than 800℃), when the molten material dropped into coolant surface, some coolant micro-jet could get into the molten material in liquid-phase in the case of the Taylor instability and the coolant in molten material was heated and vaporized. And then vapor explosion occurred.

References

1 Yang Yanhua. Multi-phase simulations for phenomena in vapor explosions, University of Tokyo, Doctoral Dissertation, 1996.

2 Theofanous T G, Yuen W W. "The prediction of dynamic loads from ex-vessel steam explosions". Proceedings of the International Conference on New Trends in Nuclear System. Thermohydraulics, Pisa, 1994. 257-270.

3 Yutaka Abea. J Nuclear Engineering and Design, 2004, **230**: 277-291.

4 Corradinietal M L. J Nuclear Safety, 1991, **32**(3): 337-362.

5 Huhtiniemi I, Magallon D. J Nuclear Engineering and Design, 2001, **204**: 391-400.

6 Kim B, Corradini M L. J Nuclear Science and Engineering, 1988, **88**: 16-28.

7 Nelson L S. "Steam explosion triggering phenomena; stainless steel and corium-E stimulants studied with a floodable arc melting apparatus" SAND77-998, NUREG/CR-0122, Sandia National Laboratories, May 1978.

8 Buchanan D J. Phys D, 1974, **7**: 1441.

9 Henry R E. Fauske H K "Nucleation characteristics in physical explosion," Proc. 3rd Specialists' Mtg. Sodium Fuel Interaction, Tokyo, Japan, March 1976.