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Experimental investigation on the moving characteristics of molten metal droplets impacting coolant

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Abstract

This paper reports the results of an experimental investigation on the moving characteristics of molten metal droplets impacting coolant free surface. A visualization experimental facility of molten fuel coolant interactions (MFCI) is designed and set up in the present study. The lead–bismuth (Pb–Bi) alloys are employed as the metal materials. An automatic control circuit is designed and applied to control the release of the molten droplets. High-speed camera is employed to record the movement of the molten metal droplets falling down and into a coolant pool. Based on the analysis of the experimental data, a so-called "J-region" of the droplet's velocity–time curves was found and the melt droplet enters the "J-region" when it impacts the free water surface. In the "J-region", the velocity of the melt droplet decreases rapidly and suddenly at first, and then increases again. The droplet gradually reaches a comparatively steady velocity when it leaves the "J-region". The present study provides essential information for further study on the fragmentation behavior of high-temperature molten droplets in coolant.

Keywords: Molten metal droplet; Coolant; MFCI; Experimental investigation

1. Introduction

Molten fuel coolant interactions (MFCIs) are an important phenomenon during hypothetical severe reactor accidents in nuclear power stations. It is also an important sub-process in the evolution of the so-called vapor explosions, as well as attracting the most concern in industrial production [1]. During the process of MFCIs, high-temperature molten droplets may impact vapor–coolant interface and interact with the coolant due to a great temperature difference between the molten droplet and the coolant of which the saturation temperature is low, and strong boiling and evaporation of the coolant may take place on the droplet–coolant contacting surface. The intensity of the coolant boiling on the molten droplet surface closely relates to not only the temperature difference between the melt droplet and the coolant but also the contact area between the high-temperature droplet and the coolant. Chemical reactions between the high-temperature metal and the coolant may even be involved as well. Under certain conditions, a large amount of vapor may be produced in a relatively short time because of the strong boiling evaporation. The volume of the vapor–water mixture may expand sharply and quickly due to the large difference in the specific volume of the vapor from that of water, and may possibly generate high-pressure shock waves and even vapor explosion. This may cause damage to nuclear reactors and surrounding buildings and finally even result in the leakage of radioactive materials to the environment.

A generally acknowledged view is that two kinds of actions exist in the process of MFCIs at the same time: the hydrodynamics interactions caused by the speed difference between the droplet and coolant, and the thermodynamics interactions caused by the droplet–coolant temperature difference [2]. On one hand, deformation, and even fragmentation, may take place in the falling

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course of molten droplet because of the speed difference between the droplet and the coolant. On the other hand, strong heat transfer takes place between the droplet and coolant due to the fact that the temperature of molten droplet is much higher than the coolant saturation temperature. The coolant then evaporates and produces a large quantity of vapor. At the same time, the melt droplet rapidly cools down and finally even solidifies. Vapor explosion took place in the Chernobyl nuclear power plant accident in the former Soviet Union because of the violent interaction between the melted reactor core and coolant, which brought serious consequences affecting the lives of the people around the accident site. The research related to molten fuel–coolant interactions has gained great attentions of both the nuclear industrial field and the nuclear reactor research institutions all over the world. Molten fuel–coolant interaction has been one of the top research focuses in order to search for effective ways to prevent or at least to alleviate the severe accidents of nuclear power stations.

In the past 20 years, interactions of high-temperature droplets/particles with coolant have been studied in lots of experiments, which can be divided into two categories according to the quantities of droplets/particles used in the experiments:

(1) *Large-scale experiments* performed with the metal mass even up to 100 kg in each test, designed to supply data that can be used to directly extrapolate to the practical reactor conditions. For examples, in the TERMOS [3] experiments, about 100 kg of molten UO_2 were poured into the liquid sodium. The large-scale experiments include MIXA experiments (1992), MAGICO22000 experiments (1995), QUEOS experiments (1996), FARO experiments (1996), BILLEAU22200 experiments (1997), SIGMA22000 experiments, ZREX tests, KROTOS tests [4,5], and so on. The main parameters of some of the experiments are collected and listed in Table 1.
(2) *Small-scale experiments* performed to supply basic information on the mechanisms of various interactions present in the MFCIs. The metal mass used in small-scale experiments is usually little, and the experiments were performed with individual droplet/particle or multiple droplets/particles. Kaiser [9] investigated the interaction between molten aluminum and the sodium coolant. Saito et al. [10] studied the interaction between high-temperature stainless steel particles and water.

It is worth noting that the experimental data obtained in small-scale experiments cannot be directly used in the design of real reactors, the small-scale experiments are easy to control, can be operated simply and flexibly, and can be used to investigate the basic influencing factors and offer basic experimental data. In addition, interactions among a large number of high-temperature droplets/particles will affect the movement characteristics of individual droplet/particle. The interactions between high-temperature droplets/particles and coolant will become more complicated. In this case, it is difficult to analyze in depth the interaction mechanism between the high-temperature droplet/particle and the coolant. Therefore, it is necessary to perform the experiment with individual droplet/particle to investigate the movement characteristics of the droplet/particle and the influencing factors of the evaporation around adjacent droplet/particle.

Li [11] investigated the interaction between an individual high-temperature sphere of zirconium dioxide and cold water, and found that the velocity of the hot sphere increases with the temperature of the hot spheres. Zhan [12] studied the movement of high-temperature steel spheres falling into cold water and also suggested that the velocity of the hot sphere increases with the temperature of the hot spheres. However, Chen [13] investigated the drag characteristics of hot steel spheres moving in coolant, and suggested that the higher the sphere temperature, the lower the velocity of the sphere.

Cho [14] performed tests to investigate the effects of boiling on particle drag by letting hot steel sphere fall into a pool of the sub-cooling Freon 113. Based on his observations, Cho [14] suggested that when the boiling appears, the resistance of the coolant to the hot sphere is reduced and the falling velocity of the hot sphere is increased. Zvirin [15] has also investigated the effect of boiling on the moving behavior of free-falling spheres by using copper spheres of different diameters to impact the cooling water. Zvirin [15]

Table 1
The main parameters of some previous experiments

Facility	QUEOS [6,7]	MAGICO-2000 [6,7]	BILLEAU-2200 [6,7]	MIXA [4,8]	FARO(L-06) [4]
Sphere material	Zirconia/molybdenum	Zirconia/(silicon carbide)	Zirconia	Uranium dioxide/ molybdenum	Zirconia
Sphere diameter (mm)	5/10/4.3	2.4–3.4/1–4	10	6	<10
Total mass (kg)	3.9/7/10/14/20	6.2–8.6	0.6–1.5	3	20
Sphere temperature (°C)	20/1540 ± 30 to 2200 ± 50	1300–2000	2000 ± 100	3567	
Water depth (cm)	100	60/80	87	60	100
Water sub-cooling (°C)	0 to 5 ± 0.5/20	0/3/18	80	Near-saturated water	Near-saturated water