



Hydrodynamic fine fragmentation of partly solidified melt droplets during a vapour explosion



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ARTICLE INFO

Article history:

Received 10 July 2013

Received in revised form 20 March 2014

Accepted 20 March 2014

Available online 14 May 2014

Keywords:

Vapour explosion

Droplet solidification

Fine fragmentation

Modified Weber number

ABSTRACT

In this paper we investigate the fine fragmentation criterion for partly solidified droplets during the explosion phase of a vapour explosion. First, a modified Weber number is proposed for the determination of the critical conditions for the fine fragmentation. Next, this introduced dimensionless number, which considers the crust stiffness as a stabilizing force acting to retain the crust in the presence of hydrodynamic forces, is compared with experimental data. It is further investigated to see whether the limitation of the fine fragmentation by the crusts can help explain the strongly reduced explosion strength observed in experiments with corium as compared to alumina. Finally, the conclusions are used to assess the limitation due to solidification on the strength of the explosions that could occur during severe accidents in nuclear reactors.

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1. Introduction

A vapour explosion is a type of fuel–coolant interaction (FCI) that results from the rapid and intense heat transfer that can follow the interaction between the molten material and the coolant [1,2]. Such an interaction can occur in nature as well as in industry (e.g. foundries, severe accidents in nuclear power plants) when the melt (e.g. molten nuclear fuel) is poured into the coolant or the coolant is injected into the melt or when the melt and the coolant interact as stratified layers.

When the melt pours into the coolant, the vapour explosion phenomenon is divided into the premixing and the explosion phases [1,2]. The explosion phase is further commonly divided into the triggering, the propagation and the expansion phases. The premixing phase covers the interaction of the melt with the coolant prior to the vapour explosion. The continuous melt (e.g. the melt jet) is fragmented into melt droplets of the order of several millimetres in diameter, which may be further fragmented by coarse break-up processes. The coolant vaporizes around the melt-coolant interface, creating a vapour film (i.e. a film boiling regime due to the large temperature difference between the coolant and the melt). The mixture may remain in this metastable state for a period of up to a few seconds. If a destabilization of the vapour film occurs, due to external pressure pulses, collisions of

the melt droplets, contacts with the walls or entrapment events, a vapour explosion may be triggered by the resulting melt-coolant contact. The fine fragmentation of the melt droplets into fragments of the order of some tens of micrometres in diameter may occur. The most effective mechanism for the droplets' fragmentation is hydrodynamic fragmentation, which occurs due to the velocity difference between the melt droplets and the coolant inside the propagating pressure wave itself. The fine fragmentation process rapidly increases the surface area of the melt, resulting in an increased amount of heat transfer into the coolant, which then starts to boil, leading to an increase in the pressure. Finally, this energetic fuel–coolant interaction spreads through the premixture due to propagating pressure waves and the induced processes leave a highly pressurized water–steam mixture behind. Subsequently, this high-pressure region expands and performs work on its surroundings. The time scale for the vapour explosion phase itself is of the order of milliseconds.

The strength of the vapour explosion very much depends on the ability of the melt droplets to be fine fragmented. Experiments revealed that not only the liquid droplets but also the partly solidified droplets can participate in the fragmentation process. In the experiments performed by Haraldsson et al. [3], single melt droplets of Wood's metal and Pb–Bi were dropped into a tank filled with water. The droplets were falling through the air before entering the water. The droplet fragmentation was induced by the relative water velocity established after entering the water. The solidification and fragmentation processes were competing

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Nomenclature

C_s	crust stiffness
D	droplet diameter
d	borehole diameter
E	Young modulus
H	height
k	wave number; constant
n	growth constant
p	pressure
t	time
T	temperature
u	velocity in the x direction
U	flow velocity
v	velocity
w	velocity in the z direction
We	Weber number
We^*	modified Weber number
x	coordinate
z	coordinate

Greek symbols

μ	Poisson ratio
δ_s	crust thickness
λ	wavelength
ξ	displacement
ρ	density
σ	surface tension
ϕ	velocity potential

Subscripts

0	maximum; initial
c	coolant
cal	calculated
crit	critical
m	melt
rel	relative

in the experiments, in a similar way as might occur in the premixing phase of vapour explosions. Nelson and Duda [4] performed bridge-wire-triggered vapour explosion experiments with single melt droplets of iron oxide in sub-cooled water. The droplets were melted with a laser and then dropped into the water. By inducing vapour film collapse by means of short pressure pulses from wire explosions, explosive interactions (thermal fragmentation) between the melt droplets and water were produced. The experimental results suggest that an explosion could be induced with a 2.9 mm diameter droplet of iron oxide even after being frozen inwards to about 10% of its radius. It appears, however, that this result needs confirmation. If the result was valid, crust formation must, in general, be doubted as a way to hinder droplet fragmentation, even without strong relative flows, only under the effect of vapour film collapse and the resulting thermal interaction. However, such interactions are interpreted as being due to steam bubble collapse over a hole or a thin part in the crust, resulting in water injection into the molten part with the consequent entrapment explosion [5]. Such events may occur, but can hardly be considered as a systematic process for larger masses. Also, the whole thermal interaction typically extends over some milliseconds. It is not considered as a mechanism that systematically provides for the rapid break-up in an established detonation or explosion wave providing the rapid coupling of fragmentation in large masses. In the experiments performed by Yang and Bankoff [6], melt droplets of Wood's metal falling through a water–glycerol solution were fragmented upon being overtaken by a shock wave. Here, the relative water flows were produced by shock waves. The break-up was only detected in three cases with calculated crust thicknesses below 3 μm . However, this does not mean that no break-up occurred. Rather, break-up always occurred, although possibly with a somewhat reduced efficiency, being reflected in a reduced cloud expansion. These results do not allow more detailed analyses and conclusions. In the experiments performed by Bürger et al. [7] the hydrodynamic fine fragmentation of a single melt droplet of Wood's metal was induced by a strong water flow. The fine fragmentation also occurred in cases with crust thicknesses greater than 100 μm .

However, solidification may importantly prevent hydrodynamic fine fragmentation. The aim of the paper is to analyse the effect of the solidification on the fragmentation process during the explosion phase. First, a hydrodynamic fragmentation criterion for

partly solidified melt droplets is introduced and its theoretical limit is discussed. Next, the criterion is quantified on the available experimental data. Furthermore, the effect of the solidification on the fine fragmentation process is used to explain the strongly reduced explosion strength obtained in experiments with a corium melt in the water compared to an alumina melt in the water [8]. Finally, the obtained findings are applied to reactor cases.

2. Hydrodynamic fine fragmentation

The ability of a melt droplet to undergo hydrodynamic fragmentation depends on its surface conditions. For liquid droplets, the surface tension is acting to retain the shape of the droplets in the presence of destabilizing hydrodynamic forces. Once a crust is created on the droplet surface, the role of the surface tension is replaced by the stabilizing force of the crust.

The Weber number, which relates the inertial forces of the surrounding flow to the forces of the surface tension, is commonly used to characterize the ability of a liquid droplet to be fragmented. In this section the application of the Weber number is extended beyond completely liquid conditions to generalize its use for characterizing the fragmentation of the droplet with a crust by relative flows. Additionally, the theoretical limit for fragmentation is discussed based on a model which considers that the velocity difference causes the deformation of the droplet and the growth of instabilities at the surface.

2.1. Modified Weber number

The Weber number is defined as:

$$We = \frac{\rho_c v_{rel}^2 D}{\sigma}, \quad (1)$$

where ρ_c is the coolant density, v_{rel} is the relative velocity between the liquid droplet and the coolant, D is the diameter of the droplet and σ is the surface tension. If the Weber number exceeds some critical value, typically 12, the droplet is fragmented into smaller and more stable droplets due to the droplet deformation. When the Weber number is in the range of some hundreds, the droplet is disintegrated within a fine fragmentation process driven by shear flow instabilities.

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