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An estimate of stability of large solidifying droplets in fuel–coolant interaction

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Abstract

An initial period of surface solidification of large opaque particles of molten metal oxides is considered. It is shown that low overheating and very high melting temperature of corium lead to very fast formation of solid crust on the particle surface. The transient problem solution showed that maximal tensile stress in this crust due to pressure drop in expanding steam bubble around the particle is much less than the stress in relatively thin crust layer on the surface of alumina particle. The solidifying corium particle seems to be more stable as compared with the alumina particle of the same size. The latter is treated as one of the reason of the experimental results on relatively low explosivity of corium.

Keywords: Melt droplet; Thermal radiation; Solidification; Corium; Steam explosion; Fuel–coolant interaction

1. Introduction

The so-called fuel–coolant interaction (FCI) problem has been widely investigated during last two decades because of possible severe accident of light-water nuclear reactors. The efforts of many researchers have been focused on hydrodynamic simulation of melt jet breakup [1–3] and specific problems of steam explosion [4–6]. It is important that fine fragmentation of melt droplets at the end of premixing stage of the process increases the probability of the steam explosion. An additional fragmentation of the melt droplets after the hydrodynamic break-up may be provided by thermal interaction of hot droplets with water. The known experimental results of relatively low explosivity of corium in comparison with that of alumina melt [7] may be related with different conditions of this "thermal" stage of the fragmentation. The dominant role of thermal radiation in heat transfer from melt droplets to water [8] determines the attention to the effect of radiative properties of the substances. It has been shown in the recent papers by the author [10] that physical picture of the millimetre-size droplet solidification is quite different for semi-transparent alumina particles and opaque corium particles. The volume radiative cooling of alumina particles is accompanied by relatively slow growth of solid crust layer on the particle surface. Contrary, the corium particles are cooled mainly by thermal radiation from the surface and the solid crust is formed very fast. This crust can prevent from further fragmentation of the corium particle. The effect of semi-transparency takes no place for larger particles which are totally opaque in the near infrared (both alumina and corium particles). This latter case is considered in this paper.

We consider the particles at the end of hydrodynamic fragmentation when hydrodynamic forces cannot continue the particle fragmentation. But the pressure oscillations in a steam bubble formed around the melt droplet may have great amplitude, especially in the initial time period. It seems possible that these oscillations break up the droplet. For large melt droplets of diameter 5–10 mm, the corresponding model has been proposed by Drumheller [11] who considered the propagation of spherical pressure wave in the droplet. In more recent papers [12,13], the small

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Nomenclature

a	particle radius
J	integral defined by Eq. (7)
k	thermal conductivity
L_m	lateral heat of melting
L_w	lateral heat of evaporation
$\dot{m}$	mass rate of evaporation
q	heat flux
p	pressure
r	radial coordinate
R	gas constant
s	part of radiation power absorbed at the water surface
S	radiation–conduction parameter
t	current time
T	temperature
u	velocity
V	conduction–evaporation parameter

Greek symbols

γ	parameter in Eq. (8)
δ	thickness of solid crust
ε	hemispherical emissivity
ρ	density
σ_θ	circumferential tensile stress
σ_f	failing strength
φ	coefficient in Eq. (2)

Subscripts and superscripts

c	conductive
i	steam–water interface
m	melting
r	radiative
v	vapor
w	water
0	initial or referenced value

droplets destroyed by the pressure drop in steam layer have been considered. A comparison with the additional pressure in the droplet due to surface tension showed that the minimal radius of corium droplets is about 17 μm.

At the end of the premixing, the overheating of corium droplets is expected to be small. It means that one should take into account solidification process which can prevent further fragmentation of the droplet.

The objective of the present paper is to analyze the following competitive processes: the pressure drop in the expanding steam bubble around the particle and the formation of solid crust on the particle surface. We assume that both processes start simultaneously just after the previous fragmentation of the "mother" droplet. We will estimate the conditions when solid crust may be serious barrier for further fragmentation of the particle.

2. Model of the initial stage of surface crust formation

The main part of the radiation emitted by particles is absorbed in ambient water, at least in the case of not too high volume fraction of particles [14,15]. It allows us to assume that radiation heat transfer between the particles is insignificant compared to local heat transfer to surrounding water and consider a model problem for single particles.

Strictly speaking, there is no spherical symmetry of the heat transfer problem even in the case of almost spherical shape of the melt droplet because of considerable variation of the flow parameters along the surface of the moving particle. Nevertheless, the simple estimates showed that the total heat flux from the hot particle is almost symmetric because the contribution of convection is relatively small. In this paper, we consider a spherical particle separated from ambient water by a concentric steam layer.

In this paper, we do not take into account possible difference between temperatures of melting and solidification of the particle material assuming the phase change to be localized at the isotherm $T = T_m$. It means that we consider only pure substances or their eutectics.

The melt particles are large in comparison with the infrared radiation wavelength. Therefore, one can ignore electromagnetic wave effects in thermal radiation of the particle. We assume also that thickness of steam layer at the particle surface is much greater than the radiation wavelength. In this case, thermal radiation of opaque particles can be calculated very simple [16].

In the initial period of particle solidification, the solid crust thickness at the particle surface can be estimated as follows:

$$\delta(t) = \frac{\int_0^t (q_c + q_r)\mathrm{d}t}{\rho L_m} \tag{1}$$

The heat flux from the particle surface due to heat conduction through the steam layer q_c and the integral radiative flux q_r can be approximated as follows [12,13]:

$$q_c = k_{v0}\frac{T_m - T_i}{a}\,\frac{1 + \varphi(T_m/T_i - 1)/2}{1 - a/r_i} \tag{2}$$

$$q_r = \varepsilon\sigma T_m^4 \tag{3}$$

where $k_{v0} = 0.025$ W/(m K), $\varphi = 1.83$. Remember that linear temperature dependence of steam conductivity $k_v(T)$ was assumed in [12,13] by deriving Eq. (2). We assume also that temperature of steam–water interface $r = r_i$ is constant and equal to $T_i = 400$ K. According to Eqs. (2) and (3), the radiative flux q_r does not depend on steam layer thickness whereas the value of q_c strongly decreases with r_i.

Eq. (1) is true for very short time period when one can neglect the surface temperature drop. But the initial time period seems to be the most important because of possible very fast change of pressure in the steam bubble around the particle. Remember that we consider a melt droplet just after the hydrodynamic break-up and focus on possible further fragmentation of the droplet during its solidification. It is assumed that this fragmentation might be a result of the strong pressure drop in concentric steam layer from the initial value $p = p_v(0)$ to the current value $p_v(t)$. The circumferential tensile stress in a relatively thin crust ($\delta \ll a$) due to the pressure drop is expressed as follows:

$$\sigma_\theta(t) = \frac{[p - p_v(t)]a}{2\delta(t)} \tag{4}$$

where p is treated as a pressure in the melt inside the particle. The calculated value of σ_θ should be compared with the failing strength of solid crust σ_f.

3. Model of the pressure drop in steam layer

Consider the transient problem of thermal interaction of a spherical melt particle and ambient water. It is assumed that the particle is supplied just after the hydrodynamic break-up, so that the steam layer is very small at the initial time moment. We will focus on the beginning of dynamic stage of the problem, when surface temperature of the particle can be assumed to be constant and equal to the melting temperature. Following papers [12,13], consider the simple case when water is heated up to the saturation temperature. Note that it gives us only the minimal estimate of the vapor layer oscillations. and the case of underheated water is stronger for the fuel–coolant interaction [17].

The heat flux to the steam–water interface can be expressed as follows [12,13]:

$$q_i = (q_c + sq_r)(a/r_i)^2 \tag{5}$$

The coefficient $s(T_m) < 1$ corresponds to the fraction of total radiation flux absorbed in a thin surface layer of water. In our estimates, we use $s = 0.4$ for alumina and $s = 0.3$ for corium [14]. The specific mass rate of evaporation of water can be determined from the relation for heat balance by neglecting the work required for the movement of water:

$$\dot{m} = q_i/L_w \tag{6}$$

We do not consider the effects of possible nonequilibrium evaporation which may be important for underheated water [18]. The steam pressure p_v can be found from the integral mass balance:

$$p_v J(t) = p_v J(0) + R_v \int_0^t \dot{m} r_i^2 \mathrm{d}t, \quad J(t) = \int_a^{r_i} \frac{r^2 \mathrm{d}t}{T_v(t,r)} \tag{7}$$

where $T_v(t,r)$ is the temperature profile in the steam layer and R_v is the gas constant of steam. In order to calculate the dynamics of a spherical steam layer between corium particle and ambient water, we use the well-known Rayleigh equation [19]:

$$r_i \ddot{r}_i + \frac{3}{2}\dot{r}_i^2 = \frac{p_v - p}{\rho_w}, \quad r_i(0) = \gamma a, \quad \dot{r}_i(0) = 0 \tag{8}$$

where the parameter $\gamma > 1$ characterizes the initial thickness of steam layer. We will turn to a dimensionless set of equations and introduce the variables

$$\bar{t} = t/t_0, \quad \bar{r}_i = r_i/a, \quad \bar{u}_i = u_i/u_0, \quad \bar{p}_v = p_v/p,$$
$$\bar{\dot{m}} = \dot{m}/(\rho_w u_0) \tag{9}$$

in which the characteristic values of the parameters $t_0 = a/u_0$ and $u_0 = \sqrt{p/\rho_w}$ are used.

The designation $\overline{T}_i = T_i/T_m$ is also used for the brevity. In the dimensionless form, the mathematical formulation of the problem can be written as the following Cauchy problem for a set of ordinary differential equations:

$$\dot{\bar{p}}_v = \frac{1}{\bar{J}}\left\{ V\left[(1-\overline{T}_i)\frac{1+\varphi(1/\overline{T}_i - 1)}{1 - 1/\bar{r}_i} + sS\right] - \frac{\bar{p}_v \bar{u}_i}{\overline{T}_i}\bar{r}_i^2\right\},$$
$$\bar{p}_v(0) = 1$$
$$\dot{\bar{J}} = \bar{r}_i^2 \bar{u}_i/\overline{T}_i, \quad \bar{J}(0) = \gamma - 1$$
$$\dot{\bar{r}}_i = \bar{u}_i, \quad \bar{r}_i(0) = \gamma$$
$$\dot{\bar{u}}_i = \frac{\bar{p}_v - 1 - 1.5\bar{u}_i^2}{\bar{r}_i}, \quad \bar{u}_i(0) = 0 \tag{10}$$

Eq. (10) contain the following dimensionless complexes:

$$S = \varepsilon\sigma T_m^3 a/k_{v0}, \quad V = \frac{k_{v0}T_m/a}{u_0 L_w p/(R_v T_m)} \tag{11}$$

where S is the ratio of "radiative conductivity" to the thermal conductivity of steam and V is the ratio of conductive heat flux through the steam layer to the heat flux for water evaporation. In the calculations for corium and alumina particles we use the physical parameters from Table 1 (see papers [9,10] for details).

The typical numerical results for large corium particle are presented in Fig. 1. In contrast to small particles ($a \leqslant 100$ μm) considered in papers [12,13], effect of thermal radiation is considerable. As was shown in paper [20], the steam layer is not stable and high-order oscillations are expected to be not realized. In this material, we focus on the first phase of steam bubble expansion and on the corresponding decrease in steam pressure. The calculated time dependences of $\bar{p}_v$ from the beginning of the process to the maximum pressure drop and the corresponding results for dimensionless tensile stress in the crust layer $\bar{\sigma}_\theta = \sigma_\theta/p$ are shown in Fig. 2. As one can expect, the pressure drop reaches the greater values for relatively small particles and it is insensitive to the particle material. It is interesting

Table 1
Physical parameters of alumina and corium

	Alumina	Corium
T_m (K)	2320	2850
ρ (kg/m^3)	3000	8000
L_m (kJ/kg)	1070	400
ε	0.85	0.85

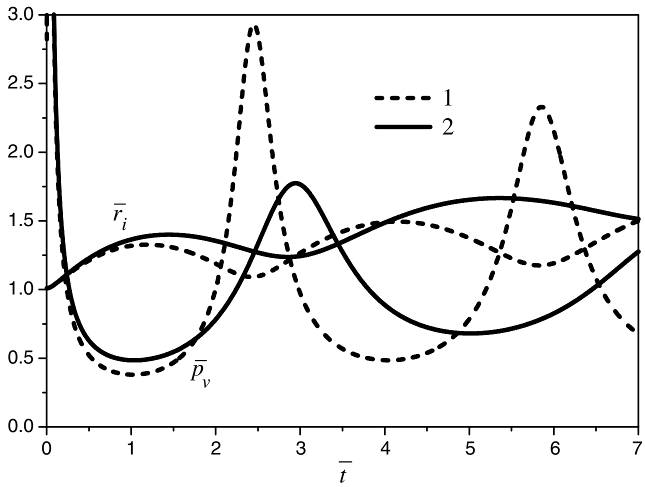

Fig. 1. Dynamics of steam layer on the surface of corium particle of radius 3 mm: 1 – calculation without radiation, 2 – with radiation.

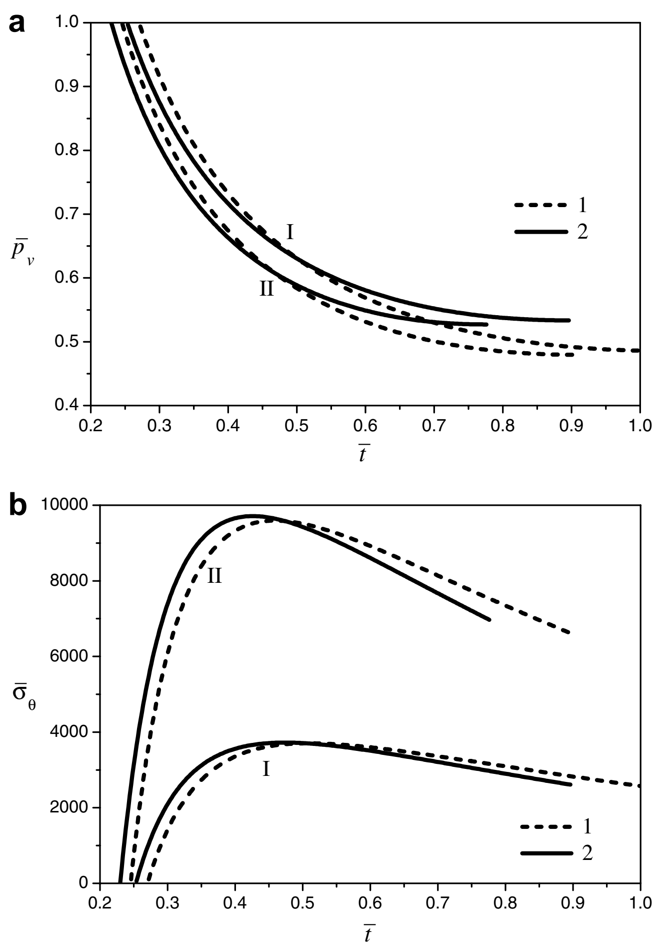

Fig. 2. Steam pressure (a) and tensile stress in the crust (b) during expansion of steam bubble around the particle: I – corium particles, II – alumina particles; 1 – $a = 3$ mm, 2 – $a = 5$ mm.

that tensile stress in the crust reaches the maximum at moderate pressure drop because the further increase of the pressure difference is not so fast as compared with the crust thickness increasing. The maximum tensile stress appears to be insensitive to the particle size: the difference between the variants of $a = 3$ mm and 5 mm is negligible. This stress is much greater in the case of aluminum oxide particles because of relatively thin crust layer. The latter is explained mainly by relatively slow radiative cooling of alumina particle as compared with that of corium particle.

The calculated maximum tensile stresses are of the same order of magnitude as the typical values of failure strength for metal oxide materials. To the best of author knowledge, there is no data in the literature for tensile failure strength of alumina and corium crust. If we assume there values are close to each other, the solidifying particles of high-temperature core melt appear to be more stable with respect to fast variations of the external pressure.

4. Conclusions

An initial period of solidification of large opaque particles of molten metal oxides is considered. A simple relation for the rate of crust growth on the particle surface is suggested. It is shown that low overheating and very high melting temperature of corium lead to very fast formation of solid crust on the particle surface.

The effect of pressure drop in expanding steam layer at the particle surface on circumferential tensile stress in the crust is analyzed. The combined transient problem solution showed that maximal stress in the crust on the corium particle is much less than the stress in the crust layer on the surface of alumina particle. The latter is explained by not so fast formation of the solid crust on the surface of alumina particle because of relatively low melting temperature.

The solidifying corium particle seems to be more stable as compared with the alumina particle of the same size. It can be treated as one of the reason of the experimental finding on relatively low explosivity of corium.

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