



# Steam explosion in nuclear reactors: Droplets of molten steel vs core melt droplets



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## ABSTRACT

Relative contributions of molten steel and core melt droplets to heat transfer from the droplets to ambient water at typical regimes of the droplet cooling and solidification are considered. It is shown that fine fragmentation of steel droplets overheated significantly with respect to the steel solidification temperature makes these droplets more dangerous for the steam explosion triggering, and this effect cannot be neglected in nuclear safety analysis. On the contrary, the solid crust on the surface of core melt droplets is formed before the first pressure drop in the steam envelope. As a result, the probability of fragmentation of these droplets is relatively small and there is no increase in the overall heat transfer due to the expected large total surface area of fine particles. The predicted low explosivity of core melt droplets is confirmed by the published data of laboratory experiments. It is recommended to revise the existing theoretical and computational models of steam explosion, paying more attention to the role of fine fragmentation of steel droplets.

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## 1. Introduction

The problem of melt–water interaction is especially important for analysis of hypothetical severe accidents in light-water nuclear reactors. A severe accident involves melting of the core and possible subsequent interaction of the core melt ( $\text{UO}_2\text{--ZrO}_2$  composition) with water. There is a widely known theoretical statement that fuel–coolant interaction (FCI) may lead to steam explosion with a significant part of the melt thermal energy converted into the mechanical energy of the detonation wave [1–8]. Physical processes that govern steam explosion energetics are multifaceted and complex [3,5,9–11]. The probability of steam explosion is determined by the so-called premixing stage of FCI when the melt jets are fragmented to numerous small droplets [9,10]. The fragmentation of the melt jets and large droplets is considered as very important process [9–19]. At the same time, many experiments with core melt (corium) jets have failed to produce strong steam explosions. It appears that explosivity of corium is extremely low [20,21]. On the contrary, the so-called micro-explosion has been observed in numerous experiments with overheated metal droplets [22–27]. One can assume that this result is explained by different conditions of droplet fine fragmentation because of specific conditions of cooling and solidification of various melt particles.

The fragmentation/breakup processes in the FCI can be conventionally subdivided into several stages. The first one is an ordinary breakup due to interfacial Rayleigh–Taylor and Kelvin–Helmholtz instabilities of a jet of relocated melt materials. The droplets typically from about to 5 mm in radius are formed at this stage. We are focused on the second stage of the droplet fragmentation in the pre-mixing zone to understand the conditions of possible further fine fragmentations of the melt droplets up to the explosion phase characterized by the presence of hot micron-size particles suspended in water.

Simple estimates have showed that thermal radiation is the main mode of heat transfer from single particles to the ambient water [28–31]. A significant part of the radiation emitted by particles is absorbed in the ambient water [32,33]. It allows us to assume that radiative heat transfer between the particles is relatively small as compared to local heat transfer to surrounding water. Therefore, it is sufficient to consider model problems for single particles.

It should be recalled about the presence of molten steel layer on the surface of the corium pool in the pressure vessel. The mass of steel is less than that of core materials but it may be about 20% of the total mass or even greater [34,35]. It was shown in papers [34,35] that molten steel is responsible for the possible failure of the pressure vessel steel wall, whereas the interaction of corium

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**Nomenclature**

$a$	radius of droplet
$c$	specific heat capacity
$h$	heat transfer coefficient
$k$	thermal conductivity
$L$	latent heat of melting
$p$	pressure
$r$	radial coordinate
$t$	time
$T$	temperature

*Greek symbols*

$\alpha$	absorption coefficient
$\gamma$	surface tension
$\delta$	solid crust thickness
$\varepsilon$	emittance, emissivity
$\kappa$	index of absorption
$\lambda$	radiation wavelength

$\rho$	density
$\sigma$	Stefan–Boltzmann constant
$\sigma_\theta$	tensile stress
$\sigma_f$	failure strength
$\tau$	optical thickness

*Subscripts and superscripts*

0	initial
c	corium
e	external
i	interface
m	melting
min	minimum
sol	solidification

with the steel wall cooled by water is accompanied by formation of a low-conductivity crust layer which prevents the wall melting.

To the best of our knowledge, the role of steel melt in vapor explosion has not been analyzed in the literature. At the same time, the steel droplets in water are much more overheated with respect to their solidification temperature as compared to droplets of corium. This physical difference may be important in the case of relatively fast solidification of corium particles because the solidification prevents fine fragmentation of these particles.

According to the well-known Rayleigh equation [36], the mechanical inertia of water which moves under the action of expanding steam envelope formed around the melt droplet leads to the pressure drop and subsequent pressure oscillations in a steam bubble [37–40]. These oscillations may have great amplitude, especially in the initial time period, and it seems possible that the pressure drop breaks up the droplet. For large melt droplets of diameter 5–10 mm, the corresponding theoretical model has been proposed in the early paper by Drumheller [41] where the propagation of spherical pressure wave in the droplet was studied. In more recent paper [37], the smaller droplets which can be destroyed by the pressure drop in steam layer have been considered. Note that estimates of paper [37] did not take into account the fast formation of solid crust on the corium droplet surface, but the last effect is really important because of small overheating of corium droplets at the end of the premixing stage.

Many researchers agree that one should take into account the solidification process which can prevent further fragmentation of the droplet. This problem is not new, and the role of particle solidification attracted the attention of researchers even in early studies [42]. In paper [40], the following competitive processes were analyzed for droplets of alumina and corium: the pressure drop in the expanding steam bubble around the particle and the formation of solid crust on the particle surface. A comparison of behavior of alumina and corium particles was motivated by the use of alumina in the early experiments on steam explosion [20,21]. It was assumed in [40] that both processes start simultaneously just after the previous fragmentation of the “mother” droplet. The calculations for the semi-transparent alumina particle and almost opaque particle of corium with the same radius of one millimeter showed that the solidifying corium particle is more stable as compared with the alumina particle. It was treated in [40] as one of the reason of the experimental finding on relatively low explosivity of corium. In the present paper, the calculations for corium particles are revised and particles of various sizes are considered. In addition,

the particles of molted steel which are really formed in the case of a severe accident of nuclear reactors are considered.

The objective of the present study is two-fold: (1) to compare theoretical predictions for the solidification time for particles of molten steel and corium and (2) to estimate the role of molten steel in triggering the steam explosion in the case of nuclear reactor severe accident.

## 2. Thermal and optical properties of substances

### 2.1. Thermal properties

It is obvious that thermal properties of molten steel and corium are quite different. Therefore, it is sufficient to use approximate values of physical quantities (without their temperature dependences) to estimate the difference between thermal behavior of steel and corium droplets. The data presented in Table 1 were taken from papers [34,35] (see also [43–45]). The great difference in the values of melting temperatures,  $T_m$ , and thermal conductivity,  $k$ , of molten steel and core melt are the most important.

The initial temperatures of both melts in the stratified pool formed in the pressure vessel in the case of a severe accident are approximately the same [34,35]. It means that overheating of corium with respect to its solidification temperature is relatively small whereas the overheating of steel is great. As a result, the solidification of corium may prevent multiple fragmentation of the melt droplet but a similar effect is not important for steel droplets and a lot of fine steel droplets can be generated during the melt–water interaction.

Note that relatively high thermal conductivity of steel enables one to use an isothermal approach in thermal analysis of behavior of steel droplets with radius less than about one millimeter. On the contrary, the millimeter-sized corium droplets are not isothermal and their surface temperature is much less than that in the droplet center. The latter makes the transient heat transfer problem for

**Table 1**  
Thermal properties of molten steel and corium used in calculations.

Property	Molten steel	Core melt
$T_m$ , K	1700	2850
$\rho c$ , MJ m <sup>−3</sup> K <sup>−1</sup>	4.5	4.8
$k$ , W m <sup>−1</sup> K <sup>−1</sup>	20	3
$L$ , kJ kg <sup>−1</sup>	280	400

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