Annals of Nuclear Energy 78 (2015) 130–139

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Eulerian modelling of melt solidification impact during fuel–coolant interaction

Mitja Uršič [a,*], Matjaž Leskovar [a], Renaud Meignen [b]

[a] Jožef Stefan Institute, Jamova cesta 39, SI-1001 Ljubljana, Slovenia
[b] Institut de Radioprotection et de Sûreté Nucléaire, BP 3, 13115 Saint-Paul-Lez-Durance Cedex, France

ARTICLE INFO

Article history:
Received 1 August 2014
Received in revised form 4 December 2014
Accepted 2 January 2015
Available online 17 January 2015

Keywords:
Fuel–coolant interaction
Eulerian code
Solidification modelling

ABSTRACT

Melt droplet solidification is one major phenomenon acting on the mitigation of the strength of vapour explosions in situations related to nuclear safety. The modelling of solidification effects is then an important challenge for the evaluation of fuel–coolant interaction. We present an attempt for modelling the crust that might develop around melt droplets and its effect on the fine fragmentation within an Eulerian formulation of the flow equations, with application to the MC3D code.

A physically-based modelling of the melt droplets temperature profile and a fragmentation criterion for partly solidified droplets are presented. The implementation of these models in the specific case of Eulerian modelling of the melt droplet phase is described. Two additional transported model parameters based on the most important droplets features regarding the fuel–coolant interaction behaviour are derived. The first property to transport is the crust stiffness because it enables the correct prediction of the amount of droplets participating in the droplet fragmentation process. The second is related to the energy transfer from the droplet interior to the surface. This enables to improve the surface temperature determination and reflects the history of the droplet cooling. Also the potential effect of solidification on the vapour explosion strength is shown.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Vapour explosions are of a potential concern in nuclear power plants but also in nature, foundries and the paper industry (Berthoud, 2000; Chadwick et al., 2008; Corradini et al., 1988). Such an energetic fuel–coolant interaction (FCI) can occur when a molten material (called hereafter melt or fuel) is poured into a volatile coolant. Alternatively, the phenomenon can also occur when the coolant is injected into the melt or when the melt and the coolant interact as stratified layers. In this paper we investigate the case where a molten jet is poured into a pool of coolant that is the configuration where the most powerful explosions are expected.

When the melt is poured into the coolant, FCI phenomena are divided into the premixing and the explosion phases (Berthoud, 2000; Corradini et al., 1988). In the premixing phase, the continuous melt (e.g. a jet) is fragmented into melt droplets of the order of several millimetres in diameter, which can be further fragmented. A vapour explosion can occur during the premixing phase. In that sense, premixing can be considered to be in a meta-stable state that might undergo a transition phase. The destabilization of the meta-stable state can have several causes. It can be strictly spontaneous, in general through a local change of boiling processes, or triggered either intentionally (e.g. a chemical explosion, a high pressure gas capsule) either through external energetic phenomena. The destabilization causes the fine fragmentation of the melt droplets into fragments of the order of some tenths of microns in diameter. The fine fragmentation process rapidly increases the surface area of the melt, vaporizing more coolant and increasing the local pressure. This fast vapour formation and the fine fragmentation spatially propagate throughout the melt–coolant mixture, causing the whole region to become pressurized by the coolant vapour. If the concentration of the melt in the mixture is large enough and sufficient coolant is available, the propagation velocity can rapidly escalate and can be sustained by energy released behind the propagation front. Subsequently, the high pressure region behind the propagation front expands and performs work on its surrounding. The time scale for the vapour explosion itself is of the order of some milliseconds.

The FCI phenomena are governed by physical laws which are mathematically described with balance equations for the mass, the momentum and the energy approximated through a space and time discretization. As for any CFD modelling, the discretiza-

* Corresponding author. Tel.: +386 1 588 53 42.
E-mail address: mitja.ursic@ijs.si (M. Uršič).

http://dx.doi.org/10.1016/j.anucene.2015.01.003
0306-4549/© 2015 Elsevier Ltd. All rights reserved.

tion acts as a filter and the balance equations are then to be complemented by appropriate constitutive relations, the purpose of which is to specify the sub-grid processes involved in the phenomena (heat and mass transfers, frictions) (Meignen et al., 2005, 2014a,c; Pohlner et al., 2006). This is particularly true in FCI modelling since, currently, the space scales for the numerous fragmentation processes and heat and mass transfers cannot be resolved with the general balances. For the FCI phenomena the constitutive relations related to the local heat transfer mechanisms between the melt and the surrounding are crucial. The heat transfer is roughly proportional to the contact area between the melt and its surrounding and occurs through various mechanisms as film boiling and thermal radiation, which are functions of the surface temperature of the melt. In the premixing phase the fragmented part of the melt contributes the most to the heat transfer.

Fragmentation processes occur in a very complex manner with the development of transient filaments that are finally transformed into droplets (Dinh et al., 1999). Such complexity can hardly be taken into account in FCI codes and it is assumed for simplification that the fragmentation directly results into droplets. During the premixing phase, quenching of the melt occurs. A temperature profile develops inside the melt droplets and a solid crust can grow on the droplet surface. Melt solidification limits the fragmentation and coalescence of the melt droplet. Thus, as the explosion is driven by the fine fragmentation of the melt, solidification can strongly mitigate its strength. The quenching conditions around the droplet depend on many parameters, e.g. surface temperature, surface roughness, coolant sub-cooling, void fraction, relative velocities, finally resulting in non-uniform solidification (Bürger et al., 1986). The complexity in the solidification process and the complexity in the properties of the crust could be further increased by e.g. melt super-cooling at large quenching rates, coolant entrapment, changes in chemical composition and the presence of porosity in the solid phase (Piluso et al., 2005; Tyrpekl and Piluso, 2012; Tyrpekl et al., 2014). Moreover, chemical interactions might supply internal energy to the melt and modify both the corium properties and the solidification characteristics. Also, the characterization of oxidation during FCI is still not satisfactory and it will be a major axis of research for near future (Meignen et al., 2014b). To summarize, currently the abovementioned complexities can hardly be taken into account in the crust formation modelling and therefore simplified droplet quenching models are used (Chen et al., 2013; Dombrovsky, 2009; Moriyama et al., 2006; Pohlner et al., 2006; Uršič and Leskovar, 2012).

The quantification of the conditions at the surface of the melt droplets is strongly related to the modelling of the temperature profile inside the melt droplets which locally depends on fragmentation, heat transfers and melt transport. Thanks to the tracking process of the position of the melt droplets, the Lagrangian formulation enables a direct modelling of the temperature profiles and consequently the crust growth and its effect on the coalescence and the fragmentation. Ideally, in such a description, each and every droplet should be tracked. As it may not be computationally feasible due to the large number of droplets (Crowe et al., 1998), they are grouped, and each group has its own specific properties (e.g. a velocity, a droplet size, a crust thickness, a surface temperature). An example of such modelling is found in (Pohlner et al., 2006). A major drawback of the Lagrangian formulation is the numerical complexity of the treatment of the interaction with the ambient (Eulerian) fluid. On the other hand, in the Eulerian formulation, the interaction of the melt droplets with ambient fluid is treated "naturally" since the melt droplets and the ambient fluid are treated similarly. The issue of the Eulerian formulation is the difficulty of accounting for specific properties of the melt droplet (e.g. diameter, surface temperature, crust thickness). It is in general made use of transport equations of those properties. For example, interfacial transport area equations are common in Eulerian description to evaluate the average size of a droplet population. Similarly, a temperature profile can be constructed from a finite number of characteristics which can be transported to improve the heat transfer calculations and to evaluate the growth of a crust.

The aim of the paper is to present the solidification model (ISIM – Improved Solidification Influence Model) developed for the premixing and explosion models of the MC3D code (IRSN, France), which is an Eulerian 3D CFD code for multiphase flow, mainly used for severe accident studies in nuclear safety (Meignen et al., 2014a,c). The purpose of the ISIM model is to enable the assessment of the inhibiting effect of solidification on the hydrodynamic fine fragmentation during the explosion phase. The demonstration of the potential effect of the developed ISIM approach on the simulation results with vapour explosions is finally provided.

2. Melt flow and present solidification influence modelling in MC3D

Before describing ISIM, it is necessary to describe how the melt flow and solidification are modelled in the standard MC3D premixing and explosion models.

In the version 3.7, the melt flow in the premixing module is described with two fields (Meignen et al., 2014a,c):

- the JET field, which is used to describe a continuous field as a jet, a pool or a film. The JET field is modelled using a VOF–PLIC (Volume of Fluid–Piecewise Linear Interface Construction) method;
- the DROP field, which is used to describe a discontinuous field, i.e. the melt droplets. The interfacial area, and thus the droplet Sauter diameter, is computed with an interfacial area transport model.

Now, it is important to notice the following important specifications that impact the solidification modelling:

- the JET field is not affected by solidification during the premixing in the present model. Further analyses are required to analyse a possible influence of solidification of the melt jet;
- the melt droplets are created through fragmentation of the jet, at the local jet temperature, supposed to be initially homogenous;
- the melt droplets can further undergo secondary fragmentation, depending in particular on the solidification;
- the melt droplets can further coalesce into the JET field from an impact on a structure (e.g. at the bottom of the pool). Coalescence among the melt droplets themselves is not accounted for.

Coalescence and fragmentation are subject to criteria related to solidification. For any criterion, the term "liquid" is used to express the fact that the melt droplet can fragment or coalesce, although there might be a thin crust. Similarly, "solid" expresses the fact that the droplet cannot fragment/coalesce. The various processes can be somewhat complex but the current standard criteria to decide upon the melt droplet fragmentation/coalescence are simply related to the mean temperature of the droplet. There is no particular physical picture attached to this criterion. For example, it is found that, for fine fragmentation during explosion, the solidus temperature gives a satisfactory criterion to express the possibility of fragmentation. This certainly does not mean that the whole droplet must be solid. It was nevertheless found important to improve the modelling with a stronger physical ground and this was the purpose of the present work.

Download English Version:

https://daneshyari.com/en/article/1728098

Download Persian Version:

https://daneshyari.com/article/1728098

Daneshyari.com