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Numerical simulation of metal jet breakup, cooling and solidification in water

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ABSTRACT

During transient intrusion of molten metal into water, metal go through cooling, breakup before fully solidified. This paper describes a numerical code which combines cooling, solidification and breakup in a single computation. In the code free surface of jet is tracked by Volume of Fluid Method (VOF), both the heat transfer and viscosity variation during liquid-solid phase change are taken into account. The simulation results of melt jet pattern, front position history, jet breakup length and breakup time are in good agreement with the experimental results. The effects of interfacial temperature and jet velocity are also determined. The molten jet thermal history and solidification, droplet generation rate at different penetration times, which are difficult to observe in experiment, are presented to gain an insight into this complicated process. Solidified metal proportion increases with jet penetration depth. Melt jet breakup with surface solidification can be divided into three zones in space: (1) liquid core, (2) solidifying zone, (3) solid droplets. These simulation data are helpful to substantiate the understanding of the phenomena during molten melt jet interactions with water.

1. Introduction

The so-called molten fuel-coolant interaction (FCI) has been studied over the past three decades in the context of a hypothetical severe accident in nuclear reactors. In a hypothetical core disruptive accident of sodium-cooled fast breeder reactor, there is a possibility that a large amount of molten fuel which release from the core will get cool, break up and solidified in sodium coolant. For Post accident heat removal in core disruptive accident, it is important to have good understanding of this heat and mass transfer transient process in order to estimate the molten jet behavior quantitatively.

The efforts of many researchers have been focused on hydrodynamic behaviors of melt jet breakup in the adiabatic condition [2–7]. There are different regimes of jet breakup which are ranging from axisymmetric, varicose breakup under influence of surface tension at low velocity to the atomization region at high velocity, characterized by intense spray production at the jet outlet [8]. According to previous works [9,10], the results of basic adiabatic experiments show that the jet breakup can be classified into three modes, namely deformation, boundary layer stripping and surface waves instability caused by Kelvin–Helmholtz instability or Rayleigh–Taylor instability. After the liquid jet enters into water, jet leading edge will deform and breakup due to Taylor instability [8], and there is continuous stripping from the jet surface which causes the thinning of jet and finally the coarse breakup of a coherent core may occur. Besides there hydrodynamic descriptions of melt jet and coolant interactions, the jet breakup during reactor severe accidents can be more complicated due to thermal effect such as jet surface solidification. In nuclear reactors such as fast breeder reactors and light water reactors, the interfacial temperature between the molten fuel and the coolant is considered to be lower than the melting point of molten fuel. Therefore, solidification of jet surface is an important phenomenon and will affect the subsequent phenomena such as mass breakup rate, particle size and distribution. In order to study surface solidification effect quantitatively, some researchers carried out the experiments in which melt jet was injected into water [1,11,12]. The experiment results showed that the speed of solidification of a molten jet is an important factor for the jet breakup behavior. Depending on the different initial conditions, the molten jet behavior changes from breakup to the falling into coolant without collapse. However due to measurement technology limitation, the thermal history including solidification inside metal and flow characteristics cannot be obtained in the experiments.

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Nomenclature

a	acceleration (m/s^2)
C_P	specific heat (J/(kg K))
D, d	diameter (m)
F_l	liquid fraction (–)
Fr	Froude number (–)
g	gravity (m/s^2)
h	enthalpy (J/kg)
K	coefficient (–)
L	length (m)
n	unit normal vector (–)
p	pressure (Pa)
S, b	source term (–), coefficient (–)
t	time (s)
T	temperature (°C)
V, u, v	velocity (m/s)
ΔH	latent heat for solidifying (J/kg)

Greek symbols

α	fractional volume (–), thermal diffusivity (–)
δ	dirac distribution (–)
k	curvature (–)
ρ	density (kg/m^3)
σ	surface tension (N/m)
μ	dynamic viscosity (Pa s)
λ	wave length, heat conductivity (W/m °C)
Γ	diffusion term (–)
ϕ	variable (–)

Subscripts

i	phase index
j	jet
l	liquid
c	pool, cool
p	main control volume
E	east control volume
W	west control volume
m	melt
max	maximum
N	north control volume
S	south control volume
s	solid
0	initial

The CFD approach can help for a better understanding of thermal and hydraulic behavior during the jet cooling, solidification and breakup process. In order to analyze the molten melt jet interactions with water, numerical methods need to be developed for disintegration of liquids as well as large deformation of free surfaces. Both Moving Particle Semi-implicit (MPS) method [13] and Volume-of-fluid (VOF) method are adopted to simulate this free surface flow process successfully [14–19]. However, molten jet breakup behaviors were always simulated in the adiabatic condition and the solidification effect was not considered. During a phase change process (metal solidification), a large amount of energy is released or absorbed, which cause a jump discontinuity in the energy dissipation. In order to simulate metal solidification and solve this mathematical discontinuity problem, a review on the numerical simulation of convective-diffusion phase-change problems is given [20]. Metal solidification behaviors in other backgrounds were simulated successfully. The enthalpy formulation method is adopted in RIPPLE code and the solidification of liquid metal droplets impacting onto a substrate was simulated successfully [21]. In Zhang's study [22], the process of the melt solidification in a cavity was also calculated by solving the enthalpy formulation energy equation. In addition, viscosity effect during metal solidification must be considered. Viscosity change in the mush region can be simulated by two popular approaches: 1. Adding source term in momentum equation [21]; 2. Viscosity function method, viscosity is calculated by a function of temperature [23]. When metal jet is in the solid phase, the addition darcy source term in momentum equation is so large and it dominates all components of momentum equation and forces the velocity to zero which is inconsistent with the facts [21]. Unlike first method, viscosity function method only forces internal relative velocity to zero, which is suitable to use in falling molten jet problem.

In order to analyze the multiphase flow and heat transfer process during fuel coolant interaction, a multiphase flow and heat transfer process code (MH code) was firstly developed in 2008 by Yuan et al. [24]. Two dimensional Navier-Stokes equations are solved by SIMPLE method and the Volume-of-Fluid (VOF) method based on piecewise linear interface construction (PLIC) is used to track free surfaces in MH code. And MH code has been successfully applied to fuel coolant interaction area to deal with free surface flow and the problems with large deformation, such as thermal fragmentation and hydrodynamic fragmentation of melt droplets [14–18], hydrodynamic breakup of liquid jet [19]. However, MH code does not incorporate solid-liquid phase change effects.

The purpose of this work is to develop a solid-liquid phase change model and integrate into MH code. The improved MH code is applied to identify and analyze the breakup and solidification characteristics of melt jet to provide a better understanding of the phenomena. The study starts with model introduction. Then, experimental data [1] is chosen for verification of the capability of the current approach. Jet breakup pattern, jet breakup length and droplet generation, thermal history and solidification are qualitatively analyzed.

2. Physical model and numerical methods

2.1. Physical model

The governing equations of the present code include the following continuity, momentum and energy equations,

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}=0 \tag{1}$$

Corrected Momentum equation:

$$\frac{\partial \rho u}{\partial t}+\frac{\partial \rho uu}{\partial x}+\frac{\partial \rho uv}{\partial y}=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+g_x\rho-\frac{\partial p}{\partial x}+\sigma k\delta_s n_x \tag{2}$$

$$\frac{\partial \rho v}{\partial t}+\frac{\partial \rho uv}{\partial x}+\frac{\partial \rho vv}{\partial y}=\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+g_y\rho-\frac{\partial p}{\partial y}+\sigma k\delta_s n_y \tag{3}$$