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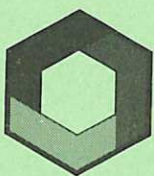
# A review of the available modelling of mixing in subcooled water

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D. F. Fletcher

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# **A review of the available modelling of mixing in subcooled water**

D.F. Fletcher

## **ABSTRACT**

In this paper we review the available models of melt/water mixing, for the situation where the water is subcooled. We present both simple analysis and experimental data to illustrate why water subcooling is important. We also examine the related issue of vapour superheating. We then present the conservation equations which describe this situation and the constitutive relations currently available. Finally, we draw some conclusions about the current state of knowledge in this area.

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## Nomenclature

$c_v$	heat capacity at constant volume
$c_p$	heat capacity at constant pressure
$d$	particle size
$e$	internal energy
$g$	acceleration due to gravity
$h$	heat transfer coefficient or enthalpy
$h_{fg}$	latent heat of vaporisation
$K$	momentum equilibration term
$k$	thermal conductivity
$L$	lengthscale
$Nu$	Nusselt number
$p$	pressure
$Pr$	Prandtl number
$Q$	energy transferred per unit volume
$\dot{Q}$	energy transfer rate per unit volume
$q$	heat flux per unit area
$R$	temperature equilibration term
$r$	radial coordinate
$Re$	Reynolds number
$T$	temperature
$t$	time
$U$	radial velocity
$V$	axial velocity
$z$	axial coordinate

## Greek Symbols

$\alpha$	volume fraction or void fraction
$\rho$	density
$\sigma$	surface tension or Stefan-Boltzmann constant
$\mu$	dynamic viscosity
$\Gamma$	vapour mass source per unit volume
$\Delta T_{sub}$	subcooling

## Subscripts

$i$	value at melt water interface
$m$	melt droplets
$sat$	saturation value
$sub$	subcooled
$v$	vapour
$w$	water

## 1 Introduction

A considerable amount of modelling work has been performed to study the mixing of a high temperature melt with water [1,2,3,4]. This issue is of importance in the study of highly unlikely severe reactor accidents, in which a significant amount of core material melts and then contacts residual coolant. The coolant may be water or sodium and it may be saturated or subcooled. Most effort to date has been directed towards the study of the mixing of molten core material with *saturated* water. This work has been motivated by the need to extrapolate data obtained from small-scale mixing experiments to reactor scale situations [3] in the study of steam explosions.

If the water is saturated and the melt is in droplet form, with a size of the order of 20mm, simulations show that a considerable amount of vapour is formed which causes rapid dispersion of the melt [4,5]. This type of behaviour has also been observed experimentally at small-scale [6]. However, if the water is subcooled there is considerably less vapour produced and the dispersive effect is much reduced [6].

Besides being of importance in the study of steam explosions, mixing simulations are also required to address the issue of debris quench. If the melt is fragmented as it interacts with coolant it may be quenched to form particulate debris, which may be cooled indefinitely and the maximum temperature of the melt particles is restricted to that of the surrounding liquid. Alternatively, if the melt is not quenched it may form a molten pool in the base of the Reactor Pressure Vessel. Which outcome occurs depends on the mixing processes taking place, which themselves depend on the degree of melt fragmentation, the depth of the water pool, the characteristics of the melt jet and many other parameters. These issues are discussed further in reference 28.

In the reactor application of this work there are essentially two possible situations where subcooling may be important. The first arises if the melt comes into contact with water from the emergency core cooling system, which is at ambient temperature. In this case there could be a very large subcooling ( $>80\text{K}$ ). The second possibility is that steam generation during the melt-water mixing process could lead to pressurization of an intact primary circuit, causing the water to become slightly subcooled [27].

In this report we describe the additional processes which must be included in a model of melt/water mixing applicable to saturated conditions for it to model the interaction of melt with subcooled water. We will assume that the reader has some familiarity with the physics and equations used to model mixing in saturated conditions in the CHYMES code (see reference 4 and 5 for details). In the next section we present a more detailed account of the additional physics introduced when the water is subcooled and we also present experimental data to show why subcooling is important. In section 3 we present the partial differential equations which are used to model this situation. In section 4 we describe the modelling work performed elsewhere in this area and critically review it. Finally, in section 5 we draw some conclusions about the current state of knowledge in this area.

## 2 The Effect of Subcooling on Melt/Water Mixing

Before giving a detailed account of the physics of mixing in subcooled conditions it is worth making a brief examination of the experimental evidence for its importance. At



first sight one might wonder why it is important at all. If melt is at a temperature of, say, 3000K why should it matter whether the water temperature is 373K (i.e. saturated at atmospheric pressure) or at, say, 300K? The energy required to remove 5K of subcooling at atmospheric pressure is only 1% of that required to vaporise it. (In the saturated case this amount of energy would cause significant dispersion of the mixture due to vapour generation.) The answer lies in the fact that much of the heat added to the water gets conducted or convected into the bulk of the water or is deposited there directly by radiation. Vapour is only formed at the interface between vapour and liquid water. (At present we will ignore the effect of flashing which occurs when the pressure is suddenly reduced.) As this vapour flows, it may be condensed on cold water and the net steam production rate is low. In saturated conditions there is no condensation and any heat transferred to the water produces steam. Thus the saturated system is much more dispersive. The new features added by the need to model subcooling are:

- a means of determining what fraction of energy added to the coolant produces vapour and what fraction causes bulk heating of the water;
- a model of condensation/boiling;
- appropriate heat transfer correlations for subcooled film boiling, heat transfer to subcooled water droplets, superheated steam etc.;
- suitable energy conservation equations for water and steam;
- an Equation of State (EOS) for water and steam;
- a modified procedure to solve the resulting equations.

## 2.1 Experimental Observations

At Argonne National Laboratory experiments have been performed to study corium quenching in a deep<sup>1</sup> water pool [6]. Corium (a mixture of  $\text{UO}_2$ ,  $\text{ZrO}_2$  and stainless steel) at a temperature of 3080K was injected as a 25mm diameter jet into a pool of water 320mm deep. In one experiment (CWTI-9) the water was subcooled by 6K and in another (CWTI-10) it was subcooled by 75K. Totally different behaviour was observed in the two different cases. In the low subcooling case, rapid steam generation caused the water pool to boil up into high void fraction regime. Steam production was so rapid that for a significant time ( $\sim 0.3s$ ) steam pressurisation of the mixing vessel halted melt inflow and 13% of the melt injected was swept out of the vessel. In contrast, in the high subcooling case no net steam generation occurred and the pool remained relatively quiescent.

These differences affected the melt quenching process in a number of ways. Firstly, the melt jet was broken up more in the low subcooling case, due to the violent stripping action of the steam flow. More particulate debris was formed in this case, and this debris had a smaller size. Secondly, twice as much melt was estimated to have

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<sup>1</sup>In the sense that the water depth was many jet diameters, so one would expect significant fragmentation of the jet (see [6] for details of a comparison of the experimental data with empirical "mixing" correlations).



been quenched in the fall stage in the low subcooling case. Thirdly, there was much greater hydrogen generation in the low subcooling case (16g compared with 2g in the high subcooling case). Thus it is clear from this example alone that subcooling can have a big effect on many processes of interest and a model to investigate these effect would be very useful. However, it is not clear whether subcooling promotes or reduces the melt quenching process. This is because the presence of subcooling changes the fragmentation behaviour of jets, as well as the particle to water heat transfer rate [29,30].

## 2.2 Some Simple Scoping Calculations

In this section we present some simple calculations to illustrate why subcooling is important and why its effect is difficult to model. Consider a unit volume which contains a fraction  $\alpha_m$  of melt in the form of spheres of diameter  $d$  and at a constant temperature  $T_m$ . Also assume that the remainder of the volume is filled with water which is subcooled by  $\Delta T_{sub}$  at atmospheric pressure. Then the number of particles in a unit volume is

$$n_p = \alpha_m / (\pi d^3 / 6) \quad (1)$$

and the energy transferred from the particles in time  $t$  is

$$Q = q t n_p \pi d^2 = 6 \alpha_m q t / d \quad (2)$$

where  $q$  is the heat flux per unit area. The heat required to raise *all* the water in the unit volume to its saturation temperature is

$$Q_{sub} = \alpha_w c_{pw} \rho_w \Delta T_{sub} \quad (3)$$

Assuming the following typical conditions,  $d = 10 \text{ mm}$ ,  $\Delta T_{sub} = 50 \text{ K}$ ,  $\rho_w = 960 \text{ kg/m}^3$ ,  $c_{pw} = 4200 \text{ J/kgK}$ ,  $\alpha_m = 0.3$ ,  $\alpha_w = 0.7$ ,  $q = 4 \text{ MW/m}^2$  and  $h_{fg} = 2.2 \text{ MJ/kg}$  it can easily be shown that:

1. If all the heat transferred from the melt is used to remove subcooling, no vapour would be produced for 0.2s.
2. If no heat was used to raise the temperature of the bulk of the water the steam production rate would be 90% of that which would have occurred in saturated conditions (assuming the same heat flux and no condensation).

It is clear from these calculations that subcooling can have an important effect on the outcome of the mixing process when melt is poured into water. In large-scale mixing simulations [5] the melt front reaches the base of the vessel after about 0.5s. Thus if a significant fraction of the heat is conducted/convected into the bulk of the water, the melt/water mixture will not be dispersed during the fall phase. However, if very little of the heat is used for bulk heating of the water the mixing process will be almost as dispersive as it is in saturated conditions [5]. The evidence gained from the small-scale mixing experiments described in section 2.1 suggests that the first case is closer to reality. However, we must remember that in experiments only the *net vapour*

SUBCOOLING (K)	FRACTION OF ENERGY PRODUCING VAPOUR		
	p=0.1 MPa	p=1.0 MPa	p=10.0 MPa
0	1.00	1.00	1.00
10	0.52	0.78	0.89
20	0.29	0.60	0.81
40	0.14	0.36	0.58
60	0.10	0.23	0.48
80	0.05	0.15	0.40
100	—	0.13	0.32

Table 1: The fraction of energy producing vapour as a function of subcooling and pressure.

production rate is observed i.e. any vapour that is formed may be condensed very rapidly due to the presence of cold water.

A recent study [22] of heat transfer issues of importance in the vapour explosions process provides some quantitative data on the partition of energy between vapour production and conduction into the bulk of the fluid. The authors assume that energy is conducted from a high temperature melt across a vapour layer which is at a constant pressure. At the vapour/water interface (which is at the local saturation temperature) some energy produces vapour and some is conducted into the bulk of the water. An approximate solution to the problem was found in which the vapour film thickness grows proportional to  $\sqrt{t}$ . Table 1 shows the fraction of energy conducted across the vapour film which produces vapour as a function of pressure and subcooling. The figures in the above table show that with only  $10^\circ\text{C}$  of subcooling at ambient pressure almost 50% of the energy conducted across the vapour film is conducted into the surrounding water.

Although the validity of the model is questionable, e.g. in reality vapour would flow away, heat transfer to the water would be convective as well as conductive, radiation is neglected, heat transfer by bulk vapour flow is neglected and the approximation of treating heat conduction across the vapour layer as a steady-state problem is only justified at very high subcoolings (according to analysis performed by the authors), it provides a very useful quantitative description of the effect of subcooling. The model also highlights the difference between coolants of sodium and water. In the case of sodium at atmospheric pressure only  $\sim 1^\circ\text{C}$  of subcooling is required to halve the vapour production rate from the value at saturation.

A related issue to that of water subcooling is the effect of vapour superheating. Assume a similar situation to that described earlier except that now all the water has been vaporised and steam is flowing through the melt particles with a relative velocity  $V$ . Assuming that heat transfer to the steam is by forced convection, we have [7]

$$Nu = 2 + 0.6Re^{0.5}Pr^{0.33}. \quad (4)$$

In addition to the data given above assume that  $k = 0.024 \text{ W/mK}$ ,  $\rho_v = 0.6 \text{ kg/m}^3$ ,  $V_{rel} = 50 \text{ m/s}$ ,  $\mu_v = 10^{-5} \text{ Nsm}^{-2}$ ,  $c_{pv} = 2000 \text{ J/kgK}$  and  $T_m = 3000 \text{ K}$ . Using this data we obtain a heat transfer coefficient of  $100 \text{ W/m}^2\text{K}$ . (The Reynolds number



is 30,000 which is well inside the range of the correlation.) Now, performing a heat balance on the vapour gives

$$\frac{d}{dt}(\rho_v \alpha_v c_{vv} T_v) = 6\alpha_m \frac{h}{d}(T_m - T_v). \quad (5)$$

Setting  $T_m = \text{constant}$  and assuming  $T_v(0) = T_{sat}$  gives

$$T_m - T_v = (T_m - T_{sat})e^{-\lambda t} \quad (6)$$

where  $\lambda = 6\alpha_m h / (\rho_v c_{vv} \alpha_v d)$ . For the chosen conditions  $\lambda$  takes a value of  $22 \text{ s}^{-1}$ . Thus after only 0.1s the vapour temperature would be 2700 K. Assuming an ideal gas law for the vapour EOS suggests that this rise in temperature could increase the pressure to about 9 bars. However, mixing is not performed in a closed box so it is not possible to say exactly what effect the superheating would have. Based on this simple calculation its effect would lie somewhere between increasing the pressure by a factor of about 10 (assuming mixing in a closed box) or increasing the mixture volume by a factor of about 10 (assuming mixing at constant pressure). The first case would cause an increase in the subcooling of any water present and, hence, enhanced vapour condensation whereas the second situation would lead to greater dispersion of the melt. Since the condensation rate depends on the pressure, because this determines the temperature at the steam/water interface, and the water and steam temperatures it is not a simple matter to determine exactly how the condensation rate would be affected. The situation is further complicated by the fact that the vapour has to travel only a few metres to escape from the mixture, which takes only  $\sim 0.05\text{s}$  assuming a velocity of the order of  $50\text{m/s}$ . Thus the effect of vapour superheating can only be addressed properly by performing mixing calculations allowing for it and comparing the results with those for a situation where it is assumed not to occur.

To conclude this section, we should note that adding subcooling of the water and superheating of vapour leads to effects which are not straight forward to quantify but could potentially have a big effect on the outcome of a mixing simulation.

### 3 Conservation Equations

In this section we present the conservation equations for mass, momentum and energy which would be required to form a transient, 2d axisymmetric, 3-component model. A multiphase treatment is assumed in which each species feels a common pressure and the presence of different species is represented by using volume fractions. We use the following labelling convention: melt (m), water (w) and vapour (v). The melt is assumed to be incompressible, whereas the steam and water are treated as being compressible. We also assume that there is an average steam temperature and an average water temperature in each cell, so that this framework cannot model *local* disequilibrium processes, such as temperature boundary layers at the water/steam interface.

The equations for incompressible flow are fully described in reference 4, which gives a complete description of the CHYMES code. A compressible version of CHYMES, in which the water and steam are assumed to have barotropic equations of state (the vapour is assumed to be saturated and the water is allowed to become subcooled but



no condensation is allowed) is described in reference 8. The following equations can be found in any standard text on multiphase flow e.g. Harlow and Amsden [9].

### 3.1 Conservation of Mass

Conservation of mass applied to each species gives the following equations for mass conservation for the melt, water and steam

$$\frac{\partial}{\partial t}(\alpha_m) + \frac{1}{r} \frac{\partial}{\partial r}(r\alpha_m U_m) + \frac{\partial}{\partial z}(\alpha_m V_m) = 0, \quad (7)$$

$$\frac{\partial}{\partial t}(\alpha_w \rho_w) + \frac{1}{r} \frac{\partial}{\partial r}(r\alpha_w \rho_w U_w) + \frac{\partial}{\partial z}(\alpha_w \rho_w V_w) = \dot{m}_w \quad (8)$$

and

$$\frac{\partial}{\partial t}(\alpha_v \rho_v) + \frac{1}{r} \frac{\partial}{\partial r}(r\alpha_v \rho_v U_v) + \frac{\partial}{\partial z}(\alpha_v \rho_v V_v) = \dot{m}_v. \quad (9)$$

Conservation of mass requires that

$$\dot{m}_w + \dot{m}_v = 0. \quad (10)$$

For simplicity of notation, we denote  $\dot{m}_v = \Gamma$ . It is noteworthy that the equation for the melt is very different from those for the vapour and water. The melt equation provides a means of determining  $\alpha_m$  explicitly (see reference 4), whereas only the product  $\alpha\rho$  is obtainable for the compressible components.

### 3.2 Conservation of Momentum

Conservation of momentum in the radial and axial directions for each species gives:

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_m \rho_m U_m) + \frac{1}{r} \frac{\partial}{\partial r}(r\alpha_m \rho_m U_m^2) + \frac{\partial}{\partial z}(\alpha_m \rho_m U_m V_m) = \\ -\alpha_m \frac{\partial p}{\partial r} + K_{mw}^r (U_w - U_m) + K_{mv}^r (U_v - U_m), \end{aligned} \quad (11)$$

(melt)

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_m \rho_m V_m) + \frac{1}{r} \frac{\partial}{\partial r}(r\alpha_m \rho_m U_m V_m) + \frac{\partial}{\partial z}(\alpha_m \rho_m V_m^2) = \\ -\alpha_m \frac{\partial p}{\partial z} - g\alpha_m \rho_m + K_{mw}^z (V_w - V_m) + K_{mv}^z (V_v - V_m), \end{aligned} \quad (12)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_w \rho_w U_w) + \frac{1}{r} \frac{\partial}{\partial r}(r\alpha_w \rho_w U_w^2) + \frac{\partial}{\partial z}(\alpha_w \rho_w U_w V_w) = \\ -\alpha_w \frac{\partial p}{\partial r} + K_{vw}^r (U_v - U_w) + K_{mw}^r (U_m - U_w) + F_{mw}^r, \end{aligned} \quad (13)$$

(water)

$$\begin{aligned} \frac{\partial}{\partial t}(\alpha_w \rho_w V_w) + \frac{1}{r} \frac{\partial}{\partial r}(r\alpha_w \rho_w U_w V_w) + \frac{\partial}{\partial z}(\alpha_w \rho_w V_w^2) = \\ -\alpha_w \frac{\partial p}{\partial z} - g\alpha_w \rho_w + K_{vw}^z (V_v - V_w) + K_{mw}^z (V_m - V_w) + F_{mw}^z, \end{aligned} \quad (14)$$

$$\begin{aligned} & \frac{\partial}{\partial t}(\alpha_v \rho_v U_v) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_v \rho_v U_v^2) + \frac{\partial}{\partial z}(\alpha_v \rho_v U_v V_v) = \\ & -\alpha_v \frac{\partial p}{\partial r} + K_{vw}^r (U_w - U_v) + K_{mv}^r (U_m - U_v) + F_{mv}^r, \end{aligned} \quad (15)$$

(vapour)

$$\begin{aligned} & \frac{\partial}{\partial t}(\alpha_v \rho_v V_v) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_v \rho_v U_v V_v) + \frac{\partial}{\partial z}(\alpha_v \rho_v V_v^2) = \\ & -\alpha_v \frac{\partial p}{\partial z} - g \alpha_v \rho_v + K_{vw}^z (V_w - V_v) + K_{mv}^z (V_m - V_v) + F_{mv}^z. \end{aligned} \quad (16)$$

The terms on the RHS of the momentum equations model the effect of the pressure gradient force, the buoyancy force due to gravity, inter-component drag and the evaporation reaction force. The above equations are unchanged from those used in the incompressible case. We will assume that the drag laws used in the saturated case can also be applied in this case.

Conservation of momentum for the water and steam requires that, e.g.

$$F_{mv}^r + F_{mw}^r = 0. \quad (17)$$

If  $\Gamma > 0$ , evaporation is occurring and we define  $F_{mw}^r = -\Gamma U_w$  and if  $\Gamma < 0$ , condensation is occurring and we define  $F_{mw}^r = \Gamma U_w$ . This practice is consistent with that employed in CHYMES [4], where  $\Gamma \geq 0$ .

### 3.3 Conservation of Energy

For each species we also have an energy conservation equation. Since we are not concerned with modelling supersonic flow in this application there is no need to form stagnation energy equations. We will neglect terms arising from drag work and evaporation work since these are small compared with the inter-species heat fluxes. Thus we have the following energy equations:

$$\begin{aligned} & \frac{\partial}{\partial t}(\alpha_m \rho_m e_m) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_m \rho_m U_m e_m) + \frac{\partial}{\partial z}(\alpha_m \rho_m V_m e_m) = \\ & + R_{mv}(T_v - T_m) + R_{mw}(T_w - T_m) - \dot{Q}_{mi}, \end{aligned} \quad (18)$$

$$\begin{aligned} & \frac{\partial}{\partial t}(\alpha_w \rho_w e_w) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_w \rho_w U_w e_w) + \frac{\partial}{\partial z}(\alpha_w \rho_w V_w e_w) \\ & + p \left( \frac{\partial}{\partial t}(\alpha_w) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_w U_w) + \frac{\partial}{\partial z}(\alpha_w V_w) \right) \\ & = R_{mw}(T_m - T_w) + R_{wi}(T_i - T_w) + \dot{Q}_{mw}, \end{aligned} \quad (19)$$

$$\begin{aligned} & \frac{\partial}{\partial t}(\alpha_v \rho_v e_v) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_v \rho_v U_v e_v) + \frac{\partial}{\partial z}(\alpha_v \rho_v V_v e_v) \\ & + p \left( \frac{\partial}{\partial t}(\alpha_v) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_v U_v) + \frac{\partial}{\partial z}(\alpha_v V_v) \right) \\ & = R_{mv}(T_m - T_v) + R_{vi}(T_i - T_v) + \dot{Q}_{mv}. \end{aligned} \quad (20)$$

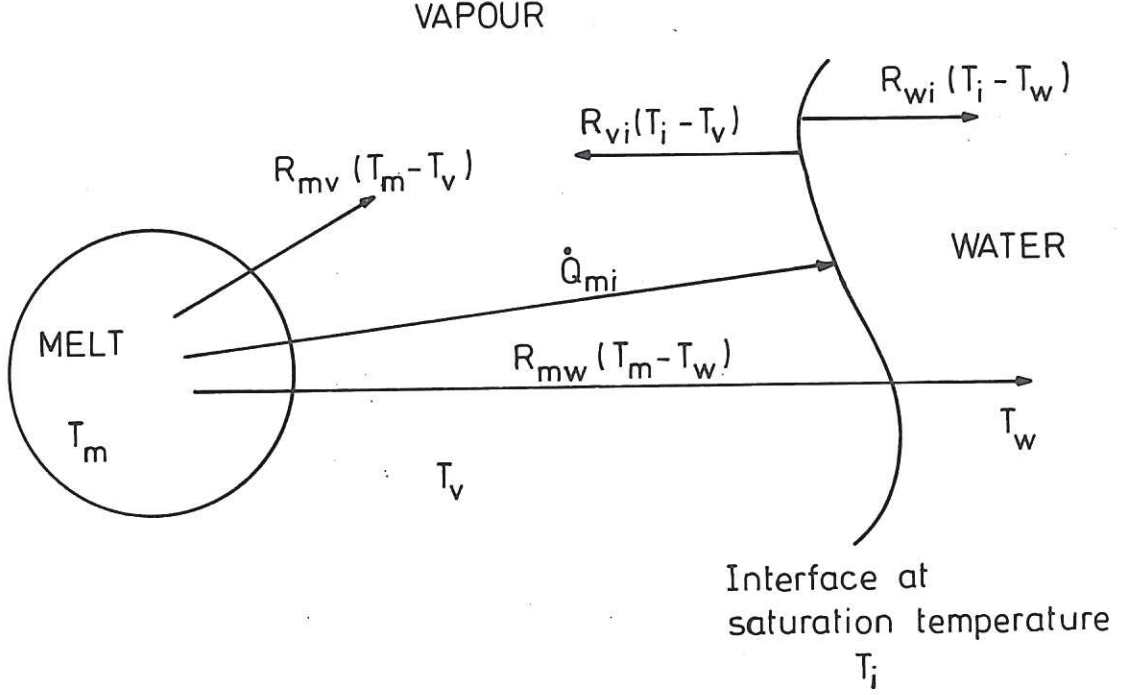


Figure 1: A Schematic Representation of the Heat Transfer Components.

The terms containing  $R_{mw}$  model heat transfer between the melt and the bulk of the water etc. The term  $\dot{Q}_{mi}$  represents the heat transfer from the melt to the steam/water interface. The terms containing  $R_{wi}$  model heat transfer from the the bulk of the water to the steam/water interface etc. and  $T_i$  is the saturation temperature corresponding to the local pressure.<sup>2</sup> These heat transfer components are shown schematically in Figure 1. Finally,  $\dot{Q}_{mv}$  and  $\dot{Q}_{mw}$  are the energy transfer terms due to phase change effects. Conservation of energy for the system requires that

$$R_{vi}(T_i - T_v) + R_{wi}(T_i - T_w) - \dot{Q}_{mi} + \dot{Q}_{mv} + \dot{Q}_{mw} = 0. \quad (21)$$

The above equation provides a means of determining  $\Gamma (= \dot{m}_v)$ . Now, we can write  $\dot{Q}_{mv} = \Gamma h_{vi}$  etc., where  $h_{vi}$  is the enthalpy of vapour at the interface. Then equation (21) can be rearranged to give

$$\Gamma = \frac{-R_{vi}(T_i - T_v) - R_{wi}(T_i - T_w) + \dot{Q}_{mi}}{h_{vi} - h_{wi}}. \quad (22)$$

The above equation simply says that the net vaporisation (or condensation) rate is the sum of the heat deposited (lost) from the interface divided by a suitable enthalpy of vaporisation. Following the procedure employed in TRAC [10] we choose  $h_{wi}$  and  $h_{vi}$  as follows: if

$$(-R_{vi}(T_i - T_v) - R_{wi}(T_i - T_w) + \dot{Q}_{mi}) > 0,$$

<sup>2</sup>This assumption is valid because condensation or evaporation act very rapidly to establish the new saturation temperature, corresponding to the new vapour pressure, at the interface [22].



then evaporation is occurring and we set  $h_{vi} = h_{v,sat}$  and  $h_{wi} = h_w$ ; if

$$(-R_{vi}(T_i - T_v) - R_{wi}(T_i - T_w) + \dot{Q}_{mi}) < 0,$$

then condensation is occurring and we set  $h_{vi} = h_v$  and  $h_{wi} = h_{w,sat}$ .

We still have to determine expressions for  $R_{mw}$ ,  $R_{mv}$ ,  $R_{wi}$ ,  $R_{vi}$  and  $\dot{Q}_{mi}$ . Using equations (1) and (2) it is easy to show that (assuming the melt is in the form of spherical droplets);

$$R_{mw} = \frac{\alpha_m}{6L_m} h_{mw},$$

$$R_{mv} = \frac{\alpha_m}{6L_m} h_{mv}.$$

The interface heat transfer terms are given by

$$R_{wi} = \frac{\alpha_w}{6L_w} h_{wi},$$

and

$$R_{vi} = \frac{\alpha_w}{6L_w} h_{vi},$$

if the water is in the form of droplets (i.e. the steam is the continuous phase) or

$$R_{wi} = \frac{\alpha_v}{6L_v} h_{wi},$$

and

$$R_{vi} = \frac{\alpha_v}{6L_v} h_{vi},$$

if the steam is in the form of bubbles (i.e. the water is the continuous phase). Extra volume fraction factors need to be added in the above expressions to ensure consistency i.e. so that water to steam heat transfer occurs only if both species are present. Also, some sort of interpolation procedure is needed in the intermediate (churn-turbulent) regime in order to determine the interfacial area.

Thus we now need to formulate models for the interfacial areas or length-scales, heat transfer coefficients and the term  $\dot{Q}_{mi}$ . This task will form the main part of section 4.

### 3.4 Additional Equations

In addition to the above equations we also have the constraint

$$\alpha_m + \alpha_w + \alpha_v = 1, \quad (23)$$

which must be satisfied everywhere. This equation plays a very important role in the determination of the pressure [8,9].

Additional equations are often solved to determine the local melt particle size. As an example we include below the form used in CHYMES.

$$\frac{\partial}{\partial t}(\alpha_m L_m) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_m U_m L_m) + \frac{\partial}{\partial z}(\alpha_m V_m L_m) = \dot{m}_L. \quad (24)$$

Other workers, for example Young [11], prefer to work with the interfacial area per unit mass. However, since the present state of modelling is such that the melt is assumed to be in the form of spherical droplets the different forms are isomorphic. If a detailed model of jet breakup is developed it would seem sensible to move to using interfacial area as the fundamental variable.

To finish this section we note that an equation of state (EOS) is required to close the model. The form of EOS required depends on the solution procedure employed but following our earlier work [8] it would seem sensible to use an explicit solution procedure to determine  $\alpha\rho$  from the mass conservation equations, to determine  $U$  and  $V$  from the momentum equations, to determine  $e$  from the energy equations and then to use equation (23) together with an EOS of the form

$$p = p(\rho, e), \quad T = T(\rho, e) \quad (25)$$

to close the system. Unfortunately, a suitable EOS of this form does not appear to be readily available. Most existing codes use implicit methods (in order to avoid modelling the rapid rate processes of interest to us) so that, for example, TRAC [10] uses an EOS of the form  $\rho = \rho(p, T)$  and  $h = h(p, T)$ .

## 4 A Review of Existing Models

In this section we present a critical review of the existing models of mixing in subcooled water. In fact there are only really two existing models: PM-ALPHA being developed by Theofanous and co-workers at the University of Santa Barbara, California [2] and IFCI being developed by Young at Sandia [11].

An Advanced Fluid Dynamics Model (AFDM) [26] is being developed as a replacement for the SIMMER code but it is not yet completed and there is no detailed description of the constitutive physics available at present. It is based on the same conservation equations as those presented in section 3 and uses the same inter-component energy transfer framework. However, all of the energy transferred from the melt to the water is added to the bulk of the water, i.e.  $\dot{Q}_{mi} = 0$  and subcooled water can only be vapourised by hot vapour.

### 4.1 The PM-ALPHA Code

This model was developed by Amarasooriya and Theofanous [2] to study the coarse mixing stage of steam explosions. Before describing the detailed constitutive models it is important to note that the model contains grave errors which mean that no reliance can be placed on the answers it gives. These errors are summarised below.

- The pressure work terms in the energy equations for the steam and water are wrong. The form used in PM-ALPHA is

$$\left( \frac{\partial}{\partial t}(\alpha_w p) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_w U_w p) + \frac{\partial}{\partial z}(\alpha_w V_w p) \right)$$

instead of the correct form

$$p \left( \frac{\partial}{\partial t}(\alpha_w) + \frac{1}{r} \frac{\partial}{\partial r}(r \alpha_w U_w) + \frac{\partial}{\partial z}(\alpha_w V_w) \right).$$

It is interesting to note that PM-ALPHA is based on the K-FIX code [12] which models the pressure work correctly.

- The phase change model used in the code is unphysical. All the heat transfer from the melt is assumed to be to the bulk of the water or steam (details are given later). The rates of evaporation and condensation are given by [13]

$$J_e = \frac{\alpha_v \rho_v}{\Delta t} \left\{ \left( \frac{p_{sat}}{p} \right)^{\frac{1}{\gamma}} - 1 \right\} \quad (26)$$

and

$$J_c = \frac{\alpha_v \rho_v}{\Delta t} \left\{ 1 - \left( \frac{p_{sat}}{p} \right)^{\frac{1}{\gamma}} \right\}, \quad (27)$$

where  $\gamma$  is the ratio of specific heats,  $p_{sat}$  is the saturation pressure and  $\Delta t$  is the computational time-step. Thus the phase change model depends explicitly on the chosen time-step and the only grid independent solution is for the system to be in thermal equilibrium. In addition, evaporation can occur even when there is no water present. Also, all the interfacial enthalpies are set equal to  $h_v$  but this hardly matters given the above errors.

- Many quantities vary discontinuously in the model. For example, at a void fraction of 0.7 the drag force changes discontinuously by over two orders of magnitude, as the flow regime is switched from churn-turbulent to dispersed droplet flow.

#### 4.1.1 Water-Steam Heat Transfer

If the void fraction ( $\alpha$ ) is less than 0.7 the system is assumed to be in thermal equilibrium and no heat transfer between the water and the steam is allowed. If  $\alpha > 0.7$  then a water droplet flow regime is assumed with heat transfer due to forced convection. The following correlation is applied [7]

$$Nu = 2 + 0.6Re^{0.5}Pr^{0.33} \quad (28)$$

where the droplet length-scale is obtained from a Weber number criterion assuming a critical Weber number of 12, i.e.

$$\frac{\rho_v |V_w - V_v|^2 L_w}{\sigma} = 12. \quad (29)$$

#### 4.1.2 Melt-Water Heat Transfer

All the heat is assumed to be deposited in the bulk of the water, i.e.  $\dot{Q}_{mi} = 0$ . For  $\alpha < 0.7$  heat transfer to the water is assumed to be the sum of a radiation term and a film-boiling term. Radiation is modelled assuming that the melt is in the form of spheres with an emissivity of 0.7. Film boiling heat transfer is modelled using the *saturated* convective film boiling model of Witte [14] which gives

$$h = 2.98 \left\{ \frac{\rho_v k_v \{ h_{fg} + 0.68 c_{pv} (T_m - T_w) \}}{d_m (T_m - T_w)} |V_m - V_w| \right\}^{\frac{1}{2}}. \quad (30)$$



If  $\alpha > 0.7$  the water is assumed to be in droplet form surrounded by melt. In this case the radiation heat flux per unit volume is given by

$$Q = \min(n_m \pi d_m^2, n_w \pi d_w^2) \sigma E_d (T_m^4 - T_w^4) \quad (31)$$

where  $n_m$  and  $n_w$  are the number of melt droplets and the number of water droplets per unit volume, respectively and are evaluated as in equation (1). The factor  $E_d$  is introduced to allow for the smallness of the drops and is set equal to 0.3. This model is highly idealized, as noted by the authors.

#### 4.1.3 Melt-Steam Heat Transfer

For  $\alpha < 0.7$ , there is assumed to be no heat transfer to the steam from the melt. If  $\alpha > 0.7$  then the model decides between the choice of two regimes. If  $\alpha_m < 0.7$  the convective heat transfer coefficient given by equation (28) is applied. If  $\alpha_m > 0.7$  the melt is assumed to form a packed bed and the heat transfer coefficient is obtained from the following correlation [7]:

$$h = 0.91 c_{pm} \alpha_v \rho_v |V_m - V_v| Pr^{-0.67} Re_v^*{}^{-0.51} \quad Re^* < 50 \quad (32)$$

$$h = 0.61 c_{pm} \alpha_v \rho_v |V_m - V_v| Pr^{-0.67} Re_v^*{}^{-0.41} \quad Re^* > 50 \quad (33)$$

where  $Re^*$  is a modified Reynolds number given by

$$Re^* = \frac{\alpha_v d_m \rho_v |V_m - V_v|}{6 \alpha_m \mu_v}$$

No check is performed to determine whether the melt is molten or not and there is no limit on the packing fraction.

## 4.2 The IFCI Code

The IFCI code is being developed as the steam explosion module of the MELPROG code. Thus it contains modelling for all stages of the steam explosion process. Unfortunately, to date it has not been extensively documented and there is no detailed description of the conservation equations or constitutive equations used in the model. However, it is known [15] that the water-steam heat transfer is based on the modelling used in TRAC-PF1 [10].

### 4.2.1 Water-Steam Heat Transfer

If  $\alpha < 0.5$  a bubbly flow regime is assumed. The bubble size is calculated using a critical Weber number of 7.5, with the constraint that the interfacial area between the water and steam does not fall below an ad-hoc minimum value. If the water is superheated  $h_{iw}$  is assumed to be the larger of that obtained from a modified Plesset-Zwick bubble growth model [16] and the Lee-Ryley convective heat transfer correlation [17]. The Plesset-Zwick model gives

$$Nu = \frac{12 (T_w - T_{sat})}{\pi \rho_v h_{fg}} \rho_w \frac{\partial e_w}{\partial T_w}, \quad (34)$$

where the term  $\frac{\partial e_w}{\partial T_w}$  is equivalent to a specific heat capacity, but the original reference does not specify what is being kept constant. For all practical purposes this uncertainty should not matter. The Lee-Ryley correlation gives

$$Nu = 2 + 0.74Re^{0.5}Pr^{0.33}. \quad (35)$$

For subcooled water,  $h_{wi}$  is obtained from a turbulent convection correlation as

$$h_{wi} = 0.02\rho_w c_{pw} |V_w - V_v|. \quad (36)$$

In this regime the vapour to interface heat transfer coefficient is set to one of two constants. If the vapour is superheated  $h_{vi} = 10^3 \text{ W/m}^2\text{K}$  and if it is subcooled  $h_{vi} = 10^4 \text{ W/m}^2\text{K}$ .

If  $\alpha > 0.75$  dispersed droplet flow is assumed. The droplet size is obtained using a critical Weber number of 4. It is suggested that this low value applies because the droplets are accelerating. If the water is superheated the following expression is used

$$h_{wi} = 15,000 \frac{k_w}{d_w}$$

and if the water is subcooled

$$h_{wi} = 0.02\rho_w c_{pw} V_{circ},$$

where  $V_{circ}$  is the the droplet circulation velocity given by

$$V_{circ} = \min \left( 0.5 \left( \frac{\mu_v}{\mu_v + \mu_w} \right) |V_w - V_v|, 1.4 \sqrt{\sigma / (d_w \rho_w)} \right).$$

The vapour-interface heat transfer coefficient is obtained from the Lee-Ryley correlation (see equation (35)).

If the void fraction is in the range  $0.5 < \alpha < 0.75$  interpolated values are obtained using cubic splines.

It is clear from the form of these correlations and from reading the TRAC manual that many of these models have been obtained by "tuning" TRAC output to match experimental data. Their validity in the steam explosion situation must be questionable.

## 5 Discussion and Conclusions

In this section we will try to make some recommendations for the best choice of constitutive relations from those available. There is no reason to doubt that the equations given in section 3 are correct<sup>3</sup> and we will assume that the main task is to provide the necessary heat transfer constitutive relations.

<sup>3</sup>Given that one is going to write conservation equations which assume a unique temperature etc. in each cell.



PATH-LENGTH (mm)	FRACTION OF INCIDENT ENERGY ABSORBED		
	$T_m = 1000K$	$T_m = 2500K$	$T_m = 3500K$
1	0.97	0.60	0.34
5	1.00	0.71	0.47
10	1.00	0.76	0.53
20	1.00	0.81	0.59
30	1.00	0.83	0.62

Table 2: The fraction of incident energy absorbed as a function of melt temperature and path-length.

## 5.1 Discussion of Models

### 5.1.1 Interfacial Area

The interfacial area between the water and steam seems to be calculated using a Weber number criterion in most codes. This assumes that droplet fragmentation is instantaneous. It would be possible to solve conservation equations for the water and steam length-scale, but the source terms are difficult to deduce. In the first instance it would probably be sensible to specify bubble and droplet sizes and to scope the effect of this parameter.

### 5.1.2 Radiation Heat Transfer

Radiation heat transfer is complicated both by the fact that the geometry is very complex, so that view factors are impossible to evaluate, and that for high temperature sources radiation is poorly absorbed in water.

Harpole [25] has studied radiative absorption by evaporating drops, for a droplet temperature of 373K surrounded by a black-body emitter with a temperature up to 1450K. He used a ray tracing approach which included the effect of polarization, refraction, external reflection, multiple internal reflections and absorption. Unfortunately, the maximum temperature studied is at least 1000K too low for our application (the work was motivated by the need to understand radiation heat transfer in core reflood experiments). However, his results show, for example, that the volumetric heat flux deposited in the drop peaks at the surface of the drop and falls by two orders of magnitude at the centre of a 3mm drop surrounded by a black-body at 1450K. Data of this sort may assist with the task of partitioning the radiation heat flux.

A detailed study of radiation heat transfer during mixing is given in Appendix 1 of Reference 18. For completeness a few illustrative results will be presented here. For water at 300 K and atmospheric pressure Table 2 gives the fraction of energy absorbed for various melt temperatures and radiation path-lengths. The results presented in Table 2 show that for high temperature melt about 40% of radiation energy is absorbed at the vapour/liquid interface (i.e. within the first millimetre) and that if the water is in the form of droplets with a diameter of 10mm only about 50-75% of the incident thermal energy is absorbed. Thus in addition to allowing for the emissivity of the melt ( $\sim 0.83$  for  $UO_2$  [19]) an allowance for the long absorption length of water is required. As a first approximation the data given in Table 2 could be used to derive an



approximate radiation energy partition between that added to the interface and that added to the bulk of the water.

All existing models neglect the absorption of radiation by steam. Calculations presented in reference 18 suggest that this is a good approximation provided the pressure is close to atmospheric. For example, for a melt temperature of 3500K only 6% of the incident energy is absorbed in 100mm of saturated steam. This figure falls to 2.5% if the steam is heated to 2000K. However, if the steam pressure is increased to 6MPa (and the temperature is held fixed at 2000K) 30% of the incident radiation is absorbed in 100mm. Thus if the model is to be applied to high pressure situations it is probably necessary to allow for radiation heating of the steam.

### 5.1.3 Film Boiling Heat Transfer

The correlation developed by Witte [14], see equation (30), is usually employed to model convective film boiling heat transfer. The model was developed by making the following assumptions:

1. the water is saturated;
2. the vapour flow is laminar;
3. radiation heat transfer can be neglected;
4. the vapour film becomes so thick 90° around from the stagnation point that there is no further contribution to heat transfer from conduction across the remainder of the vapour film.

In the present application, where the melt-water temperature difference is very large it seems likely that assumptions (2) and (3) will be in error.

Dhir and Purohit [20] have studied film boiling on solid spheres experimentally. They used 19 and 24mm spheres of steel, copper and silver. Their experiments covered the following parameter range: flow velocities of 0-0.45m/s, subcoolings of 0-50K and sphere temperatures up to about 1500K. Thus they do not cover the region of interest to us, where radiation heat transfer is significant and the flow velocities are an order of magnitude larger. For saturated flow conditions they found that their experimentally measured heat fluxes were considerably higher (a factor of 5 times higher for  $Re = 10^5$ ) than those predicted by the Witte correlation.

They found that all their data was well represented by the following formula:

$$Nu = Nu_0 + 0.8Re^{0.5} \left( 1 + \frac{ScPr_v}{ShPr_w\mu} \right) \quad (37)$$

where

$$Nu_0 = 0.8 \left( \frac{g\rho_v(\rho_w - \rho_v)h_{fg}d^3}{\mu_v k_v (T_m - T_{sat})} \right)^{\frac{1}{4}}$$

and

$$\left( 1 + \frac{ScPr_v}{ShPr_w\mu} \right) = \left( 1 + \frac{k_w(T_{sat} - T_w)}{k_v(T_m - T_{sat})} \right)$$

Film and transition boiling on solid spheres has also been studied by Zvirin et al. [24] at Harwell. Unfortunately, the maximum sphere temperature was again low ( $\sim 450^\circ\text{C}$ ) and to date the heat transfer data has not been compared with the work of others. Once this has been done it should provide an independent check on the correlation proposed by Dhir and Purohit (see above).

In the absence of more relevant data<sup>4</sup> it would seem wise to employ the above model in preference to that of Witte, since it does make some allowance for the effect of subcooling. For a melt temperature of 2000K and a subcooling of 50K at atmospheric pressure, the subcooled heat flux is approximately 1.7 times larger than the saturated heat flux, so a big error is not introduced by ignoring the effect of subcooling on this heat transfer process.

#### 5.1.4 Convective Heat Transfer

All the convective heat transfer correlations available are of the form

$$Nu = 2 + aRe^{0.5}Pr^{0.33} \quad (38)$$

where  $a$  takes the value of 0.6 in the correlation recommended by Bird, Stewart and Lightfoot [7], 0.74 in the correlation by Lee & Ryley [17] and  $0.6/B$ , where  $B = (h_v - h_{sat})/h_{fg}$ , in the correlation of Yuen and Chen [21]. In the Yuen & Chen correlation the factor  $B$  was introduced to account for the fact that the saturated steam produced by evaporation of the drop reduces the local steam temperature. (In this correlation all properties are evaluated at the film temperature, except for the density in the Reynolds number which must be that of the free stream.)

It would seem sensible to choose the correlation of Lee & Ryley, since it is the only one based on experimental data for steam flow past water droplets. (Since the spread in values of  $a$  is small it does not really matter which correlation is used.)

#### 5.1.5 Equation of State for Water

An equation of state for water and steam of the correct form (i.e.  $p = p(\rho, e)$  and  $T = T(\rho, e)$ ) does not appear to be readily available. This problem can be overcome by using an iterative procedure to correct a guessed  $T$  in a  $p(\rho, T)$  formulation, which ensures that the  $e$  produced by the EOS is the same as that predicted by the energy equation. For example, the CEGB steam table package gives a fit to the free energy [31], so that it could be used in the manner described above. However, because of the numerical differentiation involved in evaluating quantities such as the pressure it is computationally very expensive to use. Thus, it may be necessary to find a suitable approximate EOS, if the approach described in this paper is to be pursued.

## 5.2 Conclusions

In this paper we have attempted to examine the effect of water subcooling on the melt/water mixing process and to review critically the available models. It is clear

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<sup>4</sup>A recent study by Naylor [23] has highlighted the need for film boiling data relevant to the vapour explosion situation.



from experimental data that water subcooling can have a very significant effect on the mixing process because of the decreased vapour production rate and hence the reduced dispersion and fragmentation of the melt. However, the processes involved are extremely difficult to model because of uncertainties in the constitutive physics. The main points to arise in the course of the review are listed below.

1. The effects of water subcooling and steam superheating may be very important. This view is supported by both experimental observations and simple calculations. The effect of subcooling on melt quenching is complicated because the subcooling affects the steam flow rate and hence the fragmentation rate of the melt. Thus, although increased water subcooling leads to higher heat fluxes from the melt, the melt has less surface area in contact with the water.
2. Given that a multiphase flow model is to be used in which there is a uniform temperature locally in each species, the conservation equations for mass, momentum and energy are relatively well founded.
3. The constitutive relations for energy transfer are not well-known and the limited amount of previous work uses very empirical correlations. In particular, the models which determine how much energy produces vapour and how much is conducted into the bulk of the water are very crude. Unfortunately, these determine how much vapour is produced.
4. We have made recommendations for the choice of most of the constitutive relations needed to close the model. However, many of these suggestions are made on the basis of the plausibility of the models and not on their proven usefulness. Where we have not made recommendations (because the data are too sparse) it would be necessary to guess appropriate closure relations.
5. Assuming that a model was developed it is not clear that there are sufficient data available to validate it.

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## References

- [1] S.G. Bankoff and S.H. Han, *Mixing of molten core material and water*. Nucl. Sci. and Eng, **85**, 387-395, (1983).
- [2] W.H. Amarasooriya and T.G. Theofanous, *Premixing of steam explosions: A three-fluid model*. ANS Proc. National Heat transfer Conf., Houston, 24-27th July, 1988, **2**, 191-200, (1988).
- [3] D.F. Fletcher, *A review of coarse mixing models*. Culham Laboratory Report: CLM-R251, (1985).
- [4] A. Thyagaraja and D.F. Fletcher, *Buoyancy-driven, transient, two-dimensional thermo-hydrodynamics of a melt-water-steam mixture*. Comput. Fluids, **16**, 59-80, (1988).
- [5] D.F. Fletcher, *Large scale mixing calculations*. Culham Laboratory Report: CLM-R282, (1988).
- [6] B.W. Spencer, L. Mcumber, D. Gregorash, R. Aeschlimann and J.J. Sienicki, *Corium quench in deep pool mixing experiments*. Proc. National Heat Transfer Conf., Denver, Colorado, USA, August, (1985).
- [7] R.B. Bird, W.E. Stewart and E.N. Lightfoot, *Transport Phenomena.*, Wiley & Sons, (1960).
- [8] D.F. Fletcher and A. Thyagaraja, *A computer model of multiphase mixing*. Paper presented at the Polymodel XI Conference on Flow Modelling in Industrial Processes, Teesside, 24-25 May, 1988. (In press.)
- [9] F.H. Harlow and A.A. Amsden, *Flow of interpenetrating material phases*. J. Comput. Phys., **18**, 440-465, (1975).
- [10] *TRAC-PF1/MOD1: An advanced best-estimate computer program for pressurized water reactor thermal-hydraulic analysis*. NUREG/CR-3858, (1986).
- [11] M.F. Young, *IFCI: an integrated code for calculation of all phases of fuel-coolant interactions*. NUREG/CR-5084, (1987).
- [12] W.C. Rivard and M.D. Torrey, *K-FIX: A Computer program for transient, two-dimensional, two-fluid flow*. LA-NUREG-6623, (1977).
- [13] Presented by W.H. Amarasooriya at the National Heat Transfer Conf., Houston, 24-27th July, 1988 and given in a paper by S. Medhekar, M. Abolfadl and T.G. Theofanous, *Triggering and propagation of steam explosions*. ANS Proc. National Heat Transfer

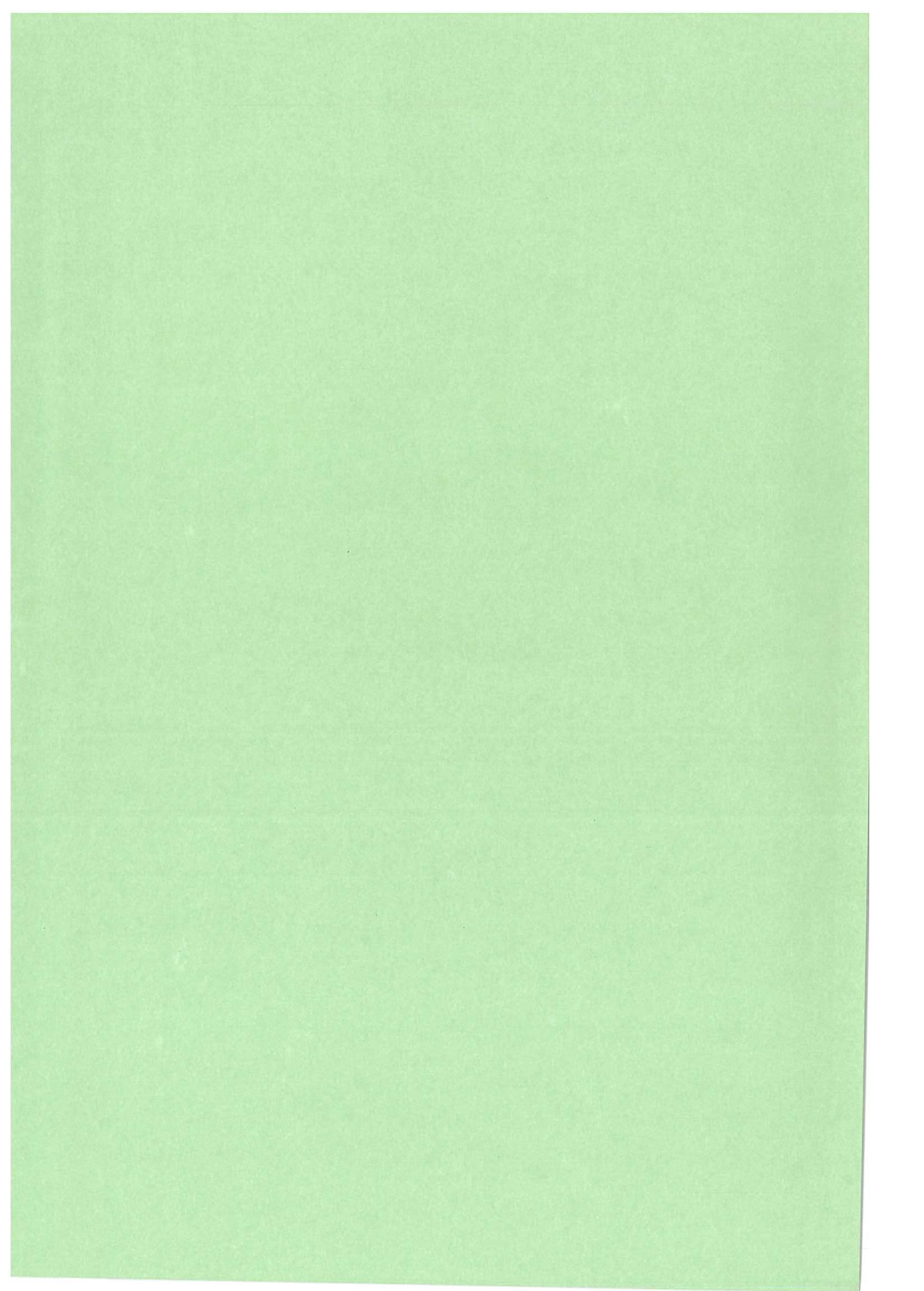
- Conf., Houston, 24-27th July, 1988, 2, 244-251, (1988).
- [14] L.C. Witte, *Film boiling from a sphere*. I & EC Fundamentals, 7, 517-518, (1968).
- [15] M.F. Young, Private Communication, (1988).
- [16] W.C. Rivard and M.D. Torrey, *Numerical calculation of flashing from long pipes using a two-field model*. LA-6104-MS, (1975).
- [17] K. Lee and D.J. Ryley, *The evaporation of water droplets in superheated steam*. ASME J. Heat Transfer, 11, 445-451, (1968).
- [18] D.F. Fletcher, *Assessment and development of the Bankoff and Han coarse mixing model*. Culham Laboratory Report: CLM-R252, (1985).
- [19] J.K. Fink, M.G. Chasanov and L. Leibowitz, *Transport properties of uranium dioxide*. ANL-CEN-RSD-80-4, (1981).
- [20] V.K. Dhir and G.P. Purohit, *Subcooled film-boiling heat transfer from spheres*. Nucl. Eng. Des., 47, 49-66, (1978).
- [21] M.C. Yuen and L.W. Chen, *Heat-transfer measurements of evaporating liquid droplets*. Int. J. Heat Mass Transfer, 21, 537-542, (1978).
- [22] C.F. Clement and P.E. Coleman, *Time-dependent heat transfer models for fuel coolant interactions*. AERE report: TP.1278, (1988).
- [23] P. Naylor, *Film Boiling Destabilisation*. PhD Thesis, University of Exeter, Exeter, Devon, UK, (1985).
- [24] Y. Zvirin, S. Aziz, G.F. Hewitt and D.B.R. Kenning, *Experimental investigation of the transition from film boiling on a free falling sphere*. ANS Proc. National Heat Transfer Conf., Houston, 24-27th July, 1988, 2, 209-216, (1988).
- [25] G.M. Harpole, *Radiative absorption by evaporating droplets*. Int. J. Heat Mass Transfer, 23, 17-26, (1980).
- [26] W.R. Bohl et al., *Multiphase flow in the advanced fluid dynamics model*. ANS Proc. National Heat transfer Conf., Houston, 24-27th July, 1988, 2, 61-70, (1988).
- [27] B.D. Turland, Private Communication, 1988.
- [28] B.D. Turland, N.J. Brealey, D.F. Fletcher and K.A. Moore. *Long-term retention of core debris*. Proc. Int. Symp. on Severe Accidents in Nuclear Power Plants, Sorrento, Italy, 21-25th March, 1988, 2, 439-451, IAEA, Vienna, (1988).

[29] B.W. Marshall, *Jet mixing experiments*. In Reactor Safety Research Semiannual Report July-December, 1986, **36**, NUREG/CR-4805, (1987).

[30] B.W. Spencer, J.D. Gabor and J.C. Cassulo, *Effect of boiling regime on melt stream breakup in water*. Proc. 4th Miami Int. Symp. on Multi-phase Transport and Particulate Phenomena, Miami Beach, Florida, 15-17 December, 1986.

[31] M.C. Cullen, *CEGB Revised Steam Table Package - Pollack Formulation, Vol. 2 - Scientific Statement*. CEGB Report CC/P662, (1982).





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