Forced convection film boiling in the stagnation region of a molten drop and its application to vapour explosions

T. R. FODEMSKI

NNC Ltd, PWR Systems Dept., Booths Hall, Chelford Road, Knutsford,
Cheshire WA16 8QZ, U.K.

Abstract—This work was undertaken as part of an investigation into the heat transfer mechanism related to thermal explosion. The theoretical model of forced convection film boiling in the stagnation point region of an axi-symmetrical molten drop is presented. The model is particularly relevant to the coarse pre-mixing stage of vapour explosion: it takes account of the fact that, at this stage, the hot substance is molten. Stagnation point momentum (Falkner–Skan) and energy equations, for cold and hot liquids and for the vapour layer, were solved numerically, with a wide range of boundary-matching conditions at the interfaces. The model presented, by covering a wide range of the conditions and parameters, is more general than the cases discussed in other publications. For this reason the results can be applied not only to the coarse pre-mixing stage of vapour explosion, but also to other situations, where three-phase forced convection occurs on an axi-symmetrical body.

1. INTRODUCTION

THE ANALYSIS of vapour explosion has been a subject of interest over many years. This phenomenon sometimes occurs when hot (molten) material mixes with more volatile liquid. To be precise vapour explosion can be considered as a subset of different outcomes of such a mixing. It is, however, most dangerous, resulting in massive rapid vapour generation, accompanied by destructive pressure wave and mechanical work upon the surroundings. The possibility that this phenomenon might occur in liquid-cooled nuclear reactors, as a result of serious reactor core overheating [1, 2], emphasizes its importance and has been the reason for extensive investigations (although it is fair to say that the earliest work was initiated by the metallurgical industry; this type of explosion has also been recorded in liquefied natural gas and paper industries and is known to occur when molten lava from volcanic eruptions encounters water).

In the case of liquid-cooled nuclear reactors, under some circumstances, the integrities of reactor vessel and/or containment could be challenged [2, 3] with the possible release of substantial quantities of fission products to the environment. Although such possibilities are considered remote the consequences could be so serious that a thorough understanding and realistic modelling of crucial stages of the phenomenon are required.

The conditions which determine whether an efficient, energetic and large-scale vapour explosion will occur are still rather uncertain [1–4]. However, there is a general consensus that one of the preconditions for a large-scale vapour explosion is the occurrence of a so-called coarse pre-mixing stage. During this stage hot liquid in the form of particles of size 1–2 cm is mixed with the pool of liquid coolant. There is relative movement between the components, but they are prevented from intimate contact by a vapour blanket of the coolant. If this vapour film is stable a substantial volume of this coarse mixture might be produced. Knowledge of the events in this mixing stage, leading to vapour collapse, is particularly important. Various models of film boiling heat transfer from a (hemi-)sphere have been published [5–8]. They are applicable to the case of a hot particle in the solid state and therefore have limited relevance to the coarse pre-mixing stage.

The model presented here takes account of the fact that, at this stage, the hot substance is molten. It considers the forced convection film boiling in the stagnation point region of an axi-symmetrical molten drop. On the basis of this model an accurate value of the vapour layer thickness in this region can be calculated, together with heat fluxes in the cold and hot liquids. This thickness at the stagnation point is of paramount significance, since it is minimal there, and it also determines the thickness of the vapour layer around the whole particle. As shown in refs. [9–11] it also constitutes a main parameter affecting stability and vapour film collapse (self-triggered or induced by a pressure pulse).

2. PHYSICAL MODEL

The analysis in this study is limited to the stagnation point region. The main aims of the work are:

NOMENCLATURE

a	constant		β	coefficient, ratio of material parameters on interface I
A	stagnation point velocity gradient			
b	constant		δ	vapour thickness
c_p	specific heat at constant pressure		ε	emissivity
d	coefficient, ratio of heat fluxes		η	dimensionless similarity coordinate in fluid
$e(\eta)$	function defined by equation (12)		θ	angle (in x direction)
$E(\eta)$	function defined by equation (13)		κ	thermal diffusivity
f	function		λ	dimensionless vapour thickness
$F(\eta)$	dimensionless fluid flow stream function (its value at interface I, $F(0)$, describes evaporation)		μ	dynamic viscosity
			v	kinematic viscosity
			ξ	dummy variable
g	gravitational acceleration		ρ	density
h	latent heat		σ	radiant constant.
k	thermal conduction			
m	evaporation mass rate			Subscripts or superscripts
N	coefficient in equation (1)		ev	evaporation
p	pressure		f	value for molten fuel
Pr	Prandtl number		l	value for liquid coolant
q	heat flux		pot	value for a frictionless flow
R	radius of molten fuel drop		r	radiation
$t(\eta)$	dimensionless fluid temperature, defined by equation (8)		s	saturation value
			v	value for vapour coolant
T	temperature		w	hot surface value
ΔT	temperature difference		x	around the particle component
u	velocity		y	normal to the particle (interface) component
x, y	coordinates.			
			∞	value at infinity (free stream) or far from the interface
Greek symbols			δ	value at interface I
α	coefficient, ratio of material parameters on interface II		*	normalized, dimensionless value
			0	reference value or non-shear stress value.

• detailed analysis of the flow of liquid around the axi-symmetrical particle, in the vicinity of the liquid–vapour interfaces, when a significant distortion from the frictionless flow case takes place;

• analysis of the influence of this distortion on the heat transfer, particularly on the heat flux at the liquid interface;

• detailed analysis of the flow and heat transfer in the vapour layer—both determined by flows in the hot and in the cold liquids and also by heat transfer between them; and

• theoretical analysis leading to an approximate formula for a 'terminal' velocity of molten particles (surrounded by vapour) free-falling in the liquid.

The following assumptions have been made:

1. The liquid flow away from the interface approaches the frictionless case (both in the cold and hot liquids; see Fig. 1).

2. The vapour layer is thin compared with the particle size.

3. The vapour velocity has two components (in the x and y directions). The vapour velocity towards the hot surface (this component is not shown in Fig. 1) varies from maximum at the coolant interface to zero at the hot surface. The flow in the vapour around the molten particle occurs as a result of the pressure gradient produced by the movement, with constant velocity, u_∞, of this particle through coolant, and also because of the motions of the cold and the hot liquids at their respective interfaces with the vapour (see I and II in Fig. 1).

4. The coolant interface temperature is constant (at the saturation value T_s), while its free stream temperature is $T_{l\infty}$.

5. The temperature at the hot particle interface, T_w, is constant and away from this surface (but still in the region of the stagnation point) it is $T_{f\infty}$.

6. The vapour layer is transparent to the radiation heat flux. All the radiation heat flux is absorbed at the liquid–vapour interface (see I in Fig. 1).

7. All physical properties of the two liquids are assumed to be constant and taken for their average temperature.

8. The vapour properties are assumed to be different at the three locations: