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ABSTRACT

Mechanistic models of boiling in a debris bed are used to predict the behaviour of beds when the surrounding coolant is strongly sub-cooled. The necessary matching between boiling and conduction zones is achieved by the introduction of a condensation region. Downward boiling is a necessary consequence of this model.

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Mechanistic models of boiling in a debris bed are used to predict the behaviour of beds when the surrounding coolant is strongly sub-cooled. The necessary matching between boiling and conduction zones is achieved by the introduction of a condensation region. Downward boiling is a necessary consequence of this model.

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Heat transfer models for self-heated debris beds in the presence of sub-cooled liquid coolant are required in the evaluation of the in-vessel retention capabilities for core debris in unlikely nuclear reactor incidents.

Lipinski (1) and Turland and Moore (2) have shown how phenomenological models developed for multiphase flow in porous media may be used to describe the boiling region in a bed of fuel debris, provided the particles remain relatively fixed. The liquid saturation is related to bed height through a differential equation derived from conservation and Darcy laws, which include relative permeability and capillary pressure functions for the medium. Lipinski (1) has shown that such models can adequately predict the dryout heat flux (the maximum heat flux at which bed temperatures everywhere remain close to the coolant's boiling point) for a wide combination of coolants and particulates when sub-cooling in the bulk coolant is small. It is desirable to extend these models to allow for significant sub-cooling (particularly for LMFBR studies).

A common approach is to include conduction layers for the sub-cooled regions (3,4); heat transfer to the surroundings is either in series or parallel with that removed from the boiling layer. In the parallel model vapour is assumed to escape through channels in the conduction zone. In the series model vapour condenses immediately it contacts sub-cooled liquid; heat that leaves the boiling layer as an efflux of vapour appears as a conducted flux in the conduction layer. The corresponding jump in liquid saturation is unsatisfactory when the models of (1) and (2) are used for the boiling region. Below, this difficulty is resolved by introducing a condensation layer between the boiling and conduction layers in which liquid and vapour temperatures differ; vapour at its boiling point penetrates the sub-cooled liquid and condenses.

The present model is time-independent and one dimensional, and applies to a uniform layer of debris on a horizontal surface. A number of extensions are possible: (i) a transient description based on (2) and the energy equation for sub-cooled regions, (ii) more than one dimension, and (iii) dried out regions by the inclusion of additional "vaporisation layers."

MODEL DEVELOPMENT

The debris bed is assumed to rest on a supporting structure (e.g. a steel plate). In regions of the bed where there is no vapour, heat transfer is by conduction alone:

$$\frac{d}{dz}\left(k_b \frac{dT}{dz}\right) + q = 0 \qquad (1)$$

Heat is also transferred through the support

by conduction but there is no internal heat source. Heat fluxes to the overlying and underlying coolant are related to the surface-to-bulk temperature differences by heat transfer coefficients of the form

$$h_i = A_i|\Delta T_i|^{\alpha_i} \; ; \; i = 1,2 \qquad (2)$$

This model is sufficient unless temperatures somewhere in the bed reach the boiling point of the coolant, when a boiling region must be introduced. As discussed above, the juxtaposition of a boiling and a conduction region is unsatisfactory. Continuity of saturation (necessary when capillary pressure is included) can be maintained by introducing a condensation layer. In this region the subcooled liquid and particulate are at temperature T, which is a function of height, and less than T_{bp}.

Heat balance in the condensation layer gives

$$q + \frac{d}{dz}\left(k\frac{dT}{dz}\right) + \rho_\ell c_\ell \frac{d}{dz}\left[u_\ell(T_{bp}-T)\right] = L\rho_v \frac{du_v}{dz} \qquad (3)$$

In general k will be a function of the liquid saturation: $k = k_d(1-s) + k_b s$ might be a good approximation, but this neglects the stirring action of the vapour on the transport process. For simplicity below, it is assumed that $k = k_b$.

The rate of condensation of the vapour is assumed to be proportional to the local degree of sub-cooling:

$$a(T_{bp} - T) + L\,\rho_v \frac{du_v}{dz} = 0, \qquad (4)$$

a, in general, is a function of the liquid saturation.

Equations (3) and (4) are combined to give a modified conduction equation for the condensation zone, the liquid flux term (the third term in equation (3)) is assumed small and neglected.

The remaining equations for the condensation zone arise from mass conservation and the equations of motion:

$$\rho_\ell u_\ell + \rho_v u_v = 0 \qquad (5)$$

$$\frac{\rho_v \nu_v u_v}{K\phi_v}\left[1 + \frac{0.01 d_p|u_v|}{\nu_v(1-\varepsilon)(1-s)}\right] - \frac{\rho_\ell \nu_\ell u_\ell}{K\phi_\ell}\left[1 + \frac{0.01 d_p|u_\ell|}{\nu_\ell(1-\varepsilon)s}\right]$$

$$= (\rho_\ell - \rho_v)g - \frac{d}{dz}\left[\sigma\left(\frac{\varepsilon}{K}\right)^{\frac{1}{2}} J\right] \qquad (6)$$

They also apply to the boiling region and are discussed in (2). The bed permeability, K, can be estimated from the mean particle diameter, d_p, and porosity, ε, using the Kozeny formula (See 1). J is the dimensionless Leverett function which depends on the liquid saturation, s.

Heat balance in the boiling region implies:

$$du_v/dz = q/(\rho_v L) \qquad (7)$$

The bed configuration is shown in Figure 1; the inclusion of downward boiling and condensation layers is discussed below. The plane $z_b = z_1 + z_2 + z_3$ is adiabatic; above z_b heat is transferred upwards, below z_b it is transferred downwards. Other internal boundary conditions arise from continuity of temperature, liquid saturation, phase superficial velocities and conduction heat fluxes.

MODEL REGIMES

Below it is assumed, for simplicity, that all bed and coolant properties are constant.

Conduction only

In this case z_2, z_3, z_4 and z_5 are all zero. The values of z_1 and z_6 are determined from Equations (1) and (2) with the requirement that the heat flux across $z = z_1$ is zero.

Without downward boiling

If, when boiling occurs, all heat generated in the boiling region is transferred upwards z_2 and z_3 are zero, and z_1 satisfies

$$\frac{qz_1}{A_2} = \left[T_{bp} - T_2 - \frac{q\ell z_1}{k_s} - \frac{qz_1^2}{2k_b}\right]^{1+\alpha_2} \qquad (8)$$

The thickness of the layer z_t from which heat is lost through the top of the bed is then determined from $d = z_1 + z_t$. There is either an upward conduction layer ($z_6 > 0$) or the condensation layer extends to the top of the bed ($z_6 = 0$). When $z_6 > 0$ Equations (1) and (4) with appropriate boundary conditions give

$$\left[\left(\frac{qz_t}{A_1}\right)^{\frac{1}{1+\alpha_1}} + T_1 - T_{bp} + \frac{qz_t^2}{2k_b}\right]\frac{a}{q} =$$

$$\frac{1}{2}\sinh^2 y_5 - (\cosh y_5 - 1) \qquad (9)$$

$$z_4 + z_5 = \sqrt{(k_b/a)}\,\sinh y_5 \qquad (10)$$

and $z_t = z_4 + z_5 + z_6$ (11)

$y_i = \sqrt{(k_b/a)}z_i$; $i = 1$ to 6.

When $z_6 = 0$, in which case the l.h.s. of Equation (9) is negative, z_4 and z_5 satisfy Equation (11) and

$$\frac{q}{A_1}\sqrt{\frac{k_b}{a}}\sinh y_5 = \left\{T_{bp}-T_1-\frac{q}{a_L}\left[\cosh y_5 - 1\right]\right\}^{1+\alpha_1} \quad (12)$$

In the boiling layer a zero-dimensional treatment (i.e. a dryout correlation) such as that of Hardee and Nilson (5) or Shires and Stevens (6) can be used. However, the more detailed model given by Equations (4) to (7) may be used to determine first the superficial velocities (using Equations (4) and (7) and the temperature profile in the condensation region), then liquid saturations in the boiling and condensation regions, and thus the dryout limit ($s = 0$ at $z = z_b$). If a conduction layer exists, continuity of liquid saturation requires $s = 1$ at the top of the condensation layer. This condition is no longer suitable if some heat is carried from the bed in the form of a vapour flux (i.e. no conduction layer). In this case a simplified level swell condition for the overlying coolant is used to obtain the boundary condition : with the approximations $s \approx 1$ and $|u_v| >> |u_\ell|$, and assuming ideal bubbly flow (see e.g. Zuber and Hench (7)) a drift flux model gives

$$u_v = 1.53(\sigma g/\rho_\ell)^{\frac{1}{4}}(1-s) \text{ at } z = d. \quad (13)$$

Without downward boiling and condensation layers the liquid saturation must also be 1 at the bottom of the upward boiling region. Turland and Moore (2) have shown that this can only be achieved when capillary pressure effects are sufficiently small.

With downward boiling

For physical consistency at higher capillary pressures it is necessary to include downward boiling and condensation zones. Downward boiling was first predicted by Lipinski (8) using a zero-dimensional model. Layer thicknesses are found by requiring continuity of saturation at $z = z_b$. As above, there are two cases for the layers cooled upwards : with and without, an upward conduction zone. For given z_t the saturation at the bottom of the upward boiling layer may be found exactly as described above.

There are two cases to consider for the layers which are cooled downwards: (i) with a downward conduction layer ($z_1 > 0$), and (ii) with the downward condensation layer extending to the bottom of the bed ($z_1 = 0$).

First we consider the case $z_1 = 0$. As heat can only be removed from the bottom of the bed by conduction, z_2 and z_3 must satisfy

$$\left\{\frac{q(z_2+z_3)}{A_2}\right\}^{\frac{1}{1+\alpha_2}} = T_{bp}-T_2 - \frac{q\ell}{k_s}(z_2 + z_3) - \frac{q}{a_L}\left[\cosh y_2 - 1\right] \quad (14)$$

$$z_2 + z_3 = \sqrt{(k_b/a)}\sinh y_2 \quad (15)$$

Superficial velocities and the saturation profile are determined in a similar manner to that described above; the boundary conditions are continuity of saturation at $z = z_b$, and $u_v = 0$ at $z = 0$.

If a conduction zone is present ($z_1 > 0$) Equation (15) still applies but Equation (14) is replaced by an analogue of Equation (9) for bottom, rather than top, cooling. In this case, the saturation must satisfy $s = 1$ at $z = z_1$, besides being continuous at $z = z_b$. This is achieved numerically by adjusting z_b until all conditions are satisfied.

RESULTS

A standard set of data thought to be typical for a debris bed resulting from an incident in a sodium cooled reactor is given in the Notation. Values of A_1, A_2, α_1 and α_2 are based on material in the review by Joly and le Rigoleur (9). For this data set the neglect of the liquid flux in Equation (3) is justified. Results using this standard data set are given in Table 1, along with results from seven other runs in which one or more parameters have been varied. (The low surface tension run was performed as a way of reducing the importance of capillary pressure.) For the standard case, the thicknesses of the various layers are shown in Figure 2 as functions of the volumetric heating rate. For comparison Figure 3 shows the layer thicknesses when downward boiling is not permitted.

The inclusion of downward boiling has only a small effect on the thicknesses of the layers in the upward region and the temperature at the top of the bed, but has a dramatic effect on the temperature at the bottom of the support plate (see Figure 4). The effect could

be measured experimentally by monitoring the temperature of the support plate as the volumetric heating rate is changed.

The temperature at the bottom of the support, T_s, depends on the downwards heat flux Q:

$$T_s = T_2 + (Q/A_2)^{(1/(1+\alpha_2))} \qquad (16)$$

(by Equation (2)). Without downward boiling Equation (8) applies; replacing z by Q/q it is seen that Q, and therefore T_s, increases as q increases. However, when downward boiling is included, and there is no pure conduction layer, Equations (14) and (15) give

$$\frac{Q}{A_2} \approx \left[T_{bp} - T_2 - \frac{Q\ell}{k_s} - \frac{Q}{\sqrt{(ak_b)}}\right]^{\alpha_2+1} \qquad (17)$$

for $y_2 >> 1$, implying a fixed heat flux downwards and thus a constant lower temperature provided that the condensation region is sufficiently thick. For the standard data set Equations (16) and (17) give $Q = 0.26 MW/m^2$ and $T_s = 674^oC$, in good agreement with the results shown in Figure 4.

CONCLUSIONS

The interface between a boiling and a sub-cooled region in debris bed models has been replaced by a "condensation layer" of finite thickness, which allows continuity of liquid saturation. The model gives a new treatment of downward boiling and suggests an experiment (the monitoring of the temperature at the bottom of the support plate as the volumetric heating rate is increased) that might be of use in deciding whether downward boiling does or does not actually occur.

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NOTATION

Values used in the standard data set are enclosed in square brackets.

A_1, A_2 : Coefficients in Equation 2 $[A_1 = 1840\ Wm^{-2}K^{-(1+\alpha_1)};\ A_2 = 540\ Wm^{-2}K^{-(1+\alpha_2)}]$.

a : Condensation coefficient $[10^6 Wm^{-3}K^{-1}]$

c_ℓ : Specific heat of liquid $[1.3 kJ\ kg^{-1}K^{-1}]$

d : depth of debris bed [0.1m]

d_p : mean diameter of particulate [0.5mm]

g : acceleration due to gravity

h_1, h_2 : heat transfer coefficients at top of bed and bottom of support to the bulk coolant.

J : Leverett function [as in (2)]

k : thermal conductivity in condensation layer

k_b, k_d : effective thermal conductivity of debris bed: k_b - fully saturated, $[20 Wm^{-1}K^{-1}]$; k_d - dried out.

k_s : thermal conductivity of support $[23.2\ Wm^{-1}K^{-1}]$

K : permeability

ℓ : thickness of support [.02m]

L : latent heat of vaporization of coolant $[3.81\ MJ\ kg^{-1}]$

q : volumetric heat generation rate

Q : downwards heat flux density

s, : liquid saturation (fraction of void occupied by liquid

T : temperature of liquid/particulate

T_1, T_2 : bulk temperatures of overlying (T_1) and underlying (T_2) coolant [both 500^oC]

T_{bp} : boiling point of coolant $[960^oC]$

T_s : temperature at bottom of the support

u_v, u_ℓ : superficial velocities of vapour and liquid

y_i : $y_i = \sqrt{(k_b/a)}z_i$; i = 1 to 6

z : vertical co-ordinate

z_b, z_t : depths of bed from which heat is transferred downwards/upwards

z_i (i=1 to 6) : thicknesses of layers in bed (see Figure 1).

α_i : exponents in Equation 2 $[\alpha_1 = 0.35, \alpha_2 = 0.20]$.

$\Delta T_1, \Delta T_2$: temperature differences between surfaces and bulk coolant (ΔT_1 at top of bed, ΔT_2 below support)

ε : porosity [0.40]

ν_v, ν_ℓ : kinematic viscosities of vapour $[4.0 \times 10^{-5} m^2 s^{-1}]$ and liquid $[2.05 \times 10^{-7} m^2 s^{-1}]$

ρ_v, ρ_ℓ : densities of vapour $[0.50 kgm^{-3}]$ and liquid $[722 kgm^{-3}]$

σ : surface tension $[0.117\ Nm^{-1}]$

ϕ_v, ϕ_ℓ : relative permeability functions for vapour $[\phi_v = 1-s]$ and liquid $[\phi_\ell = s^3]$

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Parameters varied	Onset of boiling MWm^{-3}	Onset of dryout MWm^{-3}
Standard case	4.57	12.07
$\phi_\ell(s) = s$	4.57	22.38
$\sigma = 0.001Nm^{-1}$	4.57	5.14
dp = 1mm	4.57	17.53
$a = 10^4 Wm^{-3}K^{-1}$	4.57	10.16
T_1 = 450C; T_2=600C	4.32	11.30
d = 0.2m	1.38	4.27
$k_b = 36Wm^{-1}K^{-1}$	6.69	13.35

Table 1. Volumetric heating rate for onset of boiling and dryout. All parameters, other than those shown in the first column are for the standard case.

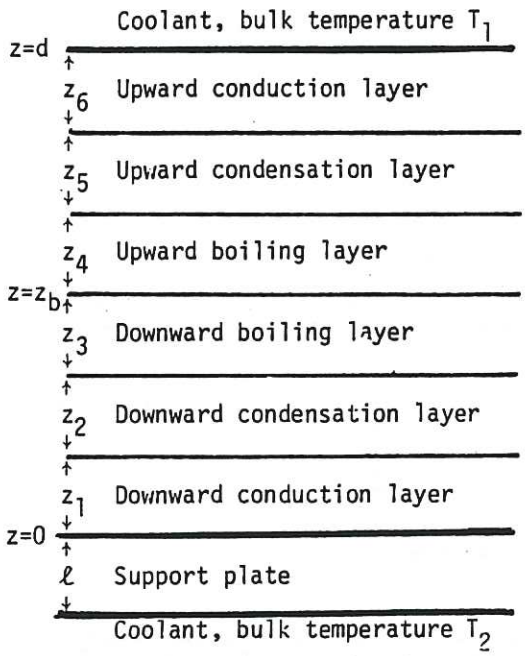

Figure 1. The bed configuration; for a given set of parameters some layers may have zero thickness (see main text for discussion).

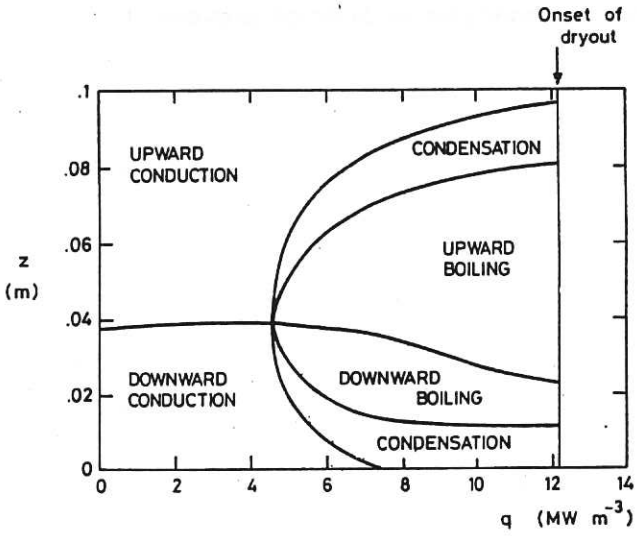

Figure 2. The configuration of the bed as a function of volumetric heating rate for the standard data set (see section 4 of the main text). Position in the bed is the vertical co-ordinate.

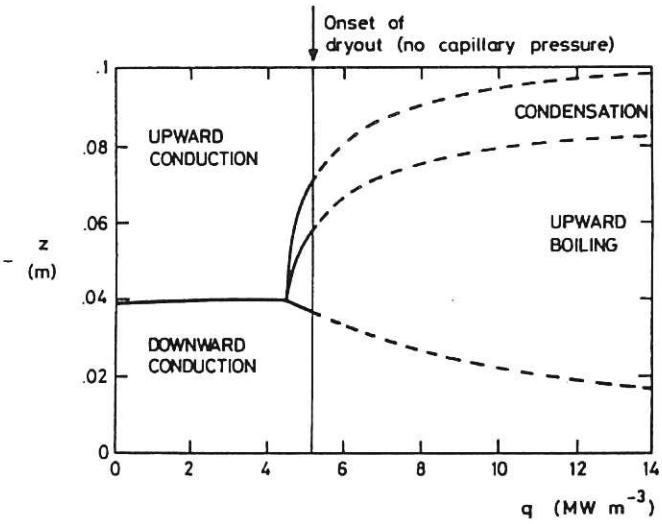

Figure 3. As Figure 2 but downward boiling has been suppressed; the dashed lines indicate the layer thicknesses ignoring the predicted onset of dryout.

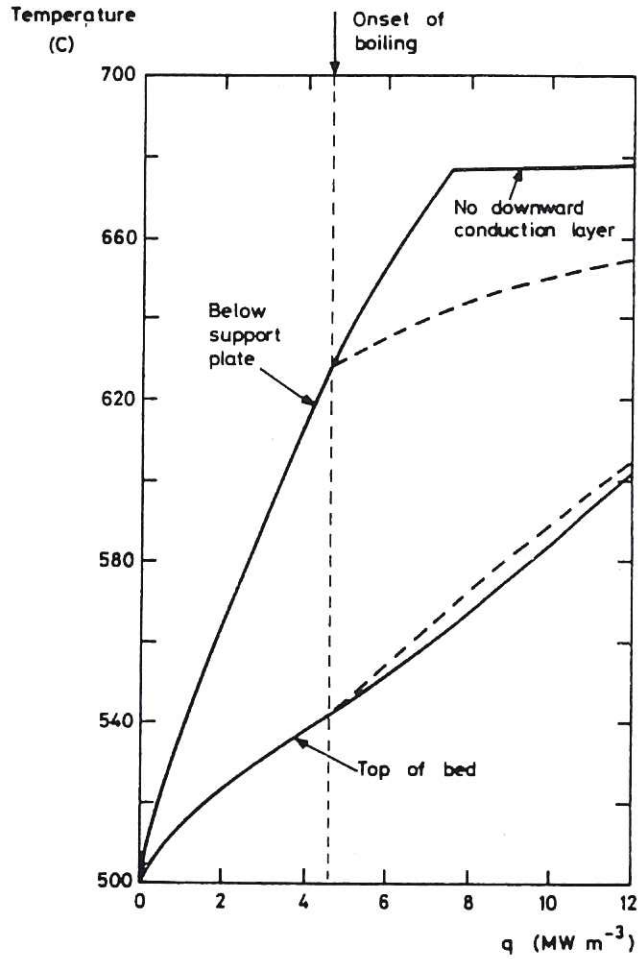

Figure 4. Temperatures at top of bed and at bottom of support plate for the standard case (solid line) and the standard case with downward boiling suppressed (dashed line).