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TRANSIENT DISSOLUTION OF A STEEL STRUCTURE IN AN ALUMINUM MELT POOL

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Abstract

A numerical model is developed to describe the process of transient dissolution of the interior surface of a reactor bottom head in a pool of molten aluminum resulting from a severe core meltdown accident. The model accounts for the transient heat conduction in the steel structure, the mass transfer due to dissolution, and the time variations of the bulk pool temperature and concentration. Results indicate that over the range of accident conditions considered in the study, the bulk pool always attains a saturated state while the interface temperature approaches an asymptotic value. Once this saturated state is achieved, no further dissolution would take place. For a given pool inventory, the critical time for achieving the saturated state is found to be a function of the Nusselt number and the dissolution coefficient. On the other hand, the fraction of the steel structure that is dissolved before reaching the saturated state is a function of the Nusselt number alone.

Nomenclature

$[A]$	coefficient matrix, equation (23)
A_1	lower surface area of the melt pool
A_2	upper surface area of the melt pool
C	concentration of dissolved steel in the melt, kg/m^3
C^*	mass fraction of dissolved steel in the melt
C_{PA}	specific heat of aluminum
C_P	specific heat of steel
C_R	heat capacity ratio, equation (22a)
C_s	saturated concentration of dissolved steel at the interface, kg/m^3
C_s^*	saturated mass fraction of dissolved steel at the interface
f_c	dimensionless factor measuring the deviation from saturation, equation (11)

h_i	heat transfer coefficient at the melt/structure interface
H_r	radiation parameter, equation (22c)
k	dissolution coefficient
K_c	dimensionless dissolution coefficient, equation (22a)
k_m	thermal conductivity of the melt
k_s	thermal conductivity of steel
L_p	average pool depth
L_s	instantaneous thickness of the steel structure
$L_b(0)$	thickness of the bottom head
Nu	Nusselt number, equation (22a)
q_1''	lower surface heat flux
q_2''	upper surface heat flux
Q_1''	dimensionless lower surface heat flux, equation (22b)
Q_2''	dimensionless upper surface heat flux, equation (22b)
$[R]$	constant vector, equation (23)
$\dot{s}$	volumetric heat-generation rate
t	time
$[T]$	temperature vector, equation (23)
T_o	temperature on the exterior surface of the bottom head
T_i	melt/structure interface temperature
T_m	bulk pool temperature
$T_m(0)$	initial pool temperature
T_s	solid steel temperature
T_∞	ambient temperature above the pool
z	spatial coordinate measured from the exterior surface of the bottom head

Greek Symbols

Φ	dimensionless volumetric heating rate
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α_s	thermal diffusivity of steel
δ_m	thickness of the dissolved layer
Δ	dimensionless thickness of the dissolved layer, equation (14a)
$\Delta(\infty)$	total fraction the bottom head dissolved
η	dimensionless spatial coordinate, equation (14a)
ϵ	surface emissivity
ρ_{Al}	density of molten aluminum, Table 1
ρ_m	density of the melt pool
$(\rho_m)_s$	density of the melt pool when saturated with dissolved steel
ρ_s	density of steel
σ	Stefan-Boltzman constant
τ	dimensionless time, equation (14a)
τ_{cr}	critical time at which a coolable equilibrium situation is achieved in the system
θ_0	solubility temperature constant, equation (22d)
θ_1	solubility temperature constant, equation (22d)
θ_i	dimensionless interface temperature, equation (14b)
θ_m	dimensionless bulk pool temperature, equation (14b)
θ_s	dimensionless temperature of the steel structure, equation (14b)
θ_{∞}	dimensionless ambient temperature, equation (22d)

Subscripts

0	initial condition on the exterior surface of the bottom head
1	lower surface of the melt pool
2	upper surface of the melt pool
Al	aluminum
c	concentration
i	melt/structure interface
m	bulk pool condition
s	solid steel
∞	ambient condition above the pool

Superscripts

*	mass fraction
"	local flux

1 Introduction

During an unlikely event of a severe core-meltdown accident in a heavy water reactor, a pool of molten aluminum could form in the reactor bottom head. Owing to the presence of radioactive material in the pool, the melt is heated volumetrically at high Rayleigh numbers. If the temperature at the interface between the pool and the solid steel structure is higher than the aluminum melting point (i.e., 933 K), the inside wall of the bottom head could suffer appreciable erosion due to dissolution of the solid steel in the molten alu-

minum. To assess the integrity of the reactor bottom head and to assure long-term in-vessel coolability, it is necessary to determine the transient wall temperature distribution and estimate how much thinning of the wall would result. The former is needed to assess potential creep failure of the structure whereas the latter is needed to evaluate the likelihood of vessel penetration.

Most studies of dissolution processes occurring in liquid metal systems have been limited to steady state and relatively simple geometries. Gairola, Tiwari, and Ghosh (1971) investigated the dissolution of a vertical nickel cylinder immersed in molten aluminum under free convection conditions. They found that the dissolution rate is controlled by mass transfer in the fluid boundary layer. Niinomi, Veda, and Sano (1982) studied the controlling kinetic step of the dissolution of ferrous alloys in molten aluminum. They used the free convection mass transfer correlation developed by Ravoo et al. (1970) to analyze their experimental results and concluded that the dissolution process is controlled by the diffusion of iron in molten aluminum. Niinomi, Suzuki, and Veda (1984) investigated the dissolution of ferrous alloys in molten aluminum under forced flow conditions. Again, they found that the diffusion of iron in molten aluminum is the controlling mechanism of the dissolution process. Recently, Dybkov (1990) measured the dissolution of stainless steel in molten aluminum in the temperature range of 700 to 850°C. He observed that during dissolution, all the constituents of the stainless steel dissolve into the molten aluminum in approximately the same ratio as they are present in the solid phase. This clearly indicates that the dissolution of stainless steel in molten aluminum is non-selective. Dybkov also found that the solubility of stainless steel in molten aluminum is about the same as the solubility of iron in molten aluminum.

None of the above studies can be applied directly to the dissolution problem occurring in the bottom head of a heavy water reactor under a severe accident condition. This is because the dissolution process under consideration is highly transient and strongly coupled to the heat transfer process of the system. During the course of melt/structure interaction, both the temperature of the steel structure and the bulk pool temperature are functions of time. Since the solubility of stainless steel in molten aluminum is strongly temperature-dependent, the rate of dissolution cannot be estimated without simultaneously determining the transient temperature behavior of the system.

In this study, a numerical model is developed to describe the transient dissolution and heat transfer processes taking place in a reactor bottom head containing a heat-generating aluminum melt pool.

2 Problem Formation

Following a severe core meltdown accident in a heavy water reactor, a pool of core melt consisting mainly of aluminum is assumed to form in the bottom head of the reactor. Initially, the melt pool is at a uniform temperature equal to the melting point of aluminum whereas the steel structure (i.e., the bottom head) is also at a uniform temperature equal to the boiling point of water. Owing to decay heating

of the core melt, natural convection is considered to be the prevalent heat transfer mechanism in the pool. The decay heat generated in the melt pool is partially removed from the upper surface of the pool by thermal radiation and from the lower surface through the steel structure by downward-facing boiling of water in the cavity. If the rate of cooling is not sufficiently high, which is true in the initial stage of the melt/structure interaction, the bulk pool temperature will rise. This trend will continue until the differences between the bulk pool and the surface temperatures are large enough to remove all the decay heat from the pool. In the meantime, dissolution of the steel structure in the molten aluminum pool will take place at the melt/structure interface. This dissolution process will proceed until the pool becomes saturated. To formulate the problem, the following simplifying assumptions are employed:

1. During dissolution the constituents of the steel structure dissolve in the molten aluminum in the same proportion as they are present in the solid phase. This non-selective characteristics has been observed by Dybkov (1990). Thus the pool concentration can be described in terms of the mass fraction of steel in the molten phase.
2. Both the dissolution process taking place at the melt/structure interface and the transient conduction process in the steel structure can be treated as locally one-dimensional.
3. A local phase equilibrium is assumed at the melt/structure interface. Accordingly, the concentration of the molten material at the interface can be determined from the solubility of steel in molten aluminum, which depends only on the interface temperature.
4. The rate of volumetric heating is uniform throughout the pool. Also, the heat of dissolution can be ignored since it is very small compared to the decay heat generated in the melt pool.
5. The melt pool is well mixed by the natural convection flow. As a first approximation, the sensible heat of the melt pool can be represented by the bulk pool temperature which of course is a function of time.
6. Water is always available in the containment cavity so that the exterior surface of the reactor bottom head is maintained at a constant temperature by downward-facing nucleate boiling of water. This assumption is consistent with the current concept of in-vessel cooling of a melt pool by cavity flooding.

Based upon the above assumptions, time variation of the bulk pool temperature T_m can be determined from an overall energy balance on the melt pool as a whole. The result is

$$\frac{d}{dt} [\rho_{Al} C_{P,Al} L_p + \rho_s C_{P,s} \delta_m(t)] T_m = \dot{s} L_p - q_1''(t) - \frac{A_2}{A_1} q_2''(t) \quad (1)$$

where L_p is the average pool depth based upon the lower surface area A_1 , δ_m the instantaneous thickness of the steel structure dissolved in the molten aluminum, $\dot{s}$ the rate of volumetric heating, q_1'' the lower surface heat flux, and q_2'' the upper surface heat flux. Other symbols are defined in the Nomenclature. Physically, the left hand side of equation (1) represents the sensible heat of the melt pool including the dissolved steel whereas the right hand side represents

the difference between the amount of heat generated in the pool and the total amount of heat removed from the pool boundaries. The ratio A_2/A_1 accounts for the difference in the heat transfer area between the upper and lower surfaces of the pool. Note that $\delta_m(t)$, $q_1''(t)$, and $q_2''(t)$ are unknown functions of time to be determined in the course of analysis. Since the thermal time constant is usually much smaller than the dissolution time constant, the term involving $d\delta_m/dt$ can be ignored relative to the term involving dT_m/dt .

In terms of the unknown interface temperature T_i and the bulk pool temperature T_m , the lower and upper surface heat fluxes are given by

$$q_1'' = h_i(T_m - T_i) \quad \text{and} \quad q_2'' = \epsilon \sigma (T_m^4 - T_\infty^4) \quad (2)$$

where h_i is the convective heat transfer coefficient at the melt/structure interface and T_∞ the ambient temperature above the pool.

To determine the interface temperature, the process of transient heat conduction in the steel structure needs to be considered. Using the locally one-dimensional assumption, the temperature of the steel structure is governed by the following system of equations:

$$\frac{\partial T_s}{\partial t} = \alpha_s \frac{\partial^2 T_s}{\partial z^2} \quad (3)$$

$$t = 0: \quad \text{or} \quad z = 0: \quad T_s = T_0 \quad (4a)$$

$$z = L_s(t): \quad T_s = T_i, \quad k_s \frac{\partial T_s}{\partial z} = h_i(T_m - T_i) \quad (4b)$$

where z is a local spatial coordinate measured from the exterior surface of the steel structure in a direction normal to the structure, T_0 the initial temperature of the steel structure, and $L_s(t)$ the instantaneous thickness of the structure. The latter is given by

$$L_s(t) = L_s(0) - \delta_m(t) \quad (5)$$

where $L_s(0)$ is the initial thickness of the steel structure.

In the above formulation, the dissolved layer thickness δ_m is a major unknown variable. To find an expression for $\delta_m(t)$, the following equation is employed (Dybkov 1990):

$$\frac{d\delta_m}{dt} = k_c \frac{(C_s - C)}{\rho_s} \quad (6)$$

where k_c is the dissolution mass transfer coefficient, C the concentration of the dissolved steel in the melt pool in kg/m^3 , C_s the saturated value of C at the interface temperature T_i , and ρ_s the density of steel. In terms of the mass fractions C^* and C_s^* of the dissolved steel in the melt pool, C and C_s can be expressed respectively by

$$C = C^* \rho_m \quad \text{and} \quad C_s = C_s^* (\rho_m)_s \quad (7)$$

where ρ_m is the bulk pool density and $(\rho_m)_s$ the bulk pool density under saturation conditions. These two quantities are directly related to the densities of the molten aluminum and steel by

$$\rho_m = \rho_{Al} \left[1 - \left(1 - \frac{\rho_{Al}}{\rho_s} \right) C^* \right]^{-1}$$

and

$$(\rho_m)_s = \rho_{Al} \left[1 - \left(1 - \frac{\rho_{Al}}{\rho_s} \right) C_s^* \right]^{-1} \quad (8)$$

It follows from equations (7) and (8) that

$$C = \frac{\rho_{Al} C^*}{1 - C^* + C^* \rho_{Al}/\rho_s} \quad \text{and} \quad C_s = \frac{\rho_{Al} C_s^*}{1 - C_s^* + C_s^* \rho_{Al}/\rho_s} \quad (9)$$

Substituting equation (9) into equation (6) and integrating the resulting equation using the initial condition of $\delta_m(0) = 0$, an expression for $\delta_m(t)$ can be derived. This is

$$\delta_m = \frac{\rho_{Al}}{\rho_s} \int_0^t k_c \left(\frac{f_c C_s^* - C^*}{1 - C^* + C^* \rho_{Al}/\rho_s} \right) dt \quad (10)$$

where

$$f_c = \frac{1 - C^* + C^* \rho_{Al}/\rho_s}{1 - C_s^* + C_s^* \rho_{Al}/\rho_s} \quad (11)$$

is a dimensionless factor measuring the deviation of the pool concentration from its saturation state.

To close the governing system, time variations of C^* and C_s^* need to be determined. In terms of the unknown variable δ_m , an expression for C^* can be derived from a mass balance on the melt pool. The result is

$$C^* = \frac{\delta_m}{\delta_m + L_p \rho_{Al}/\rho_s} \quad (12)$$

The value of C_s^* , on the other hand, is a function of the unknown interface temperature T_i . Since the solubility of steel in molten aluminum is not available in the temperature range under consideration, the finding of Dybkov (1990) is employed in this study. The saturation concentration of steel in molten aluminum is taken to be the same as the saturation concentration of iron in molten aluminum. Using the experimental data for the solubility of iron in molten aluminum at high temperatures (Hatch 1988, Dybkov 1990), the following correlation was obtained by data fitting (Tutu 1991) using the least squares technique:

$$C_s^* = 0.916 \exp \left[- \left(\frac{T_i - 1823}{446} \right)^2 \right] \quad (13)$$

where T_i is in degree Kelvin. The above expression is valid over the temperature range of $923 \text{ K} \leq T_i \leq 1823 \text{ K}$.

3 Analysis

To facilitate numerical solution of the governing system, a dissolution-front-immobilization technique is employed to fix the melt/structure interface location in a dimensionless space. This is done by invoking the following transformation:

$$\eta = z/L_s(t), \quad \tau = \alpha_s t/L_s^2(0), \quad \Delta = \delta_m/L_s(0) \quad (14a)$$

$$\theta_s = \frac{T_s - T_o}{T_m(0) - T_o}, \quad \theta_m = \frac{T_m - T_o}{T_m(0) - T_o}, \quad \theta_i = \frac{T_i - T_o}{T_m(0) - T_o} \quad (14b)$$

In the dimensionless space, the melt/structure interface is always located at $\eta = 1$ whereas the steel structure is bounded by $0 \leq \eta \leq 1$. The governing equations can be written as follows:

(a) Solid Steel Region

$$\frac{\partial \theta_s}{\partial \tau} = \frac{1}{(1 - \Delta)^2} \left[\frac{\partial^2 \theta_s}{\partial \eta^2} - \eta(1 - \Delta) \frac{d\Delta}{d\tau} \frac{\partial \theta_s}{\partial \eta} \right] \quad (15)$$

$$\tau = 0 \quad \text{or} \quad \eta = 0: \quad \theta_s = 0 \quad (16a)$$

$$\eta = 1: \quad \theta_s = \theta_i, \quad \frac{\partial \theta_s}{\partial \eta} = Nu \frac{k_m L_s(0)}{k_s L_p} (1 - \Delta)(\theta_m - \theta_i) \quad (16b)$$

(b) Bulk Pool Region

$$\frac{d\theta_m}{d\tau} = \frac{k_m L_s(0)}{k_s L_p} (C_R + \Delta)^{-1} \left[\Phi - Q_1'' - \frac{A_2}{A_1} Q_2'' \right] \quad (17)$$

$$Q_1'' = Nu(\theta_m - \theta_i) \quad \text{and} \quad Q_2'' = H_r(\theta_m - \theta_\infty) \quad (18)$$

(c) Dissolution Front

$$\Delta = \frac{\rho_{Al}}{\rho_s} \int_0^\tau K_c \left(\frac{f_c C_s^* - C^*}{1 - C^* + C^* \rho_{Al}/\rho_s} \right) d\tau \quad (19)$$

$$C^* = \Delta \left[\Delta + \frac{L_p \rho_{Al}}{L_s(0) \rho_s} \right]^{-1} \quad (20)$$

$$C_s^* = 0.916 \exp \left[- \left(\frac{\theta_i - \theta_1}{\theta_o} \right)^2 \right] \quad (21)$$

In the above equations, Nu is the Nusselt number at the melt/structure interface, K_c the dimensionless dissolution coefficient, C_R the heat capacity ratio, Φ the dimensionless heat-generating rate, Q_1'' and Q_2'' the dimensionless lower and upper surface heat flux, respectively, H_r the dimensionless radiation heat transfer coefficient, θ_∞ the dimensionless ambient temperature, and θ_o , θ_1 the solubility temperature constants. These dimensionless parameters are defined respectively by

$$Nu = \frac{h_i L_p}{k_m}, \quad K_c = \frac{k_s L_s(0)}{\alpha_s}, \quad C_R = \frac{\rho_{Al} C_{pAl} L_p}{\rho_s C_{ps} L_s(0)} \quad (22a)$$

$$\Phi = \frac{s L_p^2}{k_m [T_m(0) - T_o]}, \quad Q_1'' = \frac{q_1'' L_p}{k_m [T_m(0) - T_o]}, \quad Q_2'' = \frac{q_2'' L_p}{k_m [T_m(0) - T_o]} \quad (22b)$$

$$H_r = \frac{\epsilon \sigma T_m^3 L_p}{k_m} \left[1 + \frac{T_\infty}{T_m} + \left(\frac{T_\infty}{T_m} \right)^2 + \left(\frac{T_\infty}{T_m} \right)^3 \right] \quad (22c)$$

$$\theta_\infty = \frac{T_\infty - T_o}{T_m(0) - T_o}, \quad \theta_o = \frac{446}{T_m(0) - T_o}, \quad \theta_1 = \frac{1823 - T_o}{T_m(0) - T_o} \quad (22d)$$

Note that equations (15), (17), and (19) are strongly coupled through their dependence on the dissolved layer thickness, Δ , and interface temperature, θ_i .

The above system of governing equations is solved numerically. In particular, an implicit finite-difference technique is used to calculate the transient temperature distribution in the solid steel region, the fourth-order Runge-Kutta method is employed to compute the bulk pool temperature, and the dissolved layer thickness is determined by integrating equation (19) using the Simpson's rule. A variable grid structure with the grid size decreasing in the η -direction toward the melt/structure interface is utilized to treat the steep temperature variation near the interface. In formulating the

finite-difference equation for the transient heat conduction in the solid steel region, a fully implicit scheme with central difference in space and backward difference in time is employed. The final form of the finite-difference equation can be expressed as

$$[A] [T] = [R] \quad (23)$$

where the coefficient matrix $[A]$ is a tri-diagonal matrix, $[T]$ the temperature distribution in the solid steel, and $[R]$ a constant vector. The Thomas algorithm along with an iterative updating procedure is used to calculate the unknown temperature $[T]$.

It should be mentioned that in the initial stage of dissolution, C_s^* is always larger than C^* . However, as more dissolved steel is present in the melt pool and as the melt/structure interface gradually approaches an asymptotic value, C^* would approach the value of C_s^* . Beyond that point, the melt pool is saturated, and no further dissolution would take place. Once this coolable equilibrium condition is reached, numerical computation will stop. The following termination criteria are employed in the numerical program:

$$C^* = C_s^* \text{ and } d\theta_i/d\tau = 0. \quad (24)$$

4 Results and Discussion

Numerical computation has been performed for a 2,500 MW special-purpose heavy water reactor with an area ratio of $A_2/A_1 = 0.92$. Assuming the entire core has been molten and relocated in the reactor bottom head, the average pool depth is estimated to be $L_p = 0.31$ m. In view of the fact that the dissolution process is a rather slow process, the decay heat level is taken to have an average value of 0.5% of the full power, giving rise to a volumetric heating rate of $\dot{q} = 1.62 \times 10^3$ kW/m³. The initial melt temperature and the ambient temperature are assumed to be at the aluminum melting point, i.e., $T_m(0) = 933$ K and $T_\infty = 933$ K. Note that in reality, T_∞ would vary with time. However the effect of T_∞ is not of primary importance. The bottom head thickness is taken to be $L_b(0) = 0.075$ m. It is assumed that nucleate boiling prevails in the flooded cavity throughout the transient, so that the exterior surface of the bottom head is maintained at a constant temperature equal to $T_b = 383$ K. The thermophysical properties of the system employed in the present work are given in Table 1.

There are two key dimensionless parameters controlling the transient behavior of the system. These are the Nusselt number for the melt pool heat transfer, Nu , and the dimensionless dissolution mass transfer coefficient, K_c . Typical values of these parameters for the system under consideration have been estimated to be $Nu = 10$ and $K_c = 1.65 \times 10^{-2}$ (Tan *et al.* 1992 and Cheung *et al.* 1992). During the transient dissolution process, both Nu and K_c are likely to vary with time. In order to account for the variations of Nu and K_c from typical values envisioned for severe accident conditions, numerical computations have been performed for the ranges of $1 \leq Nu \leq 100$ and $1.65 \times 10^{-3} \leq K_c \leq 0.165$. The values of $Nu = 10$ and $K_c = 1.65 \times 10^{-2}$ are used as the baseline case for comparison.

Transient Wall Temperature Distribution

Figure 1 shows the transient temperature distribution in the bottom head for the baseline case. In the initial stage of the melt/structure interaction, the steel temperature rises very quickly, owing to heating by the pool. The steel temperature reaches a maximum at about $\tau = 4$. For $\tau > 4$, the steel temperature gradually decreases and approaches asymptotically a steady-state distribution at $\tau = 500$. Beyond this critical time, there is no further change in the steel temperature. Note that for small values of τ , the temperature profile is nonlinear. However, for $\tau \geq 4$, a linear temperature distribution is obtained, indicating that a quasi-steady heat conduction process has been achieved in the bottom head. Figure 2 presents the transient temperature distribution for the same baseline case in the original physical domain. There is no appreciable dissolution taking place at the melt/structure interface until 5×10^3 s after the onset of melt/structure interaction, corresponding to $\tau = 4$. At this time, the temperature profile is almost linear. This clearly indicates that the thermal time constant is much smaller than the dissolution time constant. For $t > 5 \times 10^3$ s or $\tau > 4$, the bottom head becomes thinner and thinner due to dissolution, so the conduction resistance gradually decreases. This results in a decrease in the steel temperature. A critical time is reached at 6.25×10^5 s, beyond which the thickness and the temperature distribution of the bottom head remain unchanged. This clearly indicates the attainment of a coolable equilibrium situation.

Melt/Structure Interface and Bulk Pool Temperatures

Time variations of the melt/structure interface and bulk pool temperatures are depicted in Figure 3 for the cases of $Nu = 1$ and $Nu = 10$ with $K_c = 1.65 \times 10^{-2}$. For small values of τ , both the interface and bulk pool temperatures rise quickly with time. They then decrease gradually after reaching their peaks and approach asymptotically their steady-state values at large τ . Note that an increase in the Nusselt number results in a decrease in the bulk pool temperature but an increase in the interface temperature. Physically, this is due to the effect of natural convection in the pool. A higher heat transfer coefficient gives rise to a larger heat removal rate from the lower surface, thus preventing the pool from overheating. This leads to a smaller value of T_m . On the other hand, a much higher interface temperature is required to conduct a higher heat flux through the bottom head. As shown in Figure 4, a much larger value of Q_1'' together with a much smaller value of Q_2'' are obtained as Nu varies from unity to ten. It should be stressed that at large τ , all the decay heat generated in the melt is removed from the pool boundaries, i.e., $Q_1'' + (A_2/A_1) Q_2'' = \Phi$, and a coolable situation is attained.

Time Variation of the Melt Concentration

Figure 5 illustrates the variations of the concentration with time for the cases of $Nu = 1$ and $Nu = 10$ with $K_c = 1.65 \times 10^{-2}$. The mass fraction C_s^* at the interface increases very sharply at first, but then decreases after reaching a peak value. It finally approaches an asymptotic value at a critical time τ_c . This behavior of the interface concentration is a direct consequence of the overshoot in the interface temperature (see figure 3), which affects the solubility of steel

in molten aluminum. On the other hand, the mass fraction C^* in the bulk pool is a monotonically increasing function of time for $\tau < \tau_{cr}$. This is expected since more and more steel is being dissolved in the pool. At the critical time τ_{cr} , the melt pool is saturated, i.e., $C^* = C_s^*$. No further dissolution would take place beyond this point. Note that an increase in the Nusselt number results in relatively large increases in both the values of C_s^* and C^* . However the critical time actually decreases with an increasing value of Nu ($\tau_{cr} = 750$ for $Nu = 1$ and $\tau_{cr} = 500$ for $Nu = 10$). Although the steady-state bulk pool concentration is considerably higher for the case of $Nu = 10$, the rate of dissolution is also higher due to the presence of a much larger concentration difference ($C_s^* - C^*$) across the pool for $Nu = 10$.

Effect of Nusselt Number

The effect of Nu on the dissolved layer thickness is shown in Figure 6 for the case of $K_c = 1.65 \times 10^{-2}$. For $\tau \leq 1$, there is virtually no dissolution of the bottom head. Most dissolution occurs in the period of $1 < \tau < \tau_{cr}$, where the critical time τ_{cr} depends on the value of Nu . For $\tau > \tau_{cr}$, Δ assumes a constant value of $\Delta(\infty)$. Physically, $\Delta(\infty)$ represents the total fraction of the bottom head that is dissolved in the aluminum pool when reaching a coolable equilibrium situation. An increase in the Nusselt number results in a larger value of $\Delta(\infty)$. However, owing to the fact that the rate of dissolution increases very quickly with the Nusselt number, the value of τ_{cr} actually decreases as the Nusselt number is increased. Note that $\Delta(\infty)$ is a strong function of the Nusselt number in the range of $1 \leq Nu \leq 10$. For $Nu > 10$, $\Delta(\infty)$ is a weak function of Nu . In fact, for $Nu \geq 100$, $\Delta(\infty)$ is almost independent of the Nusselt number. The maximum value of $\Delta(\infty)$ corresponding to $Nu \rightarrow \infty$ is about 0.343. Evidently, because of saturation, the extent of dissolution is limited to about one-third of the initial bottom head thickness, thus leaving the remaining two-thirds intact.

Effect of Dissolution Coefficient

Figure 7 illustrates the effect of the dissolution coefficient on the dissolved layer thickness for the case of $Nu = 10$. For all values of K_c under consideration, the time variation of $\Delta(\tau)$ exhibits a similar behavior. There is no appreciable dissolution until a certain incipient time after the onset of melt/structure interaction. Significant dissolution takes place only in a period between the incipient time and the critical time τ_{cr} . For $\tau \geq \tau_{cr}$, Δ approaches an asymptotic value of $\Delta(\infty)$, and the dissolution process essentially ceases. It is of interest to note that $\Delta(\infty)$ is independent of the dissolution coefficient. For a given Nusselt number, the steady-state interface temperature is uniquely determined, which in turn dictates the steady-state solubility limit. Thus the total fraction of the bottom head dissolved in the aluminum melt pool at the end of the dissolution process is fixed by the thermal conditions of the system, independent of the value of K_c . However, the dissolution coefficient has strong influence on the time scale of the dissolution process. As K_c is increased from 1.65×10^{-3} to 0.165, the value of τ_{cr} decreases from 7,000 to 50.

Total Fraction of Steel Structure Dissolved

The fact that $\Delta(\infty)$ is independent of K_c suggests that the total fraction of the steel structure dissolved in the melt

pool can be correlated to the Nusselt number alone. This is done in Figure 8 where the numerical data for $\Delta(\infty)$ are plotted against Nu for three different values of K_c . As expected, the three sets of data merge nicely onto a single curve. Evidently, $\Delta(\infty)$ is a monotonically increasing function of Nu . However, the dependence of $\Delta(\infty)$ on the Nusselt number gradually diminishes as Nu becomes much larger than ten. The numerical data can be fitted by the least squares technique for $Nu \geq 1$ to give

$$\Delta(\infty) = 0.343 - 0.285(0.165 + Nu)^{-0.98} \quad (25)$$

At the limit of $Nu \rightarrow \infty$, $\Delta(\infty)$ assumes the maximum value of 0.343. Note that at $Nu = 10$, $\Delta(\infty)$ is within 10% of the maximum value whereas at $Nu = 100$, $\Delta(\infty)$ is within 1% of the maximum value. For $Nu > 100$, $\Delta(\infty)$ is essentially constant, equal to 0.343.

5 Conclusions

Within the specific range of conditions under consideration in this study, the following conclusions can be made:

1. Both the bottom-head temperature and the melt temperature tend to overshoot their respective equilibrium values during the thermal transient. However, this overshoot behavior does not seem to affect the ultimate extent of dissolution.
2. An increase in the Nusselt number results in a decrease in the bulk pool temperature but an increase in the melt/structure interface temperature. This leads to a smaller upper surface heat flux but a considerably higher lower surface heat flux.
3. Most dissolution takes place in a period between the incipient time and the critical time. During this period, the rate of dissolution appears to depend primarily on the Nusselt number.
4. For all values of the Nusselt number and dissolution coefficient under consideration, a coolable equilibrium situation is always achieved in the melt/structure system as the critical time is approached. No further dissolution nor changes in the thermal conditions of the system would occur beyond the critical time.
5. The critical time is a strong function of the dissolution coefficient but a mild function of the Nusselt number. In general, an increase in either K_c or Nu would result in a decrease in the value of τ_{cr} .
6. The ultimate extent of dissolution (i.e., the total fraction of the steel structure dissolved) is a function of the Nusselt number alone, independent of the dissolution coefficient. For $1 \leq Nu \leq 10$, $\Delta(\infty)$ increases rather quickly with an increasing value of Nu . However $\Delta(\infty)$ depends rather weakly on the Nusselt number for $Nu > 10$. At large Nusselt numbers ($Nu \geq 100$), $\Delta(\infty)$ is essentially constant, having the maximum value of 0.343.

References

Cheung, F.B., Cho, D.H. and Tan, M.J., 1992, "Natural Convection Dissolution Boundary Layer on a Vertical Surface,"

to be published.

Dybkov, V.I., 1990, "Interaction of 18Cr, -10Ni, Stainless Steel with Liquid Aluminum," *Journal of Materials Science*, Vol. 25, pp. 3615-3633.

Gairola, P.K., Tiwari, R.K., and Ghosh, A., 1971, "Rates of Dissolution of a Vertical Nickel Cylinder in Liquid Aluminum Under Free Convection," *Metallurgical Transactions*, Vol. 2, pp. 2123-2126.

Hatch, J.E. (ed.), 1988, "Aluminum: Properties and Physical Metallurgy", American Society of Metals.

Kulacki, F.A., Emara, A.A., Korpela, S.A., Lambha, M.K., and Min, J.H., 1978, "Natural Convection with Internal Energy Sources: Some Recent Experimental and Numerical Results with Post-Accident Heat Removal Applications," *Proc. Third Post-Accident Heat Removal Information Exchange*, ANL-78-10, pp. 101-113, Argonne National Laboratory.

Niinomi, M., Suzuki, Y. and Veda, Y., 1984, "Dissolution of Ferrous Alloys into Molten Pure Aluminum Under Forced Flow," *Trans. Japan Institute of Metals*, Vol. 25, No. 6, pp. 429-439.

Niinomi, M., Veda, Y. and Sano, M., 1982, "On the Alloy Layers Formed by the Reaction Between Ferrous Alloys and Molten Aluminum," *Trans. Japan Institute of Metals*, Vol. 23, No. 12, pp. 780-787.

Ravoo, E., Rotte, J.W. and Sevenster, F.W., 1970, "Theoretical and Electrochemical Investigation of Free Convection Mass Transfer at Vertical Cylinders," *Chemical Engineering Science*, Vol. 25, pp. 1637-1652.

Tan, M.J., 1992, Private Communication, Argonne National Laboratory.

Tutu, N.K., 1991, Private Communication, Brookhaven National Laboratory.

Table 1: Thermophysical Properties of the Aluminum Melt Pool/Steel Structure System

Properties	Aluminum Melt Pool	Steel Structure
Density kg/m ³	$2,385 - 0.28[T_m(0) - T_o](\theta_m - 1)$	8,000
Specific Heat kJ/kg K	1.1	0.7
Thermal Conductivity kW/mK	0.1	2.54×10^{-2}
Surface Emissivity	0.3	---
Decay Heating Rate, ϕ	2.83	0
Heat Capacity Ratio, C_R	0.516

Figure 1 Transient temperature distribution in the bottom head ($0 \leq \eta \leq 1$).

Figure 2 Transient temperature distribution in the bottom head showing the instantaneous location of the dissolution front

Figure 3 Transient melt/structure interface and bulk pool temperatures for the cases of $Nu = 1$ and $Nu = 10$

Figure 5 Time variations of the melt concentration for the cases of $Nu = 1$ and $Nu = 10$

Figure 4 Transient lower and upper surface heat fluxes for the cases of $Nu = 1$ and $Nu = 10$

Figure 6 Effect of the Nusselt number on the thickness of the dissolved layer

Figure 7 Effect of the dissolution coefficient on the thickness of the dissolved layer

Figure 8 Effect of the Nusselt number on the total fraction of steel dissolved in the melt pool

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