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A Study on the Heat Source in a Molten Pool During the Severe Accident of PWRs

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Abstract

Heat transfer and fluid flow in a molten pool are influenced by internal volumetric heat generated from the radioactive decay of fission product species retained in the pool. The pool superheat is determined based on the overall energy balance that equates the heat production rate to the heat loss rate. Decay heat of fission products in the pool was estimated by product of the mass concentration and energy conversion factor of each fission product. For the calculation of heat generation rate in the pool, twenty-nine elements were chosen and classified by their chemical properties. The mass concentration of a fission product is obtained from released fraction and the tabular output of the ORIGEN 2 code. The initial core and pool inventories at each time can also be estimated using ORIGEN 2. The released fraction of each fission product is calculated based on the bubble dynamics and mass transport. Numerical analysis was performed for the TMI-2 accident. The pool is assumed to be a partially filled hemispherical geometry, 1.45 m in radius and 32,700 kg in mass. The change of pool geometry during the numerical calculation was neglected. The peak temperature sizably decreased by about 60 K as the fission products are released from the pool.

1. Introduction

A severe accident management concept known as "in-vessel retention" is based on the idea that the vessel lower head will be able to arrest the downward relocation of a degraded core. Lower head integrity can be maintained through the removal process of generated heat. Heat generation in relocated material is mainly caused by radioactive decay of fission products. As the reactor core material melts and relocates, the molten debris pool may be formed in the lower plenum of the reactor pressure vessel or the lower core. If fission product is released from the molten pool, heat source in relocated material may be decreased significantly. Results of the TMI-2 accident analysis indicate that volatile (e.g., I, Cs, Xe) fission products can mostly be released from a molten pool. In the TMI-2 accident, a pool of molten core material was formed and grown within the consolidated region

The chemical state of the fission products (i.e. vapor pressure) will depend on the temperature and oxygen potential. During the formation and growth of a pool, the release of volatile fission products would be dominated by bubble dynamics as they all behave as gases. But the release of involatile fission products is controlled by mass transfer because they are existed as condensed phases in the pool. The rate of fission product release is calculated using bubble dynamics and mass transfer. For the calculation of heat generation rate in the pool, twenty- nine (29) elements were chosen and classified (see Figure 3). The change of these fission products due to decay chain can be obtained from tabular output of ORIGEN 2 code. The flow in a molten pool is governed by natural convection with internal heat source. Heat transfer in the pool was treated with the lumped parameter method. The effect on pool temperature decrease of fission product release was estimated with energy balance. Energy balance, heat transfer and flow within a molten pool are described in below section.

2. Heat Transfer and Flow in a Molten Pool

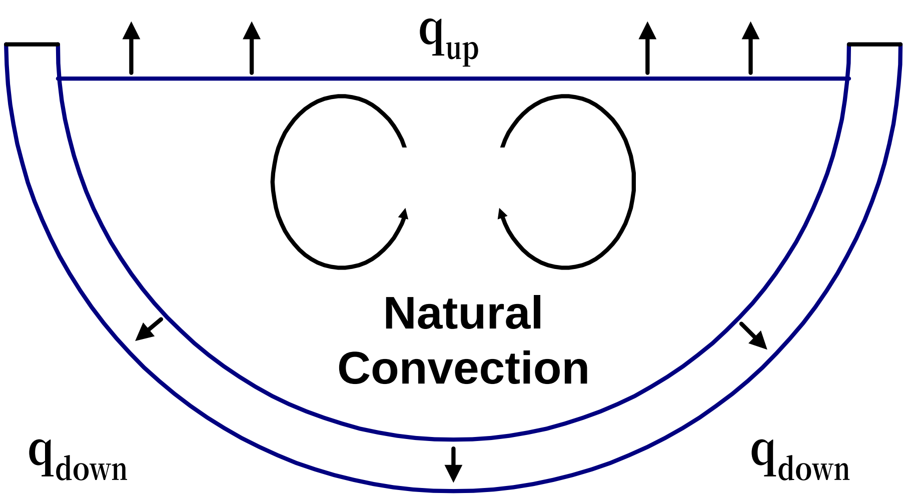


Figure 1. Heat transfer and fluid flow in a molten pool

The geometry of a molten pool is assumed to be a partially filled hemisphere. The material is (U, Zr)O_2 with a melting point of ~2850 K. It is assumed that the pool is well mixed. Heat transfer and fluid flow in an oxidic pool shown in Figure 1 are induced by internal volumetric heat generated from the radioactive decay of fission product species retained in the pool. The pattern of flow in the pool having heat-generating liquid is depicted by natural convection being governed by a Rayleigh number characterizing the relationship between the forces of buoyancy and viscous friction. If the pool is deep enough, a stable natural-convection current can be formed. Kulacki and Goldstein suggest that convective mixing of the fluid produces a temperature profile that is axially and radially uniform, except for thin laminar boundary layers at the top and at the bottom (1972). Therefore, it is assumed that heat transfer in the pool can be treated with lumped parameter methods without introducing a significant error in the estimation of the pool temperature.

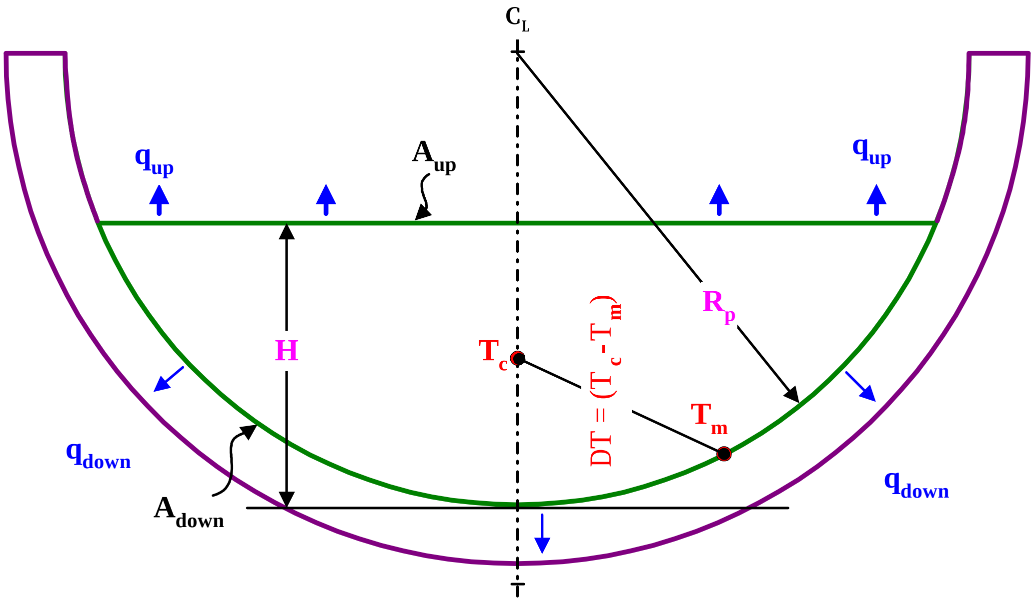


Figure 2. Schematic of the physical model

Natural convection phenomena can be scaled in terms of the Grashof, Gr, and Praldtl, Pr, numbers. The presence of volumetric heating necessitates use of the Dammköhler, Da, number. These numbers are expressed (Theofanous, et al., 1994), respectively, as

$$Gr = \frac{gb(T_{\max} - T_i)H^3}{n^2} \quad , \quad Pr = \frac{n}{a}, \quad Da = \frac{\dot{Q}H^2}{k(T_{\max} - T_i)} \tag{1}$$

The Rayleigh number is given by $Ra = Gr \cdot \Pr \cdot Da$. The behavior of overall heat transfer can be characterized by a correlation in the form of

$$Nu = f(Gr, \Pr, Da) = C_A Ra^{C_B} \tag{2}$$

where C_A and C_B are empirically determined constants, and

$$Ra = \frac{bg\dot{Q}H^5}{na\,k} \tag{3}$$

For the oxidic pool, the ranges of the Ra and Pr numbers are, respectively

$10^{15} < Ra < 6\times10^{15}$ $\quad$ $Pr \sim 0.6$

Using the best-known correlations, heat transfer is calculated at the curved bottom and the top of the pool. The correlations are summarized below (Mayinger, et al., 1976; Asfia, et al., 1994).

$$Nu_{up} = 0.36 Ra^{0.23} \tag{4}$$

$$Nu_{down} = 0.54 Ra^{0.2} (H / R_p)^{0.25} \tag{5}$$

The Schematic of the physical model is shown in Figure 2. The overall energy balance that equates the heat production rate to the heat loss rate is

$$V_p \dot{Q} = A_{up} q_{up} + A_{down} q_{down} \tag{6}$$

where A_{up} and A_{down} are surface areas of partially filled hemispherical geometry at each direction. In a partially filled hemisphere geometry, A_{up} and A_{dowun} can be determined as follows

$$A_{up} = pR_p^2(1-x^2) \quad (7)$$

$$A_{down} = 2pR_p^2 \cos(\arcsin x) \quad (8)$$

$$x = 1 - H / R_p \quad (9)$$

Substituting Equations (4) and (5) into Equation (6) to eliminate q_{up} and q_{down}, the pool superheat ΔT may readily be calculated as

$$\Delta T = \frac{HV_p\dot{Q}}{k}[0.54A_{up}(Ra)^{0.2}(H/R)^{0.25} + 0.36A_{down}(Ra)^{0.23}] \quad (10)$$

Table 1. Radionuclide Elements and Classes

Class	Member Elements
1. Noble gases	Xe, Kr
2. Alkali metals	Cs, Rb
3. Alkaline earths	Ba, Sr
4. Halogens	I, Br
5. Chalcogens	Te, Se
6. Platinoids	Ru, Pd, Rh
7. Transition metals	Mo, Tc, Nb
8. Tetravalents	Ce, Zr, Np
9. Trivalents	La, Pm, Y, Pr, Nd
10. Uranium	U
11. More volatile metals	As, Sb
12. Less volatile metals	Sn, Ag

Decrease of decay heat in the pool results from fission product release. Decay heat (i.e. heat source in the pool) of each species equals product of mass and energy conversion factor. Total decay heat in the pool is calculated as:

$$\dot{Q} = \sum_i M_i(t)h(i) \quad (11)$$

For twenty-nine (29) elements only, heat generation rate in the pool is calculated. Twenty- nine (29) elements are listed in Table 3. Note that decay power fraction of the remaining elements except the 29 elements are less than 1%. At time t, the initial mass concentration of fission product i in the pool can be obtained by

$$M_{i,0}(t) = [M_{i,j} + (M_{i,j+1} - M_{i,j})\frac{(t-t_j)}{(t_{j+1}-t_j)}](1-f_c)(m_c/m_p) \quad (12)$$

In Equation (12), $M_{i,j}$ and t_j can be obtained from the tabular output of the ORIGEN 2 code. Using ORIGEN 2, the initial core and pool inventories at each time can be estimated. With consideration of released fraction of fission product i at time t, the mass concentration of fission product i is estimated as follows.

$$M_i(t) = M_{i,0}(t)(1-f_p(t)) \quad (13)$$

3. Fission Product Release from the Pool

Volatile fission products (Xe, Kr, Cs, I) are insoluble in liquid UO_2. Release of the volatile fission products is dominated by bubble dynamics because they all behave as gases in a molten debris pool. Bubble dynamics in the pool is thus characterized by bubble nucleation, coalescence, growth and rise. The time rate of change for the bubble concentration may be represented as follows

$$\frac{dn_i}{dt} = \frac{dn_{i,nucl}}{dt} + \frac{dn_{i,coal}}{dt} + \frac{dn_{i,diff}}{dt} - \frac{dn_{i,coal}}{dt} \quad (14)$$

The nucleated bubbles have very small sizes and follow the natural convection flows. Small bubbles coalesce into larger bubbles by turbulence and differential bubble rise in the pool. These bubbles will grow by diffusion of vapor molecules to bubbles. Bubbles can be released from the pool as they sufficiently grow up.

The less volatile fission products tend to remain as condensed phases in the melt because of their low vapor pressures. The chemical forms of the less volatile fission products in the melt are determined by the oxygen potential. It is assumed that mass transport governs release of the less volatile fission product from the pool. At high temperature (>2850 K), rare earth elements such as europium and cerium exist as oxides, strontium is present as SrO, and ruthenium and antimony are present as metals immiscible in the molten pool (Petti, et al., 1989). The rate of mass transport of a species in a liquid is given by

$$\dot{m} = k_m A_{up} (C_\infty - C_{surf}) \quad (15)$$

The mass transfer correlations for the top of the pool can be obtained by means of a heat and mass transfer analogy

4. Results and Discussion

For all the fission product release calculations in this work, the main parameters were obtained from the analysis report of the TMI-2 accident (Akers, et al., 1989). The pool is assumed to be a partially filled hemisphere, 1.45 m in radius and 32,700 kg in mass. The change of pool geometry during the numerical calculation is neglected. The fission product inventories in the pool are about 24.5% of the total core inventories. The parameters used in the numerical calculations are listed in Table 2. From the numerical analysis, the height of the pool is 1.014 m and peak temperature at the pool center exceeds 3000 K.

The calculations were carried out with p=10 MPa, ns_t=5000, and initial inventory = 100 %. In each cases of $M_{b,0}/M_0$=0 and 0.5, times to release 60 % of volatile gas inventory are about 4350 and 750 sec as shown in Figure 3-(d) and 4-(d). From concentrations of the 29 elements in the pool, total heat generation rate was obtained at time t. Figure 3-(a) and 4-(a) comparatively show the difference of volumetric heat generation rate between the volatile and involatile fission products. Figure 3-(b) and (c) show decrease of decay heat by fission product release and the peak temperature in the pool. When release of the fission products from the debris pool is considered, the peak temperature of the pool decreases from 3224 K to 3166 K at 4346 sec as shown in Figure 3-(c). In Figure 4-(c), also, the peak temperature in the pool decreases from 3260 K to 3194 K at 745.5 sec.

Table 2. Values and Ranges of Parameters

Parameter	Value
Pool mass , M_p [kg]	32,700
Pool radius, R_p [m]	1.45
Pool pressure, *p* [MPa]	10.0
Pool velocity, V_{conv} [m/sec]	0.13
Pool depth, H [m]	1.014
Number of temperature-dependent nucleation sites, ns_t [no./kg]	5,000
Diffusivity of fission product, D [m^2/sec]	1.0×10^{-9}
Surface tension of liquid in pool g [N/m]	1.0

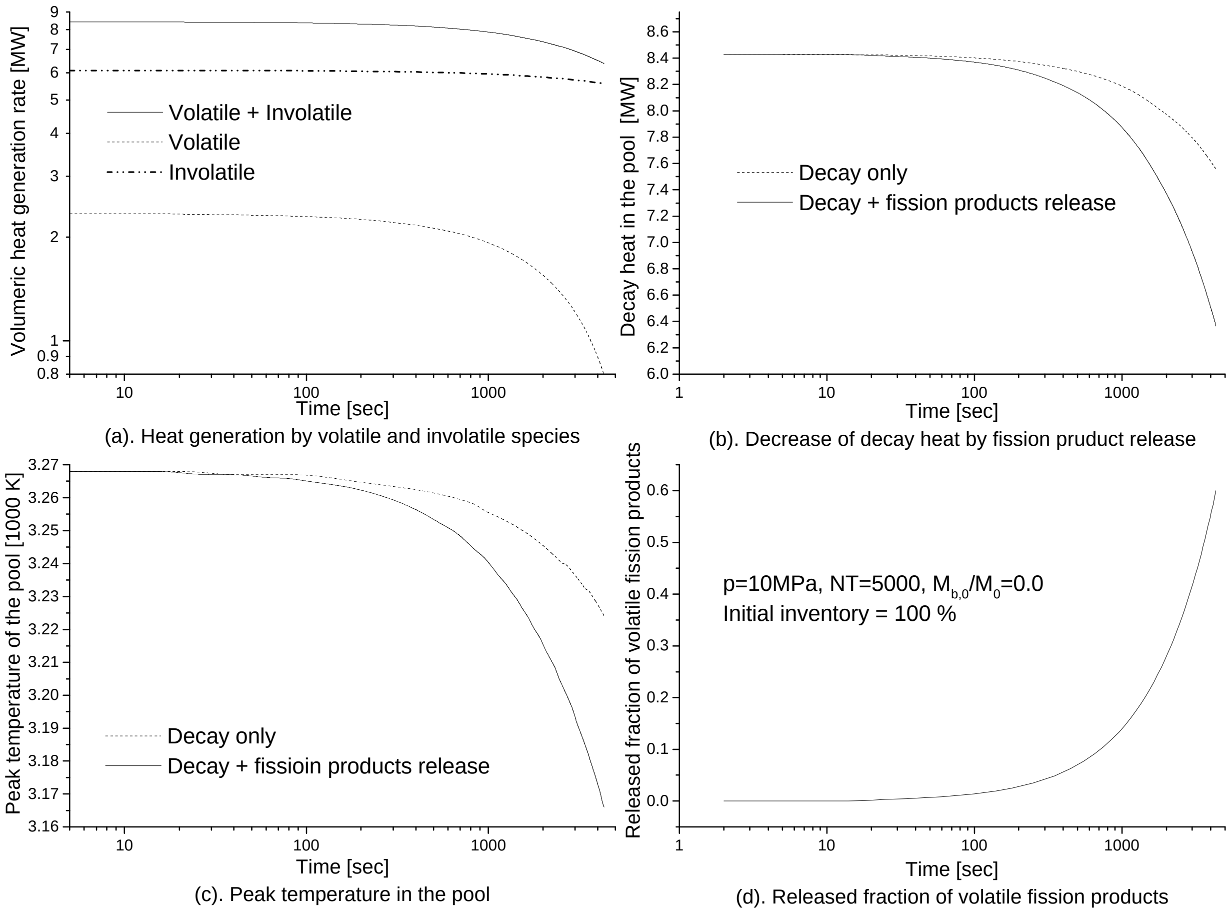
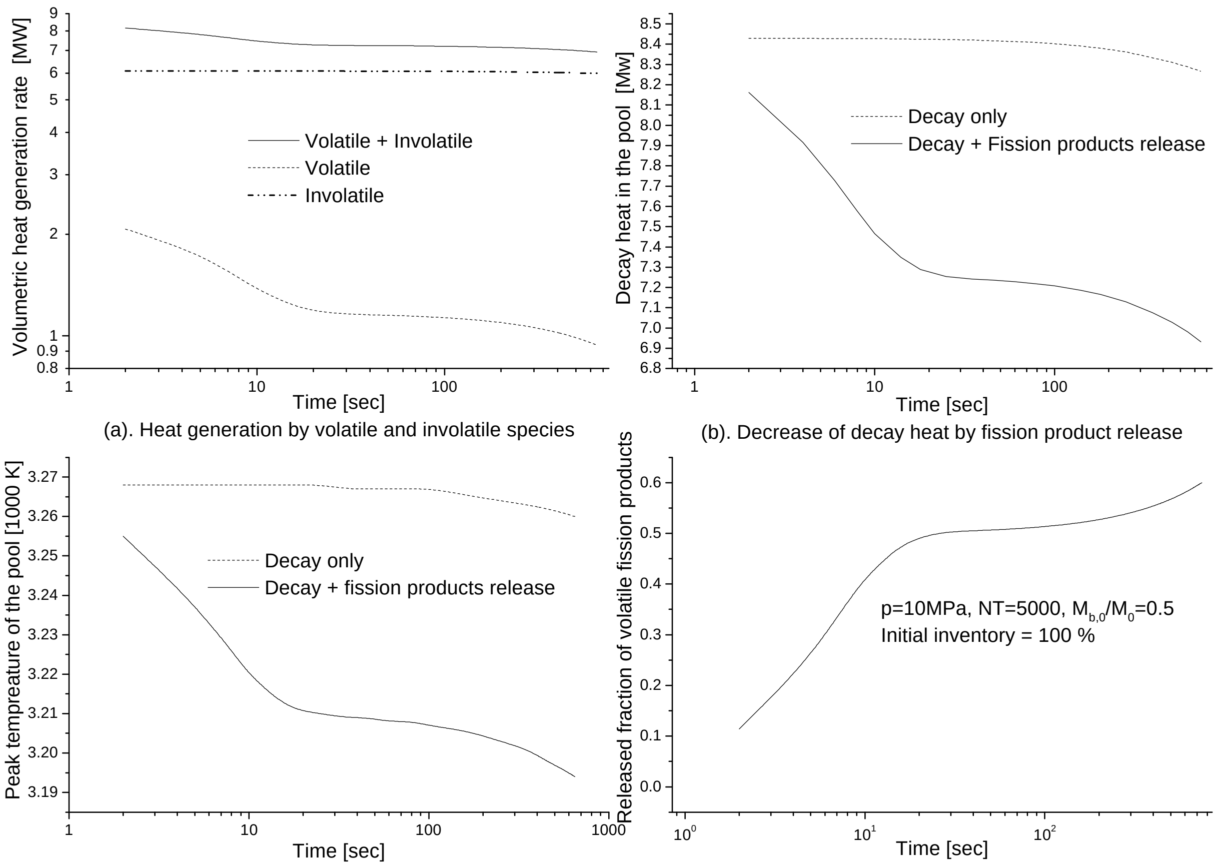


Figure 3. Heat generation and transfer in case of mass ratio ($M_{b.0}/M_0$) = 0.0



(a). Heat generation by volatile and involatile species

(b). Decrease of decay heat by fission product release

(c). Peak temperature in the pool

(d). Released fraction of volatile fission products

Figure 4. Heat generation and transfer in case of mass ratio ($M_{b.0}/M_0$) = 0.5

Because Initial bubbles interact and rapidly grow by coalescence and diffusion to a bubble, if bubbles in molten core material exist before the formation of the pool, pool peak temperature decreases faster.

Table 3. Pool specific heat and heat flux of the pool

	Release	Decay heat rate, $\dot{Q}$ [MW]	Pool specific heat, ΔT [K]	Heat flux, q_{down} [W/M^{-2}]
Mass ratio = 0.0	No	7.55	374.5	9.34E5
	Yes	6.37	315.6	7.61E5
Mass ratio = 0.5	No	8.27	409.8	1.04E6
	Yes	6.93	343.7	8.42E5

When thermal properties of the pool are taken to be: $k = 4\ W/mK$, $a = 9.1 \times 10^{-7}\ m^2/s$, $n = 5.9 \times 10^{-7}\ m^2/s$, and $b = 9.1 \times 10^{-7}\ K^{-1}$. Pool Rayleigh number is about $3 \sim 3.5 \times 10^{15}$. Table 3 shows pool specific heat and average downward heat flux at the time to release 60% of volatile gas inventory. Under the condition which fission products release, pool specific heat and average downward heat flux are significantly reduced by removal mechanism of heat source. Therefore, fission product release may be considered to best estimate heat source of the pool and lower head integrity.

5. Conclusions

When fission products release from the molten pool, heat source of the pool was estimated using 29 nuclides concentration data of ORIGEN 2 code and heat flux, pool specific heat and peak temperature were calculated by overall energy balance. The heat generation rate decreases faster, if initial bubbles exist in the pool, because of release of mainly volatile fission gas. The peak temperature sizably decreased by about 60 K as the fission products are released from the pool. For both cases with $M_{b,0}/M_0$ *= 0.0 and 0.5,* heat flux is reduced by ~20%. From results of numerical analysis, it is concluded that fission product release may be considered to best estimate heat source of the pool and lower head integrity

Nomenclature

A_{down}	= area for downward heat transfer	$[m^2]$
A_{up}	= area for upward heat transfer	$[m^2]$
C	= fission product concentration in the pool	$[No./m^3]$
$f_{c,i}$	= released fraction of species i before formation of the pool	
f_p	= released fraction of species i from the pool	
H	= pool depth	$[m]$
k	= thermal conductivity	$[W/m\cdot K]$
k_m	= mass transfer coefficient	$[m/s]$
$\dot{m}$	= rate of mass transport	$[kg/s]$
m_c	= mass of the core	$[kg]$
m_p	= mass of the pool	$[kg]$
$M_{b,0}$	= total mass of volatile species in the initial bubbles	$[kg]$
$M_{i,0}$	= initial inventory of volatile fission product i in the pool	$[kg]$
M_0	= initial inventory of volatile species in the pool $(=\sum_i M_{i,0})$	$[kg]$
n	= number density of bubble	$[No./m^3]$
ns_t	= number density of temperature-dependent nucleation sites	$[No./kg]$
$\dot{Q}$	= volumetric heat generation rate	$[W/m^3]$
p	= pool pressure	$[Pa]$
q	= average heat flux over a boundary	$[W/m^2]$
R_P	= radius of the molten pool	$[m]$
T	= temperature of the pool	$[K]$
ΔT	= pool superheat	$[K]$
V_P	= volume of the pool	$[m^3]$

Greek Letters

a	= thermal diffusivity	$[m^2/s]$
b	= thermal expansion coefficient	$[K^{-1}]$
h	= heat generation per unit mass	$[W/kg]$

n = kinematic viscosity $[kg/m \cdot s]$

Subscripts

0 = initial value or nominal value
∞ = value in the bulk
coal = coalescence
conv = convection
diff = diffusion
nucl = nucleation
loss = loss due to bubble rise
surf = surface

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