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Evaporation of water at high mass-transfer rates by natural convection air flow with application to spent-fuel pools

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ABSTRACT

A simple model of evaporation from warm pools of water with turbulent, natural convection flow in the vapor phase is presented. The model is applicable from the dilute, low mass-transfer rate regime (room temperature) through the high mass-transfer rate regime (up to 99 °C). The model is applied to spent-fuel pool (SFP) heat and mass transfer during emergency conditions (e.g., plant blackout), and, in particular, to Fukushima. Comparisons with previous models are made. A simple analytic formula is presented that is nearly explicit in solving for pool temperature. The formula separates the more temperature-dependent properties from less temperature-dependent ones via a non-dimensional ratio $Q_u = q_u/q_{u,b}$, where q_u is the arbitrary (but specified) evaporative (latent) heat flux (∼decay heat for SFP) and $q_{u,b}$ is the latent heat flux characteristic of incipient boiling. The latter has a simple, relatively temperature-independent expression, $q_{u,b} = (h_{fg}\, Le^{2/3}\, h^*)/C_p$, where h^* is the dilute-limit heat transfer coefficient. This formula predicts that for natural convection at 99 °C ($h^* \sim 10\ W/m^2\,K$) $q_{u,b}$ is approximately 18 kW/m², slightly greater than, but of the same order of magnitude as, pool boiling heat flux at the onset of nucleate boiling. A new blowing factor correlation is presented for high-rate mass-transfer ($B_m > 1$) of air–water vapor ($Pr \sim 0.7$, $Sc \sim 0.6$) turbulent natural convection flow over a heated horizontal surface for pool temperatures up to 99 °C (incipient boiling).

1. Introduction

Evaporation of water from horizontal surfaces (pools) via natural convection at high mass-transfer rates is a little studied mode of heat and mass transfer with an important application: nuclear power plant spent-fuel pools under emergency conditions. Nuclear power plant spent-fuel pools (SFP) rely on emergency cooling to continue removing nuclear decay heat from the pool after normal heat exchanger cooling fails. During extreme emergencies, such as station blackout, even the back-up emergency cooling may fail, and the pool will heat up into the high mass-transfer rate regime. Such conditions occurred at the Fukushima Dai-ichi nuclear power plant in March 2011.

In the wake of Fukushima a number of simple models were proposed to simulate SFP evaporation and warm-up, particularly Dai-ichi Unit 4 (SFP4) because it was so heavily loaded with spent fuel [1–6]. All of these models were based on some elements of heat and/or mass transfer theory, some without consideration of high-rate mass transfer [1–3], and some with [4–6]. Some of them relied on calibration constants from outside heat- and mass-transfer theory [1,2,4–6] and some did not [3]. In spite of being based on heat- and mass-transfer theory, these various models predicted a wide variety of results for SFP4.

Here we both review those previous models and develop a new, robust heat- and mass-transfer model for warm water pools in air under turbulent natural convection flow applicable to the high mass-transfer rate regime. Our goal is for the model to be valid up to incipient boiling. We use the classic Spalding mass transfer theory [7] and apply it to horizontal-surface, natural convection (HNC) flow. The only adjustable factor we include is the blowing factor, g/g^*, which has apparently not been studied for this type of flow. In this regard, we find that the often-used default Stagnant Film or Stefan Flow (SF) blowing factor is unsuitable for HNC flow, and we develop a new blowing factor correlation for air–water vapor ($Pr \sim 0.7$, $Sc \sim 0.6$).

We also introduce a new non-dimensional parameter based on characteristic latent heat flux in the high mass-transfer rate regime that is useful for problems with prescribed, or nearly prescribed, latent heat flux and unknown pool temperature during quasi-steady evaporation, such as SFP.

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Nomenclature

Symbols

$B_{m,h}$	spalding B-number for mass or heat transfer
C	liquid water specific heat, 4.2 kJ/kg-K
C_p	average vapor specific heat, $0.5(m_{1,e}C_{p1,e} + m_{2,e}C_{p2,e} + m_{1,s}C_{p1,s} + m_{2,s}C_{p2,s})$
D	pool length
D_{12}	binary diffusion coefficient of water (1) in air (2) at 101 kPa, $1.97 \times 10^{-5}\ [m^2/s](T[K]/256)^{1.685}$
Gr	Grashof number, $g(\rho_e - \rho_s)L^3/\rho\nu^2$
Gr_h	*Gr* with only temperature dependence of density, $g\beta(T_s - T_e)L^3/\nu^2$
Gr_m	*Gr* with only composition dependence of density, $g\zeta(m_{1,s} - m_{1,e})L^3/\nu^2$
g	generic for g_m or g_h, or gravitational constant, 9.81 m/s^2
$g_{m,h}$	Spalding gradient term, i.e., conductance for mass or heat transfer
g^*	generic for g_m or g_h in no-blowing limit
h	enthalpy or convective heat transfer coefficient
h_{fg}	latent enthalpy of evaporation
h_r	radiative heat transfer coefficient
h^*	convective heat transfer coefficient in no-blowing limit
h_m	convective mass transfer coefficient
h_m^*	convective mass transfer coefficient in no-blowing limit
j_i	species-i diffusion mass flux; Fick's law: $-\rho D_{12}\frac{\partial m_i}{\partial y}$
k	vapor thermal conductivity, $\alpha\rho C_p$
L	characteristic length
Le	Lewis number, $(D_{12}/\alpha) = Pr/Sc = 1.13$
M	average molecular weight, $(m_{1,avg}/M_1 + m_{2,avg}/M_2)^{-1}$
M_e	molecular weight at e-state, $(m_{1,e}/M_1 + m_{2,e}/M_2)^{-1}$
M_s	molecular weight at s-state, $(m_{1,s}/M_1 + m_{2,s}/M_2)^{-1}$
m_1	water mass fraction in vapor phase, $P_1/[P(M_2/M_1) - P_1(1 - M_2/M_1)]$
m_2	dry air mass fraction, $1 - m_1$
$\dot{m}''$	evaporating water mass flux at vapor–liquid interface
Nu	Nusselt number in dilute limit, h^*L/k
P	total pressure
P_{sat}	water saturation pressure
$P_1(T)$	water vapor partial pressure, $RH^*P_{sat}(T)$
Pr	Prandtl number, $(\nu/\alpha) = 0.70$
Q_u	mass-transfer rate parameter for prescribed latent heat flux, $q_u/q_{u,b} = q_uC_p/(h_{fg}\ Le^{2/3}\ h^*)$
$q_{c,s}$	heat flux conducted/convected away from the interface on vapor side, $-k \cdot \frac{\partial T}{\partial y}\Big\|_s = h(T_s - T_e) = h^*(g_h/g_h^*)(T_s - T_e)$
$q_{c,u}$	heat flux conducted to interface from liquid side (decay heat flux)
$q_{r,s}$	heat flux radiated from liquid to vapor, Eq. (15)
q_u	latent heat flux of evaporation, $q_{c,u} - q_{r,s} - q_{c,s} = \dot{m}''\ h_{fg}$
$q_{u,b}$	heat flux characteristic of high mass-transfer rate (incipient boiling) regime $(B_m \gg 1)$, $(h_{fg}\ Le^{2/3}\ h^*)/C_p$
Ra_h	Rayleigh number for heat transfer, *GrPr* (except in Eq. (11b): Gr_hPr)
Ra_m	Rayleigh number for mass transfer, *GrSc*
RH	relative humidity, $P_1(T)/P_{sat}(T)$
R	universal gas constant, 8.314 kJ/kmol-K
Sc	Schmidt number, $(\nu/D_{12}) = 0.62$
Sh	Sherwood number in dilute limit, $h_m^*\ L/D_{12}$
T	temperature
v	vertical y-component of velocity
W	pool width
y	coordinate perpendicular to interface, positive into gas phase

Greek

α	vapor thermal diffusivity, $(k/\rho C_p) = \nu/Pr$
β	sensitivity of density to temperature or thermal expansion coefficient, $-\frac{1}{\rho}\cdot\frac{\partial\rho}{\partial T}\big\|_{p,m_1} = \frac{1}{T}$
δ	column height of Stagnant Film (Stefan Flow)
ν	vapor momentum diffusivity or kinematic viscosity, $Sc * D_{12}$
ρ	average vapor density, $P/[(8.314/M_{avg})T_{avg}]$
$\rho_{e,s}$	vapor density at e- and s-states, $P/[(8.314/M_{e,s})T_{e,s}]$
σ	Stefan-Boltzmann constant, $5.67 \times 10^{-8}\ W/m^2\ K^4$
ζ	sensitivity of density to water vapor mass fraction, $-\frac{1}{\rho}\cdot\frac{\partial\rho}{\partial m_1}\Big\|_{P,T} = \frac{1}{M}\left[\frac{1}{M_1} + \frac{1}{M_2}\right]$

Subscripts

1	water species
2	air species
avg	average, $()_{avg} = 0.5[()_s + ()_e]$
c	conductive/convective
e	thermodynamic state of vapor environment
fg	saturated liquid–vapor phase change
i	species index
L	characteristic length scale for flow in vapor phase
r	radiative
s	thermodynamic state in vapor at liquid–vapor interface
u	thermodynamic state in liquid at liquid–vapor interface

Superscripts

*	low mass-transfer rate or dilute (no-blowing) limit

Acronyms and abbreviations

HNC	Horizontal-Surface Natural Convection flow
LBL	Laminar Boundary Layer (forced convection) flow
NBP	Normal Boiling Point
ONB	Onset of Nucleate (pool) Boiling
SF	Stagnant Film (Stefan Flow)
SFP4	Spent Fuel Pool, Fukushima dai-ichi unit 4

2. Analysis

2.1. Liquid-phase: pool and interface energy balances

Consider a rectangular (WxD) pool of water in air and the vanishingly thin interface between liquid water and vapor air–water where liquid–vapor phase change of water occurs (Fig. 1). A prescribed thermal power load, such as decay heat/power from submerged spent nuclear fuel, is supplied to the pool water by conduction/natural convection. The normal heat exchanger function that removes most of this heat has failed. The pool heats up to a relatively warm state with increased evaporation rate such that latent heat of evaporation takes most of the decay heat, except for small heat losses due to radiation and convection from the water surface. Water evaporates from the surface, into ambient air, typically in a reactor building at thermodynamic state-e, with mass flux $\dot{m}'' > 0$. The thermodynamic state of vapor just above the surface is the s-state, and that of liquid just below the surface is the u-state. The energy balance on the interface (Fig. 1) is: