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A three-region conduction-controlled rewetting analysis by the Heat Balance Integral Method

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ABSTRACT

Conduction-controlled rewetting of two-dimensional objects is analyzed by the Heat Balance Integral Method (HBIM) considering three distinct regions: a dry region ahead of wet front, the sputtering region immediately behind the wet front and a continuous film region further upstream. The HBIM yields solutions for wet front velocity, sputtering length and temperature field with respect to wet front. Employing this method, it is seen that heat transfer mechanism is dependent upon two temperature parameters. One of them characterizes the initial wall temperature while the other specifies the range of temperature for sputtering region. Additionally, the mechanism of heat transfer is found to be dependent on two Biot numbers comprising a convective heat transfer in the wet region and a boiling heat transfer in the sputtering region. The present solution exactly matches with the one-dimensional analysis of K.H. Sun, G.E. Dix, C.L. Tien [Cooling of a very hot vertical surface by falling liquid film, ASME J. Heat Transf. 96 (1974) 126–131] for low Biot numbers. Good agreement with experimental results is also observed.

1. Introduction

Rewetting of a hot surface is a process in which the liquid wets the hot surface by displacing its own vapour that otherwise prevents the contact between the solid and the liquid phase. This phenomenon is of practical importance in controlled rewetting in nuclear reactors during emergency cooling after a loss of coolant accident, cryogenic systems, metallurgical processes and space station thermal control. During cooling of nuclear fuel rods by a falling film of water, the heat transfer in the liquid region takes place by convection. However, closer to the wet front, the heat transfer is mainly due to nucleate boiling. It has been observed from experiments [1] that a large number of bubbles originate from the hot surface closer to the wet front. These bubbles interfere with each other and disrupt the liquid film which causes sputtering and shearing of the film from the hot surface. In such a case there exists a finite liquid-sputtering region ahead of the continuous liquid film [1]. Significant cooling is observed in the sputtering region which may be due to high turbulent nature of bubbles and also high boiling heat transfer coefficient.

Falling film rewetting for several vertical geometries such as plates [2–5], rods [4,6,7] and tube [8] has been modelled by a number of researchers. In general, in all the models, a moving rewetting front that divides the solid into two distinct regions is considered. Most of the models also consider a constant rewetting velocity that reduces the analysis to a quasi-static one. In majority of the models [2–4], conduction equation is solved considering a constant heat transfer coefficient in the wet region and an adiabatic condition is assumed downstream of the wet front. Several models have been proposed considering either an arbitrary heat flux distribution [9] or an exponentially decreasing heat flux [10] in the dry region ahead of the wet front and a constant heat transfer coefficient in the wet region for the analysis. Others [11,12] have considered rewetting as a conjugate heat transfer phenomena where the heat transfer coefficient, rewetting temperature and rewetting velocity is obtained as a part of the solution. Recently, a solution to the rewetting problem was obtained by Dorfman [13] considering a transient rewetting process.

A host of experiments have been carried out to study the phenomena of rewetting of hot surfaces. In most of the studies, the quenching is achieved by using spraying devices of various configuration to supply sub cooled water at the top of a hot object in the form of very small drops with uniform diameter [14,15]. In such a case, attempts have been made to study heat transfer mechanism between the hot surface and water droplets [16] and to study the Leidensfrost temperature [17,18]. Further, in an experimental investigation, Celata et al. [19] reported that rewetting velocity in film flow cooling is smaller than in spray cooling and Ohtake and Koizumi [20] reported the heat transfer mechanism in

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Nomenclature

a	radius of cylinder, m
$\bar{a}$, $\bar{b}$, Δ	parameters defined in text (Eq. (22))
Bi_C	Biot number with respect to convective region $h_C\delta/K$ and h_Ca/K in Cartesian rectangular and cylindrical case, respectively
Bi_B	Biot number with respect to sputtering region $h_B\delta/K$ and h_Ba/K in Cartesian rectangular and cylindrical case, respectively
C	specific heat J/kg-°C
HBIM	Heat Balance Integral Method
h_C, h_B	heat transfer coefficient in convective and boiling region, respectively, W/m^2-°C
F	defined in Eq.(20)
K	thermal conductivity, W/m-°C
L	non-dimensional distance defined in Eq. (3)
l	sputtering length, m
M	defined in Eq. (17)
M_C, M_B	effective Biot number in convective and boiling region, respectively
Pe	dimensionless wet front velocity $\rho Cua/K$
T	temperature, °C
T_b	incipient boiling temperature, °C
T_0	wet front temperature that corresponds to the temperature at minimum film boiling heat flux, °C
T_S	saturation temperature, °C
T_W	initial temperature of the dry surface, °C
t	time, s
u	wet front velocity, m/s
$\bar{x}$,$\bar{y}$, $\bar{r}$	length coordinates, m
x, y, r	dimensionless length coordinates

Greek symbols

α, β, γ	constants defined in text
λ	constants defined in Eq. (11)
$\psi_{1,2,3}$	constants defined in Eq. (11)
δ	wall thickness, m
θ	non-dimensional temperature defined in Eq. (3)
θ_1	non-dimensional temperature parameter defined in Eq. (3)
θ_2	non-dimensional temperature parameter defined in Eq. (3)
$\bar{\theta}$	non-dimensional temperature integral defined in Eq. (7)
θ_i	non-dimensional surface temperature
θ_0, ϕ_0	defined in Eq. (22)
ρ	density, kg/m^3

Subscripts

0	quench front
+	evaluated at an infinitesimal increment of distance
−	evaluated at an infinitesimal decrement of distance
f, v	liquid and dry region, respectively

transition boiling region using correlations and models. However, from the experimental investigation [1], it has been observed that a distinct sputtering region is observed near the wet front and is found to strongly influence the rewetting velocity. It is therefore necessary to incorporate the sputtering region in the wet region of hot surface to investigate its effect on the rewetting velocity.

Sun et al. [21] first considered a three-region model which divides the wet region into two distinct regions: one liquid region and another sputtering region assuming one-dimensional conduction in a rectangular slab. The two-dimensional analyses of rewetting considering a three-region model in an annular geometry have been suggested by Sawan et al. [22]. Several three-region models [23,24] based on Cartesian geometry have been developed to solve two-dimensional conduction equation of the hot object. In their analysis, Sawan et al. [22] considered the effect of decay heat generation, inlet sub-cooling and boiling heat transfer coefficient on the rewetting velocity. Previously other researchers [23,24] adopted separation of variable and series solution techniques to solve the two-dimensional conduction equations in their analysis.

HBIM is one of many semi-analytical methods used to solve conduction problems [25,26]. This is analogous to the classical integral technique used for fluid flow and convective heat transfer analysis [27,28]. This technique is simple, yet it gives reasonable accuracy. HBIM has mostly been employed for a variety of Stefan problems involving one-dimensional conduction. However, efforts have also been made to employ HBIM for two-dimensional problems [26]. Sfeir [29] and Burmeister [30] have successfully employed this technique for the analysis of two-dimensional fins. Rewetting of hot solid possesses some similarity with the classical Stefan problem. Both are moving boundary problems and in both the cases the solution space can be divided into two domains with a strong temperature gradient at the wet front.

However, so far only a few efforts have been made to employ HBIM for rewetting analysis [31]. Recently, Sahu et al. [32] presented a two-region rewetting analysis for various geometries and reported that the generalization of the predicted solution for different cases is possible by employing HBIM. Further, in their analysis they have defined a unique parameter known as effective Biot number for various geometries. Based on the effective Biot number the results of the theoretical model were compared with the measured data. In this study, the method reported previously by Sahu et al. [32] has been extended for a three-region model. Also the results obtained from the present HBIM analysis are compared with other analytical and experimental results already reported in the literature.

2. Theoretical analysis

2.1. Physical model

The physical model under consideration is a vertical rod/slab with coolant injected from the top. As the coolant progresses downward, vapour is generated near the coolant front both at liquid and vapour–liquid interface and a thin vapour film is formed which prevents the liquid from contacting the hot surface. As the process continues, the surface temperature cools off and the vapour blanket becomes unstable and collapses. This corresponds to transition boiling and is followed by a nucleate boiling regime. Beyond this brief boiling region, heat is removed by convection to a single-phase liquid.

It is evident from experiments [1], that quench front consists of a short but violent sputtering zone, where unstable boiling takes place (Fig. 1). In such a case, the droplets generated from the sputtering region causes precooling of the dry region ahead of the wet front known as precursory cooling (Fig. 1). In order to model the physical problem, one needs to know the variation of heat transfer along the hot object. In such a case, the distribution of heat transfer along the hot object becomes nonlinear and the profile varies arbitrarily along the axial direction as shown in Fig. 1c. The rate of heat removal is significant near the quench front location