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# Analysis of multi-region conduction-controlled rewetting of a hot surface with precursory cooling by variational integral method

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## HIGHLIGHTS

- The effect of sputtering region and precursory cooling on rewetting velocity is discussed.
- Closed form expression is presented for temperature distribution and wet front velocity.
- Sputtering region and precursory cooling strongly influence the wet front velocity.
- Neglecting the precursory cooling in the model may under predict the rewetting velocity.
- Variational method solution exhibit good agreement with test data and available results.

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## ABSTRACT

An analytical model has been proposed to evaluate rewetting velocity by employing variational integral method. The model considers 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. Two different models are considered in the sputtering region for the analysis. First model considers a constant heat transfer coefficient in the sputtering region; while the other one propose a variation in heat transfer coefficient in the sputtering region. Both the models consider a constant heat transfer coefficient in the wet region and exponentially varying heat transfer coefficient in the dry region ahead of wet front. For all the cases the closed form expression is obtained for temperature field along axial direction. Relationship between various rewetting parameters such as; Peclet number, Biot number, dry wall temperature, incipient boiling temperature, sputtering length, magnitude of precursory cooling and the extent of precursory cooling has been obtained from the analysis. Present prediction obtained by employing variational integral method exhibits an excellent agreement with the previous analytical results [1–4] and test data [5,6,23].



## 1. Introduction

When liquid is brought in contact with a sufficiently hot surface, a vapor blanket is formed on the solid surface that prevents the solid–liquid contact. As the surface cools off, the vapor film collapses and the liquid film re-establishes contact with the hot surface. Rewetting of hot surfaces is common in many industrial applications such as: metallurgical treatments, cooling of overheated nuclear fuel rod during postulated loss of coolant accidents (LOCA), cryogenic processes, space craft thermal control and most recently cooling systems of electronic circuits.

Numerous studies have been carried out in past to analyze the rewetting behavior of hot surfaces both through experimental investigation [5–7] and theoretical analysis [5,8–13]. It was observed that during rewetting of hot slab at lower coolant flow rates, the variation of temperature in the transverse direction is less compared to the longitudinal direction. Therefore, initial efforts were made to analyze rewetting problems based on one-dimensional approximation [4,5]. These models were successful in correlating the test data at lower flow rates. It is observed that the temperature gradient in the transverse direction is significant at higher coolant flow rates. In a view of this several two-dimensional models were proposed [8,9,12] that correlates the test data at higher flow rates. It is observed that most of the rewetting models consider the heat transfer coefficient and rewetting temperature as an input parameter to solve the conduction equation. The solution to the above problem was obtained by Olek et al. [14] by considering

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rewetting as conjugate heat transfer problem. In their analysis, the heat transfer coefficient was not specified but was obtained as a part of the solution. The solution to a transient heat conduction problem was obtained by Dorfman [15]. The author reported that the transient cooling process is governed by a dimensionless parameter termed as Leidenfrost number, expressed as the ratio of Biot number to the square of the Peclet number. Starodubtseva et al. [16] proposed a model to study the process of rewetting of overheated surface during falling film of cryogenic liquid. Davidy et al. [17] presented solution to the rewetting problem by considering an arbitrary variation in heat flux in the dry region ahead of the wet front. The authors claimed that their model can be used for the prediction of re-flooding for a wide range of operating parameters. Recently, a review on several analytical and semi-analytical models of conduction controlled rewetting has been presented by Sahu et al. [18]. The authors [18] discussed various conduction-controlled rewetting models and summarized the closed form expressions for various rewetting parameters.

A wide variety of experiments have been performed to analyze the phenomenon of rewetting [3,5–8]. Rewetting experiments demonstrate that inverse of rewetting rate increases with initial wall temperature and decreases with the coolant flow rate [5,6,8]. During experimental investigation the authors have considered various test geometry [5,19–21], different methods of venting the generated steam [22] and several modes of coolant injection system [3,23]. Tests have been carried out either for a single rod [23] or with rod bundle [24] with varied range of coolant flow rate and dry wall temperature.

During experiments [25], it is observed that at higher coolant flow rates a part of the coolant sputters away from the wet front and cools the surrounding vapor. Subsequently, droplet vapor reduces the dry wall temperature ahead of the wet front. This phenomenon is termed as precursory cooling. In order to incorporate the precursory cooling in the rewetting model usually a constant heat transfer coefficient [26,27], variation of heat transfer coefficient [28,29] or variation of heat flux [30–32] ahead of the wet front was considered.

From the experimental studies of Shires et al. [25], it is observed that the rate of heat removal is very high in a narrow region just behind the wet front. The region is called sputtering region and is strongly influence the wet front velocity. Therefore, adopting a constant heat transfer coefficient in the wet region may not be appropriate for the rewetting analysis. Several one-and two- dimensional, three-region rewetting models are reported that considers three different regions, namely, a wet region in the upstream direction of wet front, a sputtering region behind the wet front and a dry region in the downstream direction ahead of wet front [2,4,33,34]. Sun et al. [4] first considered a three region, one dimensional rewetting model to analyze falling film rewetting of hot surface. The two-dimensional analyses of rewetting considering a three region model in an annular geometry have been suggested by Sawan et al. [33]. Bera and Chakrabarti [35] proposed a three-region rewetting model for the cooling of a cylindrical rod by employing the Wiener-Hopf technique. Sahu et al. [1] reported the solution to the above problem valid for both Cartesian and cylindrical geometry by employing HBIM. During their investigation it is observed that the wet front velocity strongly depends on the boiling Biot number than the convective Biot number. It was reported that neglecting the boiling Biot number in the sputtering region may under predict the rewetting velocity. Recently, Sibamoto et al. [36] proposed a two-dimensional rewetting model to quantify the effect of precursory cooling and internal heat generation on the rewetting velocity and revealed the effect of wall depth conduction during prediction of rewetting velocity. The authors [37] proposed a one-dimensional rewetting model with Precursory cooling by modifying the model presented by Sun et al. [29]. The proposed model was correlated with their test data considering proper assumptions.

In actual situation, the distribution of heat transfer coefficient near the sputtering region and the dry region ahead of the wet front varies along the axial direction [38]. It is argued that accurate choice of shape of the heat transfer coefficient is important to precisely predict the wet front velocity and surface temperature distribution. It is observed that most of the three region rewetting model considers a constant heat transfer coefficient in the both liquid and sputtering region. Only a single investigation reported the one-dimensional rewetting model with large variations in the heat transfer coefficients near the wet front [39]. The authors [39] solved the one-dimensional heat-conduction equation by dividing the quenching zone into small segments of arbitrary temperature increment and heat transfer coefficient. A trial and error method is proposed to predict the wet front velocity, sputtering length and temperature profile along the hot surface.

Recently, Agrawal and Sahu [13,40] and Agrawal et al. [41] solved a one-dimensional rewetting model with constant heat transfer coefficient in the wet region and an adiabatic condition in the dry region by employing Variational Integral Method (VIM). The results obtained by employing VIM exhibited good agreement with available analytical results and published test data for varied range of test parameters. In this study an attempt has been made to extend the previous work [13,40,41] to analyze the multi-region rewetting model with varying heat transfer coefficient in the sputtering and dry region ahead of the wet front. Two different rewetting models are considered for the analysis. In the first model, a constant heat transfer coefficient is considered in the sputtering region and in second model, an axially varying heat transfer coefficient in the sputtering region is considered. Both the models consider an exponentially decaying heat transfer coefficient in the dry region ahead of wet front. The present prediction is found to be in good agreement with the reported analytical results and published test data covering a wide range of coolant flow rate, dry wall temperature and test geometry.

## 2. Theoretical analysis

### 2.1. Physical model

Fig. 1a schematically depicts the falling film rewetting of a one-dimensional slab of infinite length. When liquid is injected from the top, the liquid cools the hot surface in the form of falling film. As the coolant moves in the downward direction a thin vapor film is formed at the solid–liquid interface and prevents the contact of coolant on the hot surface. As the process continues, the temperature of the hot wall cools from initial temperature ($T_w$) to the wet front temperature ($T_0$) and the vapor blanket becomes unstable and collapses (Fig. 1b). The region behind the wet front corresponds to transition boiling regime and followed by a nucleate boiling regime. Beyond this, the surface temperature drops below the temperature of incipient boiling and the heat is removed by convection to the single-phase fluid. In addition to this, the dry wall ahead of the wet front is cooled due to precursory cooling. In such a case the distribution of heat transfer along the hot object becomes non-linear and the heat transfer profile varies arbitrarily along the axial direction. Fig. 1c depicts the actual variation of heat transfer coefficient along axial direction. It is shown that the magnitude of heat transfer coefficient near the wet front location is very high and it gradually decreases in the downstream direction. In order to analyze the rewetting phenomena one can assume a constant heat