

## ANALYTICAL AND SEMI-ANALYTICAL MODELS OF CONDUCTION CONTROLLED REWETTING A State-of-the-Art Review

by

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Review paper

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*The phenomenon of rewetting finds application in several fields of industrial and scientific applications including the loss of coolant accidents in nuclear reactors. In order to analyze the phenomena of rewetting, usually a conduction controlled approach or hydrodynamic approach was considered. Because of complexity, most of the studies adopt a conduction controlled approach to analyze the phenomena of rewetting. In view of this, various analytical and semi-analytical techniques have been used to solve the conduction equation. Investigations have mostly considered different geometries, various convective boundary conditions for both the dry and wet surface, effect of heat generation, variable properties, coupling between conduction and convection as well as other variations of the problem. A comprehensive review of the available analytical models is presented in this paper.*

**Key words:** *loss of coolant accidents, conduction-controlled, rewetting, quenching, flooding*

### Introduction

Rapid cooling of a sufficiently hot object is known as quenching. For long, it is a common practice to quench a hot object by immersing it in a bath of cooler liquid. Often it is observed that initially the liquid cannot wet a very hot surface. A vapour blanket formed on the solid surface prevents the contact between the solid and the liquid phase. As a result, the rate of heat dissipation is considerably low due to the poor conduction through the vapour layer. However, as the process continues, the surface cools off and the vapour blanket collapses, liquid wets the hot surface and heat transfer increases drastically. This transition is known as rewetting. It literally means the re-establishment of the solid-liquid contact. Rewetting is considered as the most important phenomenon during the process of quenching. A significant volume of work has been undertaken in the last four decades in order to understand the various phenomena associated with quenching and rewetting. Most of these studies focus on two different aspects, namely, investigation of thermo-hydraulic phenomena and improvement of physical properties of metals. The thermo-hydraulic phenomena refer to the interaction between hot wall and fluid flow for various operating conditions. These phenomena

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have been observed in many industrial and scientific applications such as metallurgical processing, refueling of space transfer vehicles with liquid hydrogen or oxygen propellant, superconducting magnets, and loss of coolant accident in nuclear reactors. It is conceived that a better understanding of the above phenomena may lead to an accurate design of cooling system in nuclear reactors. A wide variety of studies including both analytical and experimental investigations have been carried out to understand the phenomena of rewetting. However, the focus of the present study includes the summary of various analytical models and the applicability and strength of these analytical tools to solve the rewetting problems. Before we delve deep into the rewetting models, it is appropriate to describe briefly the phenomena of rewetting as is presented.

### Rewetting phenomenon

The phenomenon of rewetting mainly depends on the mode of interaction of coolant with the hot surface. Earlier, Groeneveld and Snoek [1] reported six different types of fluid wall configurations to describe the occurrence of rewetting. These are described as collapse of vapour film, top flooding, bottom flooding, rewetting following dispersed droplet cooling, rewetting of a horizontal surface by Leidenfrost cooling, and collapse of vapour film on a horizontal surface during pool boiling. During an emergency core cooling of a nuclear reactor, the hot core essentially undergoes a rewetting phase to remove heat from the fuel pin surface. In such a case, rewetting occurs due to one of the above fluid wall configurations [1]. At the same time, depending on the design of the reactor, several modes of coolant injection procedures are adopted for the rewetting of fuel pins inside a reactor core. These include, top flooding, bottom flooding, and horizontal flow of coolant in the hot core. Further details on these phenomena are presented.

*Top flooding.* Figure 1(a) depicts a schematic of the physical process during top flooding. Liquid is sprayed through nozzles at the top of the hot object. When liquid comes in contact with the hot surface, a violent sputtering occurs and a distinct quench front is formed. At this stage the liquid contact is maintained through an axially propagating liquid-film followed by a distinct quench front. It is observed from experiments [2] that the quench front travels with constant velocity known as rewetting velocity. This divides the hot object into two distinct regions namely one wet region where heat transfer to the liquid film takes place due to convection and another dry region ahead of the wet front. Apart from this, due to strong axial conduction a sharp temperature gradient is observed at the wet front. The process

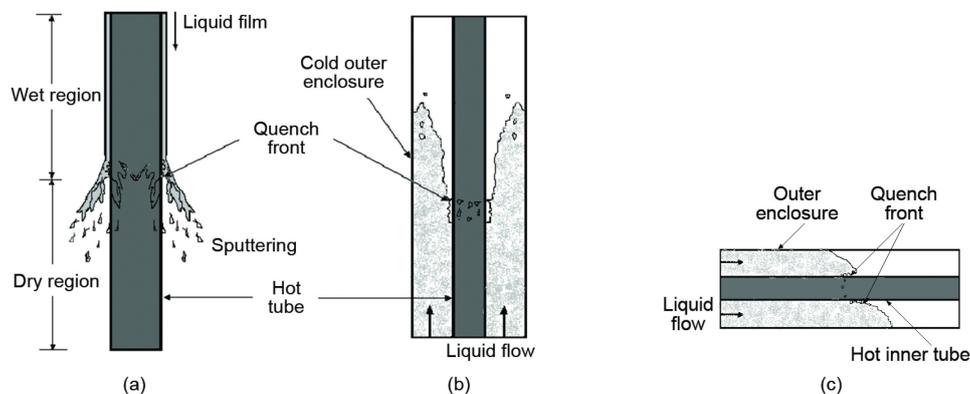


Figure 1. (a) top flooding, (b) bottom flooding, and (c) horizontal flow

of rewetting by this mode is mainly governed by axial conduction and is termed as conduction controlled rewetting. During top flooding of the vertical hot object, different boiling regimes are observed along the axial direction of the hot object.

*Bottom flooding.* Figure 1(b) schematically depicts the cooling of a hot surface through bottom flooding. Liquid is fed from the bottom of an annulus and an upward liquid front quenches the inner rod of the hot object inside the annulus. Apart from axial conduction, complex hydrodynamics and the geometry of the flow channel affects the process.

*Horizontal flow.* In certain geometries, the liquid is fed in a horizontal direction inside an annulus and cools the hot object as shown in fig. 1(c). The important characteristic of re-flooding of a horizontal system in comparison to vertical channels is the stratified nature of the refilling fluid. Because of transverse gravitational effects, the flow becomes stratified; thus the channel will be quenched in sequence: bottom, mid side, and top at a given location.

### Heat transfer regimes

The various modes of heat transfer, that occur during rewetting of hot surfaces (axially propagating liquid film, moving liquid front), can be described by two approaches. In the first approach, one can consider the chronological occurrence of the heat transfer modes at a given location. In the second approach, the transition in different boiling modes at a given time can be described in the axial direction. However, one can consider either one of these approaches for the analysis. The variation of surface temperature with respect to axial locations (at a fixed time) for an axially propagating liquid film is presented below.

Figure 2 depicts the typical variation of surface temperature with respect to axial locations (at fixed time) during the rewetting of hot vertical rod with coolant injected from the top. As the coolant is sprayed through nozzles at the top of the hot object, coolant progresses downward and a uniform film surrounds the hot object; cooling takes place by forced convection to the single phase liquid and is referred as the wet region AB. The wall temperature is below the saturation temperature of coolant and the rate of heat removal is considerably lower in this region. This region is identified as forced convective cooling region. No distortion of liquid film is observed in this region. Further downstream, at point B, the initial nucleus formation takes place and the corresponding value of temperature is the incipient boiling temperature,  $T_b$ . Additional nucleus formation takes place at the solid surface BC and the heat transfer from the solid to coolant increases; this is termed as nucleate boiling. Even further downstream, the nucleate boiling mode ( $T_q$ ) changes to film boiling through a violent sputtering zone or unstable transition boiling zone CD. Point D is considered to be the point of quenching and the temperature is denoted as the quench temperature ( $T_q$ ). Both nucleate and transi-

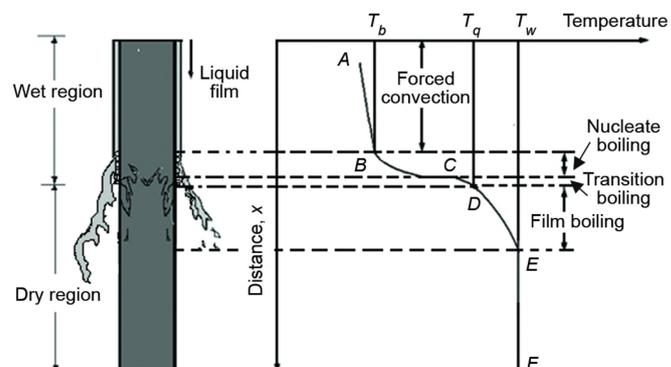


Figure 2. Variation of surface temperature with axial location at any given time

tion boiling plays a crucial role for the higher heat removal rate. Ahead of the transition boiling zone, the formation and collapse of vapour film is observed. This is termed as the film boiling region. In such a situation, the test section is cooled mainly due to film boiling. The heat transfer from the wall to the liquid takes place by convection through a vapour blanket. Next, a complete dry region is observed. This region is cooled by sputtered droplets obtained during shearing of water film and the surrounding water droplet mixtures.

### **Analytical models**

A variety of studies involving theoretical investigations have been undertaken to understand the complex phenomena of rewetting. In general, most of the rewetting models solve the Fourier conduction equation for a given set of heat transfer coefficient and rewetting temperature to obtain the temperature distribution in the hot surface. Subsequently, with the application of temperature continuity and energy conservation at the rewetting front, the velocity of wet front is evaluated. Most of the models are either 1-D or 2-D. Initially, the basic model of rewetting that considers two-regions (wet region and dry region) were considered. Later on, in order to improve the capability of predicting the physical phenomena, a number of refinements have been made over the basic model. In general, the rewetting models consider either an analytical method or numerical ones to solve the conduction equation. These include analytical techniques such as separation of variables method, Winer-Hopf technique, and heat balance integral method (HBIM), and numerical techniques such as finite difference technique, finite element method, and implicit isotherm migration technique. Some review of the early work on rewetting is available [3-9]. A recent review [10] presents various analytical and numerical solutions of the rewetting phenomena. However, the closed form expressions between various pertinent parameters from different rewetting models have not been reported since long in the literature. The aim of this study is to make an updated summary of the closed form expressions of various rewetting models as applicable to water cooled reactors following a loss of coolant accident.

### **Basic rewetting model**

The basic rewetting models consider two different regions (wet and dry) for a hot object (slab or rod) of infinite length with a quasi-steady approximation. The schematic of a 2-D object and the variation of temperature and heat transfer coefficient along the axial direction is shown in figs. 3(a-c). In these models a constant heat transfer coefficient is assumed in the wet region and an adiabatic condition is assumed in the dry region ahead of the wet front in order to solve 1-D/2-D conduction equation. While the water is sprayed to the hot surface the surface temperature of the hot object behind the wet front approaches the liquid saturation temperature  $T_s$ . In general most of the rewetting models assume suitable values of rewetting temperature and heat transfer coefficient in order to solve the conduction equation.

Initially, efforts were made to analyze rewetting problems based on 1-D approximation. In these models a constant heat transfer coefficient was assumed in the wet region and an adiabatic condition in dry region in order to analyze the rewetting process [11-15]. It was observed that during rewetting of a thin slab at lower rewetting rates, the variation of temperature in the transverse direction is less significant and the problem can be considered as 1-D. These models are reasonably successful in case of low Biot numbers ( $Bi$ ) and rewetting rates [12, 13]. However, at higher rewetting rates the temperature gradient in transverse direction cannot be neglected. Tien and Yao [16] proposed a model that demonstrates the transition between 1-D and 2-D formulations and establishes the limitation of 1-D model for high values

of Peclet number and Biot number. Therefore, several 2-D conduction models were proposed for analyzing the rewetting phenomena at higher Biot number and higher rewetting rates. The basic rewetting models [17, 18] usually consider two different regions (wet and dry) for a hot object (slab or rod) of infinite length with a quasi-steady approximation.

Because of mathematical difficulty, most 2-D analyses are either approximate or numerical ones. The solution to rewetting problem for the Cartesian geometry was first considered by Duffey and Porthouse [13] employing a separation of variables method. The model was extended to a cylindrical geometry to obtain the solution as well. They retained only the first term in the series solution and reported an approximate solution for the 2-D slab. However, Coney [17] reported that using a small number of terms in a series yields inaccurate results due to slow convergence of the series. While an exact solution to the same problem was presented by Castiglia *et al.* [19], employing the method of separation of variables. The solution to the above problem for a cylindrical rod was presented by Blair [20] and Yeh [21] employing separation of variables method.

Further, attempts were made to employ the Wiener-Hopf technique to obtain the solution of the above problems. Tien and Yao [16] first applied the Wiener-Hopf technique to a 2-D rewetting problem of a rectangular slab. However, they could not be successful in decomposing the kernel function associated with the Wiener-Hopf equation and presented the solution for very small and large Peclet numbers. Based on this, an approximate semi-empirical relation for the whole range of Peclet numbers was developed. The quench front temperature was expressed in terms of an infinite product series. Later, the successful application of Wiener-Hopf technique to the same problem was reported by Caflish and Keller [22]. They reported an explicit formula for the quench front temperature in terms of an infinite product series where the solution is valid for all Biot and Peclet numbers. Levine [23] reported an expression for the quench front temperature involving a single integral employing the Wiener-Hopf technique to the above problem. A solution to the above problem was reported by Olek [18] employing both Wiener-Hopf technique and the method of separation of variables. The quench front temperature was expressed in a simplified form and the predicted results were found to be more accurate compared to that obtained by separation of variables, especially for higher Biot numbers. Further, the solution to the cooling of an infinite slab in a two-fluid medium was provided by Bera and Chakrabarti [24] employing the Wiener-Hopf technique. The analysis of rewetting for a composite solid was reported by employing Wiener-Hopf technique [25, 26]. The model considers the fuel rod surrounded by a cladding and separated by a thermal resistance in between them. Recently, the rewetting model proposed by Sahu *et al.* [27] employs HBIM in order to solve the conduction equation. The authors have identified a unique function solely dependent on Biot number termed as effective Biot number, ( $M$ ) from the analysis. It was shown that the parameter  $M$  eliminates the need for the development of different models for different geometry, unifies 1-D and 2-D analysis and also shows a direction for comparing the experimental data with the analytical results. In addition, a correlation between  $M$  and coolant flow  $M = 3.45 \times \text{flow rate}$  is suggested [28].

Efforts were also made to obtain the solution of the above problem by employing numerical methods. In such a case, the main difficulty arises in solving the governing differential equation in a moving co-ordinate system. In view of this, either an adaptive fixed mesh [29, 30] or a moving mesh [31, 32] was adopted to solve the conduction equation. In a fixed-mesh approach, the problem can be formulated in a fixed region without altering the numerical scheme to obtain the solution. On the contrary, in the moving mesh approach, the propagation of quench front and the temperature field is determined at each time step during the com-

putation. In order to solve the problem, several numerical methods have been adopted. Thompson [33] presented a numerical solution to the rewetting problem considering 1-D approximation. Further, Elias and Yadigaroglu [34] reported a solution to the above problem by considering a large variation of heat transfer coefficient near the quench front. They adopted a trial and error method to estimate rewetting velocity, length of the quenching zone, and temperature distribution as well. Based on the numerical analysis of the above problem, Anderson and Hansen [35] suggested an empirical relationship between two dimensionless parameters, namely, modified Biot number and modified Peclet number. The solution to a 2-D rewetting problem was presented for a tube [36] and for a tube with filler material [37]. Gurcak *et al.* [38] obtained a numerical solution for the above problem for a cylindrical rod by employing isotherm migration technique. Yu *et al.* [39] reported the numerical solution in order to calculate the best fit values of heat transfer coefficient and quench front temperature from the test data. The effect of coolant flow rate and inlet sub-cooling on the rewetting velocity were reported for a wide range of test conditions. It is evident from the literature that most of the rewetting model reports the closed form expressions between Biot number, non-dimensional rewetting velocity and dry wall temperature. The available expressions are summarized in tab. 1. In order to avoid duplication of earlier reviews, only the models that predict various rewetting parameters as closed form expressions have been presented (tabs. 1-5).

### ***Refinement over basic rewetting model***

The basic conduction controlled rewetting models are successful in correlating the test data for moderate flow rates. However, in order to improve the capability of predicting the physical phenomena, a number of refinements have been made over the basic model. This have been achieved in various ways, namely, incorporating the variation in heat transfer by exponential functions, multiple step functions, property variation, effect of decay heat and coupling effect of coolant flow in the basic rewetting model.

### ***Rewetting model with precursory cooling***

Although, the basic rewetting model successfully correlates the test data at moderate flow rates, it could not accurately predict the rewetting phenomena at higher flow rates. At higher flow rates, a part of the coolant sputters away from the wet front and cools the dry region ahead of the quench front. This mode of cooling, termed as precursory cooling, has been found to strongly influence rewetting velocity [40]. Therefore, efforts were made to incorporate precursory cooling in the model while correlating with the test data at higher flow rates. In such a case, the analysis does not make a simplifying assumption such as adiabatic condition in the dry region ahead of wet front.

In order to model the precursory cooling, usually a constant heat transfer coefficient [41, 42], variation of heat transfer coefficient [43, 44] or variation of heat flux [45-47] ahead of the wet front was considered. When a constant heat transfer coefficient was considered in the dry region ahead of the wet front, it was shown that the highest heat flux from the wall occurs at the farthest location in the downstream direction of the quench front; this is physically unrealistic. Very often, an axial variation of heat transfer coefficient in the downstream direction ahead of the wet front is considered to account for the precursory cooling [43, 44]. The drawback of this model is that it requires the knowledge of the variation of temperature of the droplet-vapour mixture  $T_d$  with distance to determine the heat flux in the dry region ahead of the quench front. In view of this, an exponentially varying heat flux model was generally adopted in most of the models [45-47] to analyze the phenomena of the rewetting. The

**Table 1. Comparison of rewetting models that considers two-regions**

Source	Results
Semeria and Martinet [11] (1-D)	$\frac{\sqrt{\text{Bi}}}{\text{Pe}} = \theta_1$
Yamanouchi [12] (1-D)	$\frac{\sqrt{\text{Bi}}}{\text{Pe}} = \sqrt{\theta_1(\theta_1 + 1)}$
Duffey and Porthouse [13] (1-D)	$\frac{\sqrt{\text{Bi}}}{\text{Pe}} = \sqrt{\theta_1(\theta_1 + 1)}$
Duffey and Porthouse [13] (2-D slab)	$\frac{\sqrt{\text{Bi}}}{\text{Pe}} = \frac{\pi}{2} (\theta_1 + 1)$ with $\text{Bi} < \frac{\pi^2}{4} (\theta_1 + 1)$ for large $\text{Pe}$
Coney [17] (2-D slab)	$\frac{\text{Bi}}{\text{Pe}} = 1.6 \theta_1(1 + \theta_1)$ with $\frac{\text{Bi}}{\text{Pe}} < 1$
Andersen and Hansen [35] (2-D slab)	$Pe^* = \begin{cases} (\text{Bi}^*)^{0.5} & \text{small Bi}^* \\ 0.7355\text{Bi}^* & \text{large Bi}^* \end{cases}, \begin{matrix} Pe^* = \text{Pe}[\theta_1(1 + \theta_1)]^{1-\sqrt{\pi/2}} \\ \text{Bi}^* = \text{Bi}[\theta_1(1 + \theta_1)]^{-\sqrt{\pi/2}} \end{matrix}$
Tien and Yao [16] (2-D slab)	$\frac{\sqrt{A}}{\text{Pe}} = \sqrt{\theta_1(\theta_1 + 1)}$ small $\text{Pe}$ $\frac{\text{Bi}}{\text{Pe}} = 1.707\theta_1 + 1.456\theta_1$ large $\text{Pe}$ where $A = \frac{3\text{Bi}}{1 + 3\text{Bi}}$ $\frac{\text{Bi}}{\text{Pe}^2} = \frac{\theta_1(1 + \theta_1)^3(\bar{E}\bar{F})}{3\bar{E} + \text{Pe}(1 + \theta_1^2)\bar{F}}$ for all $\text{Pe}$ where $\bar{E} = 1.707 - 0.25 \left( \frac{\theta_1}{1 + \theta_1} \right)$ , $\bar{F} = \text{Pe}^2 \left( \frac{\theta_1}{1 + \theta_1} \right)$
Blair [20] (2-D cylinder)	$\frac{\text{Bi}}{\text{Pe}} = \frac{\pi}{2} \theta_1$
Yeh[21] (2-D cylinder)	$\frac{2\text{Bi}_1}{\text{Pe}^2} = \theta_1(1 + \theta_1)$
Dua and Tien [78]	$Pe^* = \begin{cases} (\bar{\text{Bi}}^*)^{0.5} & \text{for } (\bar{\text{Bi}}^* < 0.3) \\ 0.63\bar{\text{Bi}}^* & \text{for } (\bar{\text{Bi}}^* > 20.0) \\ [\bar{\text{Bi}}^*(1 + 0.40\bar{\text{Bi}}^*)^{0.5}] & \text{for all } \bar{\text{Bi}}^* \end{cases} \quad \bar{\text{Bi}}^* = \frac{\text{Bi}}{\theta_1(1 + \theta_1)}$
Sahu <i>et al.</i> [27] (1-D; 2-D, slab and cylinder)	$\frac{\sqrt{M}}{\text{Pe}} = \sqrt{\theta_1(1 + \theta_1)}$ The value of M depends on the model and expressed elsewhere [27] $x = \frac{\bar{x}}{\delta}$ , $\text{Pe} = \frac{\rho C_p \mu \delta}{K}$ , $\text{Bi} = \frac{h\delta}{K}$ , $\theta = \frac{T - T_S}{T_0 - T_S}$ , $\theta_1 = \frac{T_W - T_0}{T_0 - T_S}$

schematic of a 2-D object and the variation of heat transfer coefficient along the axial direction is shown in figs. 3(a, d). Thus an exponentially varying heat flux of the form  $q'' = (Q_0/N) \exp(-d\bar{x})$  is adopted in the dry region ahead of the wet front, where  $N$  is the magnitude of precursory cooling,  $d$  – the exponent in the decay of precursory cooling,  $Q_0$  – the heat flux associated at the wet front, and  $q''$  – the heat flux from the surface.

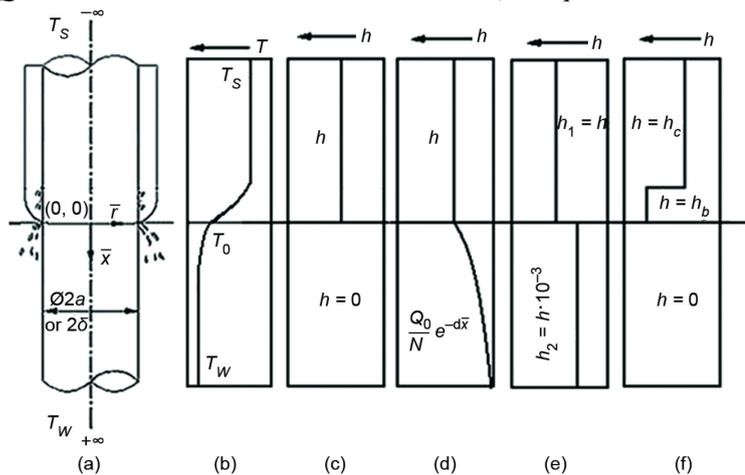


Figure 3. Schematic view of top flooding of a 2-D object

Edwards and Mather [48] provided the first solution to the 2-D rewetting model with precursory cooling. They considered an exponentially decaying heat flux in both upstream and downstream directions of the quench front. Dua and Tien [45] obtained the solution to the same problem considering an exponentially decaying heat flux in the dry region while a constant heat transfer coefficient was assumed in the wet region. Sawan and Temraz [49] suggested the solution to the above problem by considering both precursory cooling and heat generation. Olek [46, 47] provided solution to the above problem for a slab by employing separation of variables method and Wiener-Hopf technique, respectively. Further, the solution to the above problem for a solid cylinder was considered by Olek [50] using Wiener-Hopf technique. Various models [46, 47] have been proposed that employ either separation of variables method or Wiener-Hopf technique to solve the conduction equation with precursory cooling. In most of the models, the governing conduction equation is solved either considering a Cartesian geometry or cylindrical geometry. However, a few models report a unified approach for slab and cylindrical geometry. Recently, Sahu *et al.* [51] presented a two region rewetting analysis considering the precursory cooling for various geometries employing the HBIM. They correlated the experimental data set with a five-parameter relationship obtained from their analysis. It is observed that most of these rewetting models report a five-parametric relationship among various modeling parameters, namely, Biot number, wet front velocity  $Pe$ , dry wall temperature  $\theta_1$ , region of influence for precursory cooling  $a$ , and the magnitude of precursory cooling  $N$ . The available closed form expressions are summarized in tab. 2. In general, for a fixed value of several modeling parameters, an adjustable value of  $N$  is used to correlate with the test data. Based on the experimental data, a correlation has been developed between the flow rate per unit perimeter  $\Psi$  and magnitude of precursory cooling,  $N$ . The available closed form expressions have been summarized in tab. 2.

#### Rewetting model with heat generation

In case of a realistic situation, the temperature of the fuel rods increases due to the decay heat generated by fission. This implies that an internal heat source exists inside the fuel

**Table 2. Comparison of various models with precursory cooling**

Source	Mathematical expressions for rewetting velocity	$N$ as a function of flow rate
Sun <i>et al.</i> [43] (1-D)	$Pe = f(\text{Bi}, N, a, \theta_1)$ ; the solution involves Bessel functions	$N = \frac{800}{\Psi^{1.4}}$
Dua and Tien [45] (2-D slab)	$Pe \equiv P - \frac{A}{P}$ , $P \equiv \frac{1}{2} \left[ \frac{\text{Bi}}{Na\theta_1} + \sqrt{\left( \frac{\text{Bi}}{Na\theta_1} \right)^2 + \frac{4\text{Bi}(1+\theta_1)}{\theta_1}} \right]$	$N = \frac{160}{\Psi} + 1$
Sahu <i>et al.</i> [51] (2-D slab, cylinder)	$\theta_1 = \frac{\left\{ [(Pe^2 + 4M)^{1/2} - Pe] + \frac{Z_2 \text{Bi}}{Na} - \frac{2\text{Bi}a}{3N} + \frac{2\text{Bi}Pe}{3N} \right\}}{2Pe}$ $Z_2 = \begin{cases} 2 & \text{for a Cartesian geometry} \\ 4 & \text{for a cylindrical geometry} \end{cases}$	$N = \frac{24.01}{\Psi^{0.701}}$

rod. Because of the internal heat source, transient conduction may take place across the fuel rod and this affects the rewetting velocity. In this context, the basic model is inadequate to describe the physical phenomena. Depending on the coolant flow rate and internal heat source, the wet front may either propagate in downward direction or cease (dryout condition) at some location. Thus a critical internal heat generation is defined as the minimum heat generation rate at which the wet front ceases (dryout condition) at some location. The schematic of a 2-D object and the variation of heat transfer coefficient along the axial direction is shown in figs. 3(a, e). The rewetting velocity obtained by these models depends on the surface temperature and heat removal rate from the surface. In view of this, it becomes essential to include the heat source parameter in the basic rewetting model. To simulate the decay heating of fissile material, either a constant heat flux or a uniform heat generation in the fuel pin is considered. In addition, for both wet and dry region, a constant but different heat transfer coefficient,  $h$ , is assumed. The important studies that consider the decay heat in the model are elaborated.

The analysis of rewetting of hot surface with a specified heat flux [52] and with heat generation, that induce dry out, is of specific interest while considering the decay heating of a fuel element [53-55]. The transient 1-D rewetting equation with boundary heat flux was solved numerically as well as analytically by Chan and Zang [56]. They presented a closed form solution for both temperature field and rewetting velocity for both smooth and grooved plates. It was shown that solution for the smooth plate can be extended to the grooved plates as well. They reported the dominance of transient terms, contrary to commonly used [57, 58] quasi-steady state conditions. The transient analysis of rewetting of an infinitely long plate with uniform heating was reported by Platt [59]. The authors presented a closed form solution for the rewetting velocity by applying some simplifying assumptions in the heat conduction equation. The analyses of rewetting with boundary heat flux were reported for smooth plates [53, 54] and also for smooth and grooved plates [60]. The solution to the rewetting problem for the surface tension induced rewetting phenomena with an applied heat flux for both flat and grooved plates have been reported by Stores *et al.* [61].

The solution to a rewetting model for an infinite slab and tube subjected to boundary heat flux was obtained by Satapathy and Sahoo [62, 63]. The solution to the same problem for a slab was obtained by Satapathy and Kar [64] by employing finite difference method. Recently, the solution to the above problem was reported by Sahu *et al.* [65], which consider both boundary heat fluxes as well as heat generation applicable for various geometries by employing HBIM.

This yields a closed form solution for the temperature field and rewetting velocity valid for both boundary heat flux as well as heat generation as applied to different geometry of the problem. Further, it was shown that a generalization of the analysis is possible through HBIM. It is observed that the rewetting velocity is found to depend on various modeling parameters such as: wet region and dry region Biot numbers, internal heat source parameter, drywall temperature, and thickness of the fuel pin. In addition, the critical heat source parameter has been obtained as a function of various system variables, namely, wet region and dry region Biot numbers, dry wall temperature and the thickness of the fuel pin. The available closed form expressions for rewetting velocity and critical internal heat source parameter are summarized in tab. 3

**Table 3. Comparison of various rewetting models with heat generation**

Source	Results
Satapathy and Sahoo [62] (2-D slab)	Quench front temperature: $\theta_0 = \frac{Q(\lambda_2 Bi_1 + Bi_2)}{Bi_1 Bi_2 (1 + \lambda_2)} + \frac{\lambda_2}{1 + \lambda_2}$
Sahu <i>et al.</i> [65] (1-D)	$\left(1 - \frac{Q}{Bi_1}\right) \frac{Pe}{2} \left[ \left(1 + \frac{4Bi_1}{Pe^2}\right)^{0.5} - 1 \right] = \left(\theta_1 + \frac{Q}{Bi_2}\right) \frac{Pe}{2} \left[ \left(1 + \frac{4Bi_2}{Pe^2}\right)^{0.5} + 1 \right]$
Sahu <i>et al.</i> [65] (2-D slab, cylinder)	$\left(1 - \frac{\psi Q}{Bi_1}\right) \xi_2 = \left(\theta_1 + \frac{\psi Q}{Bi_2}\right) \xi_1$ <p>where <math>\psi \equiv (\varepsilon^n)^{1-m} \left[ \left(\frac{1-\varepsilon^2}{2}\right)^n \right]^m</math>, <math>\xi_1 \equiv \left(1 + \frac{4(Ms_2)^{1-n}(Mt_2)^n}{Pe^2}\right)^{0.5} + 1</math></p> $\xi_2 \equiv \left[1 + \frac{4(Ms_1)^{1-n}(Mt_1)^n}{Pe^2}\right]^{0.5} - 1, \quad Q = \frac{\bar{q}^m q^{1-m} R_2^{m+1}}{K(T_o - T_s)}$ $Mt_i = \frac{2Bi_i}{1 - \varepsilon^2 + Bi_i \left[ 2 - (1 - \varepsilon^2) + 2(1 - \varepsilon) - \frac{2}{1 + \varepsilon} - \frac{2(1 + \varepsilon + \varepsilon^2)}{3(1 + \varepsilon)} \right]}$ $Ms_i = \frac{Bi_i}{1 + Bi_i/3}, \quad j_1 = \sqrt{\frac{Ms_2}{Ms_1}}, \quad j_2 = \sqrt{\frac{Mt_2}{Mt_1}}, \quad \lambda_2 = \sqrt{\frac{Bi_2}{Bi_1}}, \quad i = 1, 2$ $n = \begin{cases} 0 & \text{for a Cartesian geometry} \\ 1 & \text{for a cylindrical geometry} \end{cases} \quad m = \begin{cases} 0 & \text{boundary heat flux} \\ 1 & \text{uniform heat generation} \end{cases}$

#### Rewetting model with multi region analysis

The basic rewetting model assumes a constant heat transfer coefficient in the wet region and adiabatic condition in the dry region ahead of the wet front. However, from experiments [40], it was observed that significant cooling takes place over a very short distance near the quench front. The intense rate of heat removal in this small region is due to the high boiling heat transfer coefficient. This region, known as sputtering region, plays an important role during the rewetting process. Therefore, adopting a single heat transfer coefficient in the wet region of hot surface may not be suitable for analyzing rewetting phenomena. In view of this, these model considers three distinct regions, namely, a dry region ahead of wet front, the sputtering region immediately behind the wet front and a continuous film region further down-

stream for the analysis. Two Biot numbers, namely boiling Biot number and convective Biot number is used to represent the heat transfer in sputtering and continuous film region, respectively. The schematic of a 2-D object and the variation of heat transfer coefficient along the axial direction is shown in figs. 3(a, f).

Various rewetting models were reported [66-69] that propose a three region analysis which divides the wet region into two distinct regions: one liquid region and another sputtering region in a hot solid. Sun *et al.* [66] first considered a three-region model assuming 1-D conduction in a rectangular slab. The 2-D analyses of rewetting considering a three region model in an annular geometry have been suggested by Sawan *et al.* [54]. Several three region models [49, 69] based on Cartesian geometry have been developed to solve 2-D conduction equation of the hot object. Bera and Chakrabarti [70] proposed a three-region rewetting model for the cooling of a cylindrical rod, with and without an insulated core by employing the Wiener-Hopf technique. Elias and Yadigaroglu [34] reported a rewetting model that considers the large variations of the heat transfer coefficient near the wet front and the temperature dependence of the thermal and physical properties of the wall. The 1-D heat-conduction equation is solved by dividing the quenching zone into small segments of arbitrary temperature increment and constant properties and heat transfer coefficient. Recently, Sahu *et al.* [71] reported the solution to the above problem valid for both Cartesian and cylindrical geometry by employing HBIM. The wet front velocity has been found to strongly depend on the boiling Biot number than the convective Biot number. It was reported that an accurate value must be used for boiling heat transfer coefficient while an approximate value for convective heat transfer coefficient for the analysis. Simple closed form solutions have been obtained for the wet front velocity of the hot object. Available closed form expressions are summarized in tab. 4.

**Table 4. Comparison of models that consider multiple regions for the analysis**

Source	Results
Ishii [67] (2-D slab)	$\bar{Pe} = \begin{cases} \left(\frac{\bar{B}}{\bar{\theta}}\right)^{0.5} & \text{for } \bar{\theta} \leq 1 \\ \left[2 \frac{\bar{B}}{\bar{\theta}} (\bar{\theta} + 1)\right]^{-0.5} & \text{for } \bar{\theta} > 1 \end{cases}$ <p style="text-align: right;">for <math>T_{cb} = T_b</math>, <math>\theta_b = \frac{T_b - T_s}{T_0 - T_s}</math></p> $\bar{\theta} = \frac{\theta_1}{1 - \theta_b}, \quad \bar{Pe} = \sqrt{\pi} \frac{Pe}{Bi} (1 - \theta_b), \quad \bar{B} = \frac{\pi}{Bi} (1 - \theta_b)$
Bonakdar and McAssey Jr. [69] (2-D slab)	$\frac{(1 - F_2)^{0.5}}{F_2} = [\theta_1(1 + \theta_1)]^{0.5}$ $F_2 \equiv (0.551 + 0.228 \ln Pe) - \ln Bi(0.111 - 0.032 \ln Pe), \quad Bi_C = Bi_B = Bi$
Sahu <i>et al.</i> [71] (2-D slab, cylinder)	$\theta_1 = 0.5 \left\{ -\psi_2 + \theta_2(\psi_2 - \psi_1) \left[ \frac{2\theta_1 + \psi_3}{\theta_2(\psi_3 - \psi_1)} \right]^{\frac{\psi_3}{\psi_2}} \right\}$ $\psi_1 = 1 - \left(1 + \frac{4M_C}{Pe^2}\right), \quad \psi_2 = 1 - \left(1 + \frac{4M_B}{Pe^2}\right), \quad \psi_3 = 1 + \left(1 + \frac{4M_B}{Pe^2}\right)$ $M_C = \frac{Bi_C}{1 + Bi_C/3}, \quad M_B = \frac{Bi_B}{1 + Bi_B/3}$

*Rewetting model with variable property*

During the cooling of sufficiently hot surfaces, the hot objects may undergo a substantial change in surface temperature and hence assumption of constant thermo-physical properties can only provide approximate results. Therefore, efforts were made to formulate rewetting models by incorporating property variation for the analysis. Olek and Zvirin [72] presented a solution considering the effect of various temperature dependent parameters namely, thermal conductivity, specific heat, density and thickness of the test object for analyzing the rewetting phenomena. It was revealed that the variation of conductivity with temperature is more significant compared to other parameters. It may be noted that with inclusion of property variation, the linear heat conduction equation becomes non-linear. Sahu *et al.* [28] proposed a model to incorporate variation in property while analyzing the rewetting of hot surface. In their analysis [28], two different techniques, HBIM and optimal linearization, were employed for analyzing the variation of properties during a rewetting analysis.

The results obtained by both the analytical methods have been presented as closed form expressions. The comparisons between the results obtained by both the models have been presented and the effect on conductivity variation on wet front velocity has been discussed. A summary of various closed form expressions for rewetting velocity is presented in tab. 5.

**Table 5. Comparison of various models considering property variation**

Source	Mathematical expressions for rewetting velocity
Olek and Zvirin [72] (1-D)	$\frac{\text{Bi}}{Pe} = \frac{\bar{A}(1+\theta_1)}{1 + \frac{\bar{A}\eta}{1+\theta_1} \frac{1}{2\bar{A}-\bar{C}}}, \quad \bar{A} = -\frac{Pe}{2} + \left(\frac{Pe^2}{4} + \text{Bi}\right)^{0.5}$ $\bar{C} = -\frac{Pe}{2} - \left(\frac{Pe^2}{4} + \text{Bi}\right)^{0.5} \quad T_r = T_s, \quad \eta = n_1(T_0 - T_s)$
Sahu <i>et al.</i> [28] (1-D) (HBIM)	$\frac{\sqrt{\text{Bi}}}{Pe} = \frac{2\theta_1^2 \left\{ 2\theta_1[1+\eta(1+\theta_1)] - \theta_1^2 \left( \eta + \frac{\eta}{K} \right) + \theta_1^2 \varpi \right\}}{\left\{ 2\theta_1[1+\eta(1+\theta_1)] - \theta_1^2 \left( \eta + \frac{\eta}{K} \right) \right\}^2}$ $\varpi = 2 + \eta + \frac{\eta}{K}, \quad \varrho = \frac{2Pe\theta_1}{2\theta_1[1+\eta(1+\theta_1)] - \theta_1^2(\varpi - 2)}$
Sahu <i>et al.</i> [28] (1-D) (Optimal linearization method)	$\frac{\sqrt{\text{Bi}}}{Pe} = \left\{ \frac{\theta_1 \frac{Pe_4}{Pe_3} \left( \theta_1 \frac{Pe_4}{Pe_3} + 1 \right) \left[ (1+\eta) - \theta_1 \frac{\eta}{3} \right]}{\left[ \frac{4}{3} \left( \eta + \frac{3}{4} \right) \right]^2} \right\}^{0.5}$ $Pe_3 = \frac{Pe}{\frac{4}{3} \left( \eta + \frac{3}{4} \right)}, \quad Pe_4 = \frac{Pe}{(1+\eta) - \theta_1 \frac{\eta}{3}}, \quad Bi_3 = \frac{\text{Bi}}{\frac{4}{3} \left( \eta + \frac{3}{4} \right)}, \quad x = \frac{\bar{x}}{\delta},$ $Pe = \frac{\rho C_p \mu \delta}{K}, \quad Bi = \frac{h\delta}{K}, \quad \theta = \frac{T - T_s}{T_0 - T_s}, \quad \theta_1 = \frac{T_w - T_0}{T_0 - T_s}, \quad \eta = n_1(T_0 - T_s)$

### *Other models*

Most of the conduction controlled rewetting models consider the heat transfer coefficient and rewetting temperature as input parameter to solve the energy equation. Thus, the models solely depend on the arbitrariness of the choice of heat transfer coefficient and rewetting temperature as input parameter. In order to reduce the arbitrariness of the choice of above two parameters, efforts were made to analyze the rewetting phenomenon as a conjugate heat transfer problem. Olek *et al.* [73] presented the solutions to the rewetting problem as a conjugate heat transfer problem; energy equation was solved simultaneously in both solid and liquid taking a 2-D geometry. Heat transfer coefficient was not specified unlike other rewetting models, but it was obtained as a part of the solution. In a similar analysis, Peng *et al.* [74] and Dorfman [75] have presented solutions considering rewetting as a conjugate heat transfer problem. However, the value of heat transfer coefficient was assumed in the model to obtain the solution.

Several models were also proposed that have relevance to the rewetting problem. This includes the solution for a moving slab inside two adjacent heated media, various correlations on quench front velocity and others. Horvay [76] and Yao *et al.* [77] reported the temperature distribution of a moving slab inside two adjacent heated media by employing Wiener-Hopf technique. An empirical relationship between the dimensionless parameters namely, Biot number, Peclet number, and quench front temperature was obtained by Dua and Tien [78]. They presented a simple correlation for the quench front temperature for the entire range of Biot numbers. A similar correlation to predict rewetting velocity during rewetting of hot dry surfaces by falling water films was obtained by Oliverly *et al.* [79] valid for a wide range of the operating parameters. Apart from that, similar correlations were presented to estimate quench front temperature and heat transfer coefficients in case of rewetting with precursory cooling [80, 81]. Davidy *et al.* [82] presented solution to a rewetting model assuming an arbitrary variation in heat flux ahead of quench front. They claimed that the model can be used for the prediction of re-flooding covering a wide range of operating parameters.

### **Conclusion**

A comprehensive review of the important studies related to the phenomena of rewetting has been presented here. The survey brings out the importance of various rewetting models and presents the application and strength of various analytical and numerical tools to solve a variety of rewetting problems. A host of rewetting problems for different geometry, convective boundary condition, internal heat generation, variable property, and coupling effect of coolant flow rate is reported here. Solutions to these problems were obtained by employing various analytical and numerical techniques. These include analytical techniques such as separation of variables, Wiener-Hopf technique, and HBIM, and numerical techniques such as finite difference technique, finite element method, and implicit isotherm migration technique. Closed form expressions for various parameters, namely, rewetting velocity, sputtering length, critical heat source parameter has been summarized in the present study.

Additionally, a close observation of the past literature reveals certain grey areas that need further investigation. For example, the phenomena of quenching in the presence of convective cooling by liquid film, evaporation/boiling at the quench front and precursory cooling ahead of it are complex phenomenon. A few models have been reported to simulate various modes of heat transfer that exist behind, at and ahead of quench front. Therefore, further in-

vestigation is needed to analyze the multi-region heat transfer at the quench front. In addition, it has been observed that the hydrodynamic effects, specifically in a two-phase counter flow situation, may strongly affect the quench front propagation. Therefore, efforts should be made to simulate the propagation of quench fronts and the conditions for the stationary quench front.

### Nomenclature

$A$	– parameter defined in tab. 1	$R_1, R_2$	– inner and outer radius, respectively, [m]
$a$	– zone of precursory cooling defined in tab. 2	$T_a$	– temperature of the droplet-vapour mixture, [°C]
$\bar{A}$	– parameter defined in tab. 5	$T_b$	– incipient boiling temperature, [°C] (fig. 2)
$\bar{B}$	– modified Biot number defined in tab. 4	$T_{cb}$	– burnout temperature defined in tab. 4
$C_P$	– specific heat capacity, [Jkg <sup>-1</sup> °C <sup>-1</sup> ]	$T_0$	– wet-front temperature that corresponds to the temperature at the minimum film boiling heat flux, [°C]
$\bar{C}$	– parameter defined in tab. 5	$T_r$	– parameter defined in tab. 5
$d$	– exponent in the decay of precursory cooling	$T_s$	– saturation temperature, [°C]
$Bi$	– Biot number ( $= h\delta/K$ ) defined in tab. 1	$T_W$	– initial temperature of the dry surface, [°C]
$Bi^*, \bar{Bi}^*$	– modified Biot number (tab. 1)	$u$	– wet-front velocity, [ms <sup>-1</sup> ]
$Bi_C, Bi_B$	– convective and boiling Biot number, respectively (tab. 4)	$x$	– dimensionless length co-ordinate
$Bi_1, Bi_2$	– Biot number for wet and dry region, respectively (tab. 3)	$\bar{x}$	– length co-ordinate, [m]
$\bar{E}$	– parameter defined in tab. 1	$Z_2$	– parameter defined in tab. 2
$\bar{F}$	– parameter defined in tab. 1	<i>Greek symbols</i>	
$F_2$	– parameter defined in tab. 4	$\delta$	– wall thickness, [m]
$h$	– heat transfer coefficient, [Wm <sup>-1</sup> °C <sup>-1</sup> ]	$\varepsilon$	– radius ratio for an annular geometry ( $R_1/R_2$ )
$j_1, j_2$	– parameter defined in tab. 3	$\eta$	– parameter defined in tab. 5
$K$	– thermal conductivity, [Wm <sup>-1</sup> °C <sup>-1</sup> ]	$\theta$	– non-dimensional temperature parameter defined in tab.1
$M$	– effective Biot number, [–]	$\theta_0$	– dimensionless quench front temperature, [–]
$m$	– parameter defined in tab. 3	$\theta_1$	– non-dimensional temperature parameter defined in tab. 1
$Ms_i, Mt_i$	– effective Biot number in 2-D slab and tube, respectively ( $i = 1, 2$ ) (tab. 3)	$\theta_b$	– non-dimensional temperature parameter defined in tab.4
$M_C, M_B$	– effective Biot number in convective and boiling region, respectively (tab. 4)	$\bar{\theta}$	– parameter defined in tab. 4
$N$	– parameter defining magnitude of precursory cooling, [–] (tab. 2)	$\lambda_2$	– parameter defined in tab. 3
$n$	– parameter defined in tab. 3	$\xi_1, \xi_2$	– parameter defined in tab. 3
$n_1$	– parameter describing the variation of conductivity (tab. 5)	$\varpi$	– parameter defined in tab. 5
$P$	– parameter defined in tab. 2	$\rho$	– density, [kgm <sup>-3</sup> ]
$Pe$	– dimensionless wet front velocity ( $= u\delta\rho C/K$ ) defined in tab. 1	$\Psi$	– flow rate per unit perimeter, ( $= \text{gs}^{-1}\text{cm}^{-1}$ ) defined in tab. 2
$Pe^*$	– parameter defined in tab. 1	$\psi$	– parameter defined in tab. 3
$Pe_3, Pe_4$	– Peclet number defined in tab. 5	$\psi_1, \psi_2, \psi_3$	– parameter defined in tab. 4
$Q$	– dimensionless internal heat source parameter (tab. 3)	<i>Subscripts</i>	
$Q_{cri}$	– non-dimensional critical internal heat source parameter	$C, B$	– convective and boiling region, respectively
$Q_0$	– heat flux at the wet-front [ $= h(T_0 - T_s)$ ], [Wm <sup>-2</sup> ]	$cri$	– critical (dryout) condition
$q$	– boundary heat flux, [Wm <sup>-2</sup> ]	$S$	– saturation
$\bar{q}$	– internal heat generation, [Wm <sup>-3</sup> ]	$q$	– quench front
		$1, 2$	– separation constants

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