

TWO-DIMENSIONAL THREE-REGIONS REWETTING MODELLING USING ANSYS

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Abstract

Modelling rewetting processes is a challenging problem. One-dimensional modelling is an over simplification whereas a mechanistic unsteady three-dimensional modelling presents obvious difficulties. However, two-dimensional simulation using commercial software has been found to give reasonable results. This paper describes two-dimensional modelling studies of the rewetting of a hot plate by a moving liquid film using the ANSYS code. The entire plate is divided into three regions - namely the wet region, the dry region and the transition region between the wet and dry regions. In the transition zone, the wetting phenomenon of intermittent contact of water with metal at high temperature is modelled by imposing a time averaged (over the period of cycle) heat transfer coefficient in the transition region. The parameters studied are the intermittent contact frequency, heat transfer coefficient, and the length of intermittent contact region. The results are in plausible agreement with the experimental data.

Introduction

Quenching of hot surfaces is one of the most crucial phenomena to be considered for the safety analysis of the design basis loss of coolant accident (LOCA) in light water reactors (LWR's). In such an accident, the coolant is rapidly expelled from the reactor vessel through a large break in a feed pipe and the nuclear fuel rods undergo a rapid increase in their temperature. To mitigate the consequences of LOCA, water is sprayed on the top of heated fuel rods via an emergency core cooling system in the case of the Boiling Water Reactor (BWR) whereas it is injected from the bottom of the core through the lower plenum in the case of the Pressurized Water Reactor (PWR). In both the cases, a quench front is formed separating wet and dry regions. Ahead of the quench front, complex and chaotic processes are occurring over a very small axial range where a high temperature gradient exists. Despite extensive experimental and theoretical studies, the heat transfer mechanism in this region is still not well understood. In particular, the quench front advances at a speed much slower than the nominal rewetting flow speed, and the fundamental processes that cause this are little understood.

Yamanouchi (1968) performed experiments on top reflooding by spraying water onto the top of a 36-rod assembly heated to different temperatures at atmospheric pressure. It was observed that the water moved down the assembly as a film on the rods up to the point (the rewetting front) where the water is ejected from the surface; below the rewetting front, the surface temperature remained high. The rewetting front moved down the surface at a steady velocity. Any liquid that comes into contact with the hot surface below the rewetting front does not wet the surface. The

flow rate had only a very small effect on rewetting speed; an increase of 30 times in the liquid flow rate only doubles the rewetting velocity.

Duffey and Porthouse (1973) performed rewetting experiments with tubes and rods with a wide range of material properties. It was found that the velocity of the rewetting front was a function of the hot surface temperature ahead of the rewetting front. For a given hot surface temperature ahead of the rewetting front, the same rewetting velocities were observed for both top and bottom rewetting. The authors concluded that the processes occurring in the two cases were similar.

Pereira (1998) studied rewetting by a falling film of liquid. He measured the surface temperature during the passage of the rewetting front by using a vapour deposited gold-platinum micro-thermocouple; this gave a very rapid response. Pereira was also able to obtain high speed videos of the passage of the rewetting front by viewing this through a sapphire insert in the plate carrying the falling film. Pereira observed that temperature fluctuations occurred over a very short axial range near the rewetting front with a frequency of 10-100+ Hz for the initial wall temperature of 600 °C. On the basis of these measurements, and from the video recordings, Pereira deduced that the fluctuations were due to intermittent contacts between the liquid and the hot plate in the region of the rewetting front.

Woodfield et al. (2005) studied the flow behaviour of a free surface water jet impinging on a high temperature surface. For the case where the initial temperature of the surface was above 300 °C, an almost explosive pattern appeared. The sheet of the water was observed to appear and then disappear cyclically. The period of the time when the sheet was present gradually became longer until the sheet remained continuously. The cooling history showed that a sudden change in flow pattern occurred when the initial solid temperature was above 300 °C.

Ilyas et al. (2011) performed experiments in which a heated plate was quenched by falling film flow. Using thermal imaging system, the measurement of temperature fluctuation at the quench front was achieved through an infrared transparent substrate imbedded in the plate. The phenomenon was also visualized using high speed video camera. The temperature measurement and the photographic evidence demonstrated the existence of intermittent contacts of liquid with the heated solid surface followed by the ejection of the liquid film by explosive boiling. The period of intermittent contact is of the order of few tens of millisecond.

Beside the extensive experimental studies, a formidable body of literature on rewetting modelling is available. Almost all theoretical models involve solutions of the heat conduction equation in the solid phase. In the earlier models, most of the authors (Blair (1975), Carbajo (1986), Coney (1975), Duffey and Porthouse (1973), Yeh (1975), etc.) considered a constant wet side heat transfer coefficient whilst assuming an adiabatic wall downstream of the quench front. The specification of this wet side heat transfer coefficient and the temperature at the rewetting front are the prior inputs to these models and a wide range of values were assumed. It is generally the case that some pair of heat transfer coefficient and rewetting temperature can be found that cause the predictions to fit the data.

Davidy et al. (2001) developed a one-dimensional two-region (wet and dry) time-dependent rewetting model for flat plate geometry. In the wet region, a constant heat transfer coefficient was assumed whereas a decreasing heat transfer coefficient was prescribed in the dry region. An approximate solution of the one-dimensional heat conduction equation was obtained by splitting it into steady state and transient parts. The quenching velocity history and the temperature profile are computed analytically via a Green's function approach. The parameters in the arbitrary heat flux profile are determined by fitting the solution to the experimental data by Tatsuhiko and Mitsuru (1984). The rewetting temperature T_0 was taken as the geometrical mean of the saturation and critical temperatures. The prediction of the quench front velocity agreed with the experimental results of Duffey and Porthouse (1973) for low temperatures and low mass flow rates.

Sahu et al. (2009) analyzed conduction-controlled rewetting of two-dimensional objects (rod/plate) 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. Sahu et al. defined inter-region temperatures of T_0 between the dry and sputtering region and T_b between the sputtering region and the wetted region. The values of these temperatures were obtained by fitting experimental data. For the wet and sputtering regions, two constant but different heat transfer coefficients (h_C , h_B) were assumed. The heat transfer coefficients correspond to two Biot Numbers Bi_C (for convective heat transfer in the wet region) and Bi_B (for boiling heat transfer in the sputtering region). For the dry region, an adiabatic condition (heat transfer coefficient, $h = 0$) was assumed. A range of values of T_0 , T_b and Biot numbers were used as input parameters. The HBIM yielded solutions for wet front velocity, sputtering length and temperature field with respect to wet front. It was seen that heat transfer mechanism was dependent upon T_0 and T_b . Additionally, the mechanism of heat transfer was found to be dependent on two Biot numbers Bi_C and Bi_B .

Ilyas (2011) developed a one dimensional intermittent contact model for rewetting of heated surfaces. In this model, semi-infinite bodies of liquid (water) and solid (sapphire) at uniform but different initial temperature were suddenly brought into contact; the contact being ended when the homogeneous nucleation temperature was reached at the interface. Following cessation of contact, the contact was modelled as being immediately resumed; the delay between successive contacts was ignored. On all contacts, the water temperature was considered uniform; this corresponded to the assumption that heated water had been ejected, and that fresh cool water made the following contact. The solid temperature distribution obtained at the end of the previous contact was taken as initial condition for the next contact. The solid's lower surface was taken as adiabatic. A one-dimensional two-region numerical solution of the transient heat conduction equation was developed using the ANSYS code to apply this model. The model was used to compute the transient temperature distribution in a one-dimensional body of water and of sapphire when they are repeatedly brought into contact; the results for the case of initial solid temperature of 600 °C and initial liquid temperature of 90 °C are shown in Figure 1. The surface temperature initially recovered to the homogeneous nucleation temperature quickly (of order of a few tens of milliseconds), before being re-cooled by the arrival of fresh water. The time for temperature recovery increased to a few hundreds of milliseconds, until eventually the interface temperature no longer reached the homogeneous nucleation temperature, and (by construction) the surface was wetted permanently.

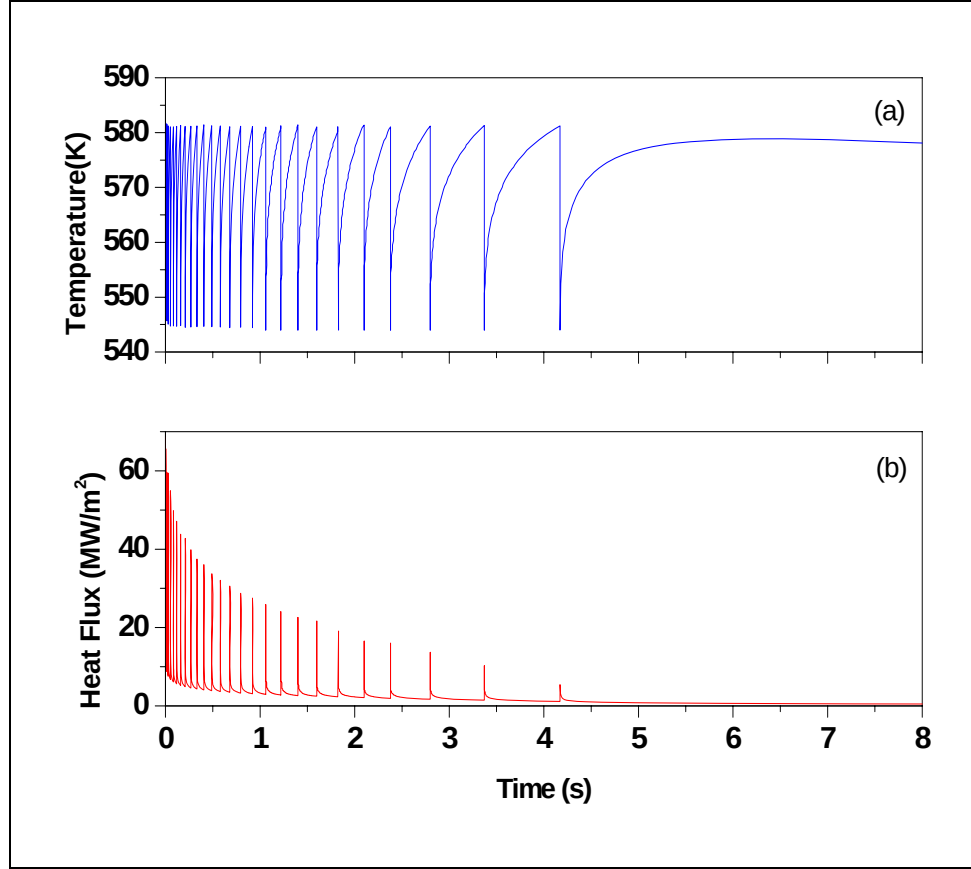


Figure 1: Interface temperature versus time. Initial solid temperature 873 K (600 °C) and initial water temperature 363 K (90 °C).

Modelling the rewetting process is a challenging problem. One-dimensional modelling is an over simplification whereas mechanistic three-dimensional modelling of the unsteady processes presents obvious difficulties. However, two-dimensional simulation using commercial software (ANSYS) has been found to give reasonable results. In what follows, a description of the phenomenological two-dimensional modelling of the rewetting process using the ANSYS code is given in Section 1. In the Section 2, a parametric study is described in which the effect of wet side heat transfer coefficient and the rewetting velocity on the quasi steady state temperature distribution for a quiescently moving film was investigated. Modelling of intermittent contacts is achieved by imposing intermittent contact heat transfer coefficient in the transition region between dry and wet regions, the description is given in Section 3 and some concluding remarks are given in Section 4.

1. Phenomenological Modelling using

In this Section, the bases of the use of the ANSYS code in modelling experiments on rewetting are presented. A two-dimensional plate as shown in the Figure 2 is considered; the plate thickness (1 mm) and the material properties are chosen as those of the sapphire insert used in the experimental work by Pereira (1998). The boundary conditions on all edges were adiabatic except on the top surface where a convection boundary condition with a variable heat transfer coefficient is considered to model processes such as intermittent contacts and cooling by a two

phase mixture ahead of quench front. Starting from the leading edge, the boundary between wetted and un-wetted parts moves with the rewetting velocity such that it represents moving liquid from left to right. After sufficient progress of the rewetting front, the moving temperature field becomes invariant with this progress, and these are the conditions used in the analysis.

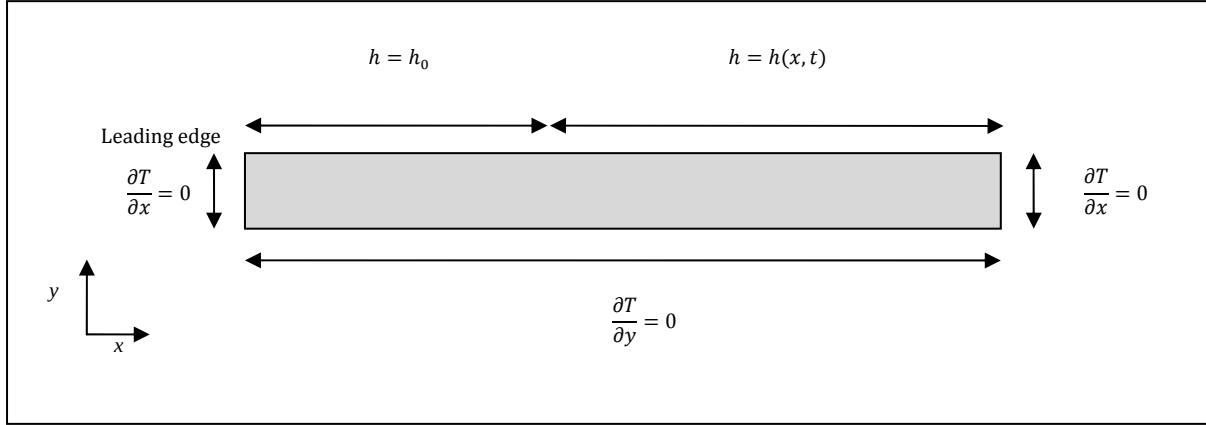


Figure 2: Schematic description of the rewetting problem

These conditions could be expected to be reasonably representative of the circular sapphire plate embodied in the stainless steel tube as used in the experiment by Pereira (1998). The application of this modelling to the case of a quiescently moving film is described in Section 2 and modelling including a region of intermittent contacts ahead of the wet front will be described in Section 3.

2. Quiescently Moving Film

A quiescently moving film case is studied first of all. In this case, the surface is considered to comprise wet and dry regions only, with the interface between these regions moving laterally (along the x-axis) at a specified speed, the rewetting speed v_{rew} . A constant heat transfer coefficient h_0 is applied to the wet side and a zero heat transfer coefficient to the dry part. The main free (arbitrary, fitting) parameters in the model are thus the rewetting speed and the heat transfer coefficient. Importantly, the model then computes fully mechanistically the transient two-dimensional temperature distribution induced in the substrate.

A parametric study was done to evaluate the effects of the parameters v_{rew} and h_0 . Following Pereira (1998), an initial plate temperature of 600 C and water at 90C was used.

We will characterize the output by showing the time dependent interface temperature of a point as the rewetting front approaches and passes.

In the computations, the “free” modelling parameters are rewetting velocity v_{rew} and wet side heat transfer coefficient h_0 and the effect of varying these parameters is shown in Figures 3 and 4. The experimental results shown are those measured by Pereira (1998) and given in Figure 5.16.1 (p. 199) of his thesis. The effect of rewetting velocity is dominant in the dry region with a characteristic decline of temperature as the quench front approaches it, showing the importance of precursory cooling by lengthwise conduction in the substrate. The results show that with

increasing quench front velocity, the temperature gradient steepens as the quench front approaches the observation point (OP). This would be expected since, for higher velocities, less time is available for heat conduction. On the other hand, the heat transfer coefficient has a dominant effect in the wet region. Increasing the heat transfer coefficient lowers the temperature of the wet side. The values of the rewetting velocity and heat transfer coefficient giving the best fit to the results of Pereira (1998) are 4 mm/s and 12000 W m⁻² K⁻¹ respectively.

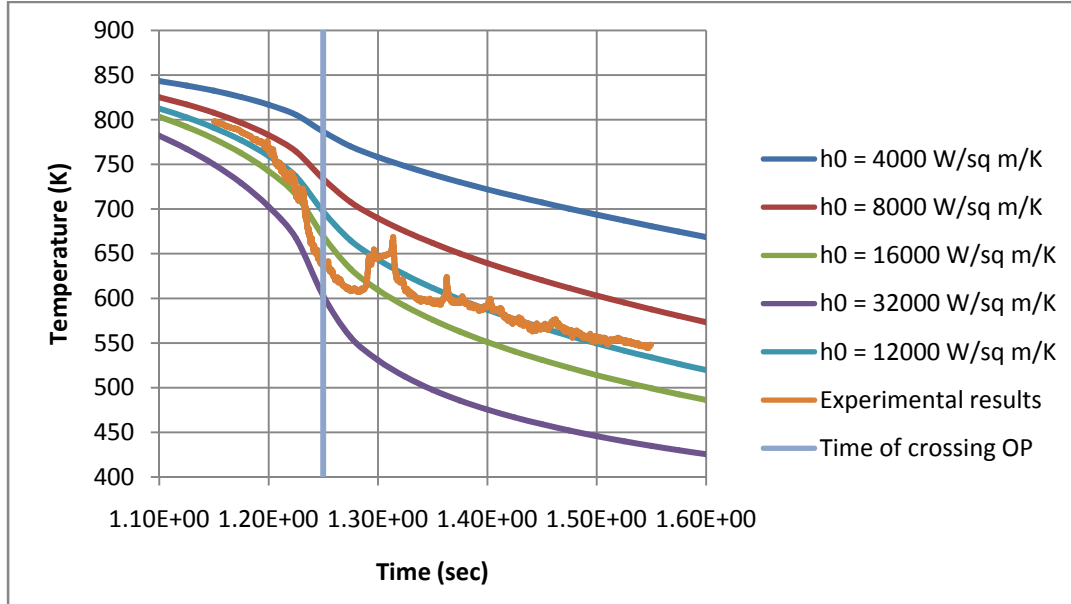


Figure 3: Temperature history for different values of wet side heat transfer coefficient with a rewetting velocity of 4 mm/s

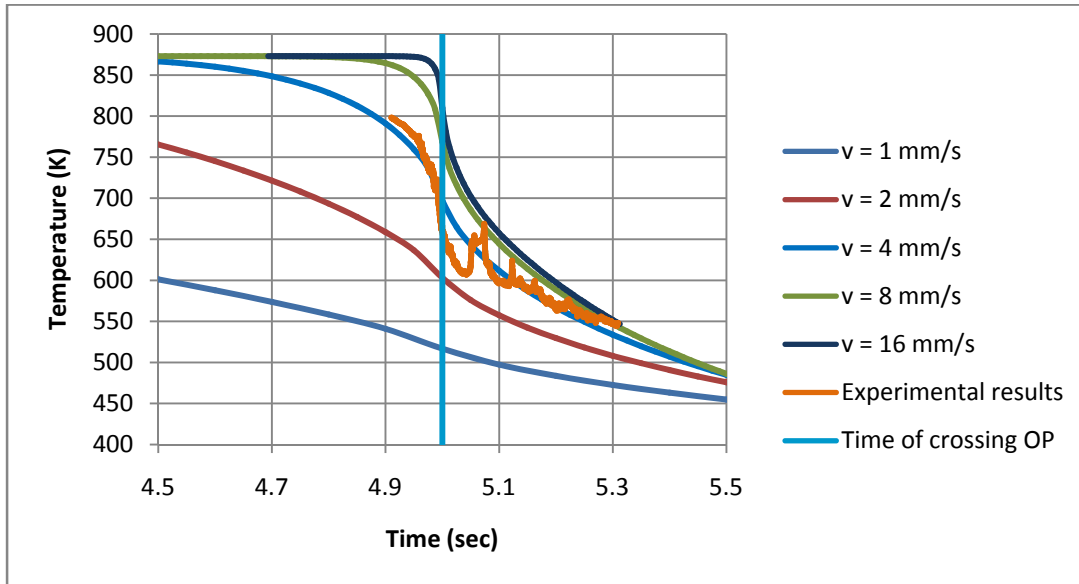


Figure 4: Temperature history for different values of quench front velocities with a wet side heat transfer coefficient of 12000 W m⁻² K⁻¹

This analysis indicates that even with that combination of heat transfer coefficient and rewetting velocity which best matches the leading and trailing trends of temperature, there is a difference in the temperature at the very front of the liquid tongue. This indicates that a higher heat transfer coefficient is needed in this location to cause this rapid decline in temperature. In the next section we introduce a transition region, between the dry and the wet regions, better to model the experimentally-observed intermittent contact of liquid with hot solid surface.

3. Modelling Intermittent Contacts

In this section we will attempt to construct a model which simulates rapid heat transfer by high frequency intermittent contacts in the transition region. There will obviously be free parameters in our model, in addition to those already discussed in the quiescent-progress model presented above. The additional parameters are the length of the intermittent contact region, δ , and the value of the heat transfer coefficient taken to obtain there.

Whilst these are both free parameters, it is actually possible to make an estimate of the time averaged heat transfer coefficient beneath this film for a given frequency of intermittent contacts using recently developed one-dimensional transient model. In one-dimensional ANSYS simulations of multiple contacts of water with a heated solid (Ilyas 2011), the interface temperature and heat flux were computed for each contact. The amount of heat transferred (Q) per unit surface area over a complete period τ is obtained by integrating the heat flux over the contact time. (The heat flux during the non-contact period is negligible). Thus knowing the heat transferred, an estimate of Q , the average heat transfer coefficient h_c over the period τ is then given by:

$$h_c \Delta T = \frac{Q}{\tau} \tag{1}$$

where ΔT is the difference between the homogeneous nucleation temperature and the bulk liquid temperature ($\approx 581-363 = 220$ K). For the series of contacts given in Figure 1(b), the average heat transfer coefficient can be estimated using equation (1) as a function of the period τ . The results are shown in Figure 5. For a frequency of 60 to 140 Hz (consistent with the experimental observations), the average heat transfer coefficient varies over the range 2×10^4 to 3×10^4 W m⁻² K⁻¹.

In our model we will apply a heat transfer coefficient h over a short zone of length δ upstream of the rewetting front. A parametric study was performed to investigate the effects of δ and h_c on the temperature/time plots. A value of h of 12000 W m⁻² K⁻¹ in the wetted region beyond the intermittent contact region and a rewetting front velocity of 4 mm/s were assumed consistent with the results shown in Figures 3 and 4.

The results are shown in Figure 6 and Figure 7.

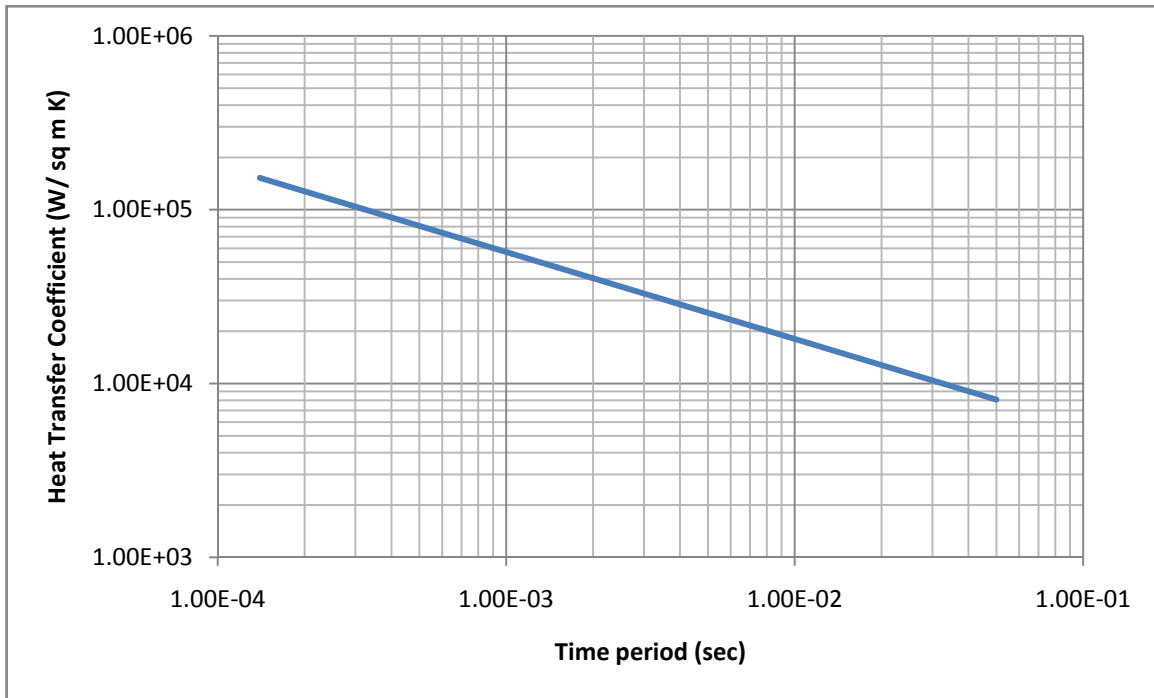


Figure 5: Average intermittent contact heat transfer coefficient as a function of contact period (assuming that the contact and non-contact times are equal)

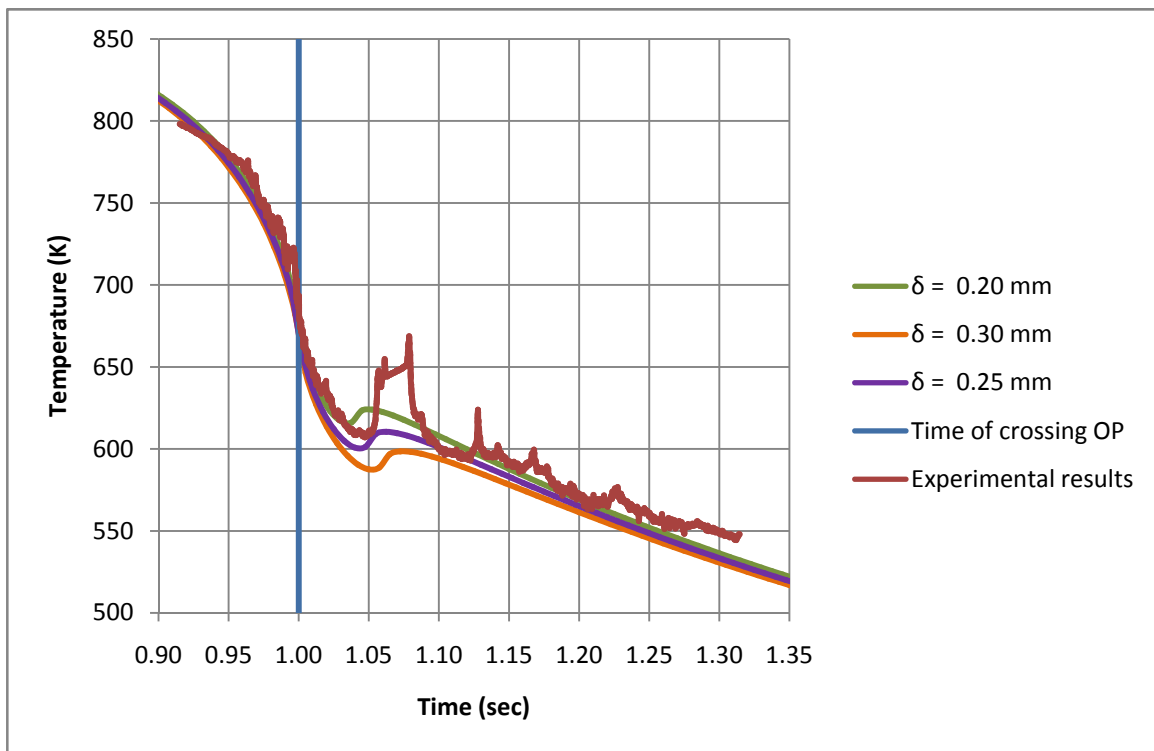


Figure 6: The effect of intermittent contact length for a constant intermittent contact heat transfer coefficient of $12000 \text{ W m}^{-2} \text{ K}^{-1}$

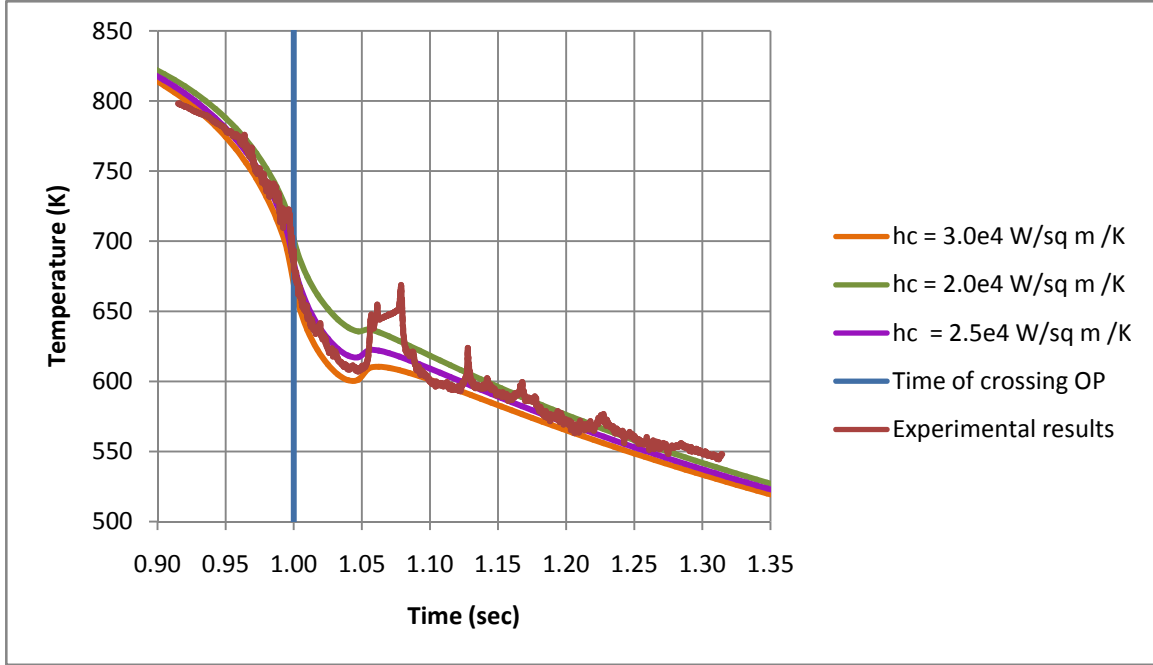


Figure 7: The effect of intermittent heat transfer coefficient for a constant length, δ , of intermittent contact region 0.25 mm

The closest match with the Pereira results was obtained with $\delta = 0.25$ mm and $h_c = 2.75 \times 10^4$ W m⁻² K⁻¹. Comparison of Figures 3 and 4 with Figures 6 and 7 shows that modelling the experimentally-observed intermittent contact via a high value of local heat transfer coefficient improves the prediction of the rapid decline of the temperature just prior to arrival of quench front. It has been observed that when this high heat transfer patch passes over the observation point, it leaves behind an increasing interface temperature. The increase in the interface temperature behind the quench front results from recovery of the temperature due to conduction from beneath the surface. As shown in Figure 6, with increasing δ , the elapsed time between the temperature fall and subsequent rise increases and, also, the minimum temperature decreases. The minimum temperature decreases with increasing heat transfer coefficient h_c as shown in Figure 7.

4. Concluding Remarks

Considerable insight has been obtained into the processes occurring during rewetting by carrying out transient conduction calculations using a commercial computer package (ANSYS). This is not a complete solution of the problem; specifically, the length of the intermittent wetting zone near the rewetting front and the heat transfer coefficient in this zone has to be specified to fit the experimental data. That said, the use of plausible values predicts temperature histories that have much the same characteristics as those observed experimentally.

With this present model, incorporating both transient heat conduction into and along the substrate, along with a very small region of high heat transfer coefficient at the rewetting front, it seems probable that the basic features of the process (intermittent contact between the liquid and solid in the rewetting front region) has been captured. Future work in this area will be focused on

a more deterministic modelling of the intermittent contact region, combining the present two-dimensional model with the cyclical one dimensional model, with the specific objective of estimating, from first principles, the detailed characteristics of this region.

5. Acknowledgement

This work was carried out during the first author's PhD studies at Imperial College London, as part of the TSEC programme KNOO, and we are grateful to the EPSRC for funding under Grant EP/C549465/1.

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