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A NEW CORRELATION FOR QUENCH FRONT VELOCITY

E. OLIVERI, F. CASTIGLIA, S. TAIBI and G. VELLA
Istituto di Applicazioni e Impianti Nucleari, Facoltà di Ingegneria,
Università di Palermo, Viale delle Scienze, 90128, Palermo, Italy

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Abstract—The purpose of this paper is to present a new correlation for the prediction of the quench front velocity in the rewetting of hot dry surfaces by falling water films. This correlation is valid in the full range of the operating parameters where it proves very successful, providing a root mean square error of about 2.5%, with respect to accurate numerical solutions of the mathematical problem involved.

NOMENCLATURE

- Bi, Biot number, $h\varepsilon/k$;
- c, solid specific heat;
- h, heat transfer coefficient;
- k, solid thermal conductivity;
- T_0, sputtering temperature;
- T_s, saturation temperature;
- T_w, initial dry wall temperature;
- u, dimensionless rewetting velocity, $\rho c\varepsilon v/k$;
- v, rewetting velocity.

Greek symbols

- ε, slab thickness;
- θ, dimensionless sputtering temperature, $(T_0 - T_s)/(T_w - T_s)$;
- ρ, solid density.

1. INTRODUCTION

IN THE unlikely event of a major rupture in the primary circuit pipework of a light water reactor much of the cooling water would be expelled through the breach. This accident, called Loss Of Coolant Accident (LOCA), would cause the shut-down of the reactor because the coolant is also the reactor moderator. However, following the LOCA, the fuel cladding heats up due to the dissipation of all the stored heat in the fuel rods and due to continuing fission product decay heat. When the core uncovers the Emergency Core Cooling Systems (ECCS) must prevent the cladding temperature from exceeding safe limits. In this case, a process of fundamental importance is the rewetting of the hot dry surfaces, that is the reestablishment of liquid in contact with the surfaces the initial temperature of which is higher than the sputtering temperature.

A considerable number of analytical and experimental studies have been carried out to investigate the rate of rewetting, or quench front advance, of a falling water film, as in the case of BWR spray cooling.

It is generally recognized that in the rewetting by a falling water film, cooling occurs by means of axial and transverse heat conduction from the hot to the cool region, where the heat is removed by boiling and convection.

A physical model frequently employed [1–4] consists of an infinitely extended vertical slab with the back face thermally insulated and the front face with a region (ahead of the falling film) treated as adiabatic and a wet region (behind the quench front) associated with a constant heat transfer coefficient.

For this model, in addition to the 1-dim. analysis [1, 2], a number of 2-dim. analyses have been also carried out [3–7] and some simple formulae for the prediction of the dimensionless rewetting velocity have been proposed. These formulae are generally of an asymptotic nature, that is they are valid only either at very small or very large Biot numbers and dimensionless velocities.

In this paper we propose a new correlation for the prediction of the dimensionless rewetting velocity valid in the full range of practical interest of both Bi and u. The proposed correlation is simple and agrees very well with the numerical results reported [7, 8].

2. SOME OF THE MOST QUOTED FORMULAE

The mathematical problem of the rewetting by a falling water film is to seek the solution to the 2-dim. conduction equation, written in a coordinate system moving along with the wet front at a constant velocity v, employing appropriate boundary conditions; the mathematical details are reported in ref. [3].

It should be noted, however, that to seek an exact solution in order to derive the dimensionless rewetting velocity u is impractical. In view of this, many workers have looked for approximate solutions; some of the most quoted formulae are reported below.

$$u = Bi^{1/2}\left[\frac{\theta}{(1-\theta)^{1/2}}\right]. \tag{1}$$

This formula was deduced from a 1-dim. analysis [2], consequently it is valid only for very small values of both Bi and u.

$$u = 2^{-0.25\pi^{1/2}} Bi \left[\frac{\theta^2}{(1-\theta)} \right]^{(0.5+0.25\pi^{1/2})}. \qquad (2)$$

This formula, which is valid for large Bi, was deduced from numerical calculations [6].

$$u = \frac{Bi}{K(\theta)} \left[\frac{\theta^2}{(1-\theta)} \right]. \qquad (3)$$

This equation, which is a convenient correlation of the numerical results [4, 8] of Coney may be used over the full range of Biot numbers, provided the value of u predicted by it is higher than about 4. Table 1 supplements the formula [8] and is reproduced below.

We have previously reported an equation similar to equation (3) [7] but $K(\theta)$ was given by

$$K(\theta) = 1.04 + 0.60\theta. \qquad (4)$$

This correlation, which provides good results for $u \geq 3$, was deduced from the finite-difference RISET code results [7].

$$\frac{Bi}{u} = 1.707 \left[\frac{(1-\theta)}{\theta} \right] + 1.457 \left[\frac{(1-\theta)}{\theta} \right]^2. \qquad (5)$$

This expression is a 2-dim. asymptotic solution valid only for large values of u [5].

$$u^2 = \left[\frac{Bi\theta^2}{(1-\theta)} \right] \left[1 + \frac{0.4Bi\theta^2}{(1-\theta)} \right]. \qquad (6)$$

This correlation is presented as valid in the full range of Bi and θ [9].

3. THE PROPOSED CORRELATION

The starting point of the formula here proposed is the following functional relationship:

$$\frac{w^{2m}u^{4m}}{w^{2m} + u^{2m}} = \left[\frac{Bi\theta^2}{(1-\theta)} \right]^{2m} \qquad (7)$$

where m is thought to be a positive constant and w is, in principle, a function of Bi and θ only.

It is readily seen that equation (7) has some interesting features: (i) for $u \ll w$ it reduces to equation (1); (ii) for $u \gg w$ it reduces to equation (3); (iii) for any m the dimensionless rewetting velocity can be easily obtained in an explicit form.

As for the values of the parameters w and m, they will be evaluated by fitting equation (7) over the numerical results of the RISET code [7], reported in Table 2.

It should be noted, however, that while the value of w has very little influence on the smaller values of u, it strongly affects the higher ones, as may be seen by evaluating the ratio $(du/u)/(dw/w)$.

In view of this, when correlating the parameter w to Bi and θ, it is worth using, instead of the full equation (7), the limiting expression (3) which is valid when u is not too small. This procedure allows a straightforward correlation of w in terms of Bi and θ, leaving out the parameter m.

Figure 1 shows a plot of w^2 vs θ, for all the Bi values reported in Table 2 and for $u \geq 5$. This plot suggests that w is independent of Bi and shows that it is reasonable to assume a linear dependence of w^2 on θ. The least squares method provides the following correlation:

$$w^2 = 1.018 + 1.598\theta. \qquad (8)$$

Turning to the parameter m, we have tested equation (7), where the expression (8) was introduced, for various values of m.

We have optimized the choice of this parameter by minimizing the root mean square (RMS) error on u, on the basis of all the numerical data reported in Table 2. As shown in Fig. 2, the minimum occurs at $m = 1.04$; it is nevertheless convenient to assume $m = 1$, without significant changes in the results, as the choice of m is not too critical.

In conclusion, the expression to be used in evaluating the dimensionless rewetting velocity reduces to

$$\frac{w^2u^4}{w^2 + u^2} = \left[\frac{Bi^2\theta^4}{(1-\theta)^2} \right] \qquad (9)$$

where w^2 is given by equation (8).

4. RESULTS AND DISCUSSION

In order to test the accuracy of the correlation proposed, we have compared the values of the dimensionless rewetting velocity as deduced from equation (9) with the corresponding numerical values of Table 2. The results are shown in Fig. 3.

It is noteworthy that the estimates on the basis of equations (8) and (9) provide very good approximations for u, with a -0.32% mean error and a 2.56% RMS error.

An analogous comparison with the numerical data [4, 8] is shown in Fig. 4. Also in this case it is readily seen that equation (9) agrees very well with the data points, even those which fall outside the velocity range covered in Table 2. The numerical comparisons provide a -1.20% mean error and a 2.31% RMS error.

Table 1

θ	1.000	0.833	0.667	0.500	0.400	0.333	0.250	0.200	0.167	0.143
K	1.570	1.478	1.395	1.315	1.256	1.220	1.172	1.139	1.117	1.094

Table 2. Numerical values of θ obtained from RISET code

Bi \ u	0.10	0.50	1.00	2.00	3.00	5.00	10.00	15.00	20.00	25.00
0.10	0.2696	0.7588	0.9054	0.9647	0.9787	0.9877	0.9939	0.9959	0.9969	0.9975
0.50	0.1311	0.4890	0.7053	0.8575	0.9069	0.9434	0.9706	0.9801	0.9849	0.9879
1	0.0945	0.3788	0.5856	0.7670	0.8380	0.8964	0.9440	0.9614	0.9706	0.9762
2	0.0677	0.2850	0.4646	0.6524	0.7401	0.8219	0.8973	0.9275	0.9439	0.9543
5	0.0432	0.1896	0.3238	0.4880	0.5798	0.6805	0.7930	0.8456	0.8766	0.8972
10	0.0307	0.1370	0.2390	0.3733	0.4557	0.5550	0.6821	0.7496	0.7927	0.8228
15	0.0251	0.1128	0.1985	0.3146	0.3886	0.4818	0.6092	0.6817	0.7303	0.7654
20	0.0217	0.0981	0.1734	0.2772	0.3448	0.4320	0.5563	0.6303	0.6813	0.7192
30	0.0177	0.0804	0.1429	0.2306	0.2890	0.3667	0.5827	0.5557	0.6081	0.6484
50	0.0137	0.0624	0.1115	0.1814	0.2290	0.2940	0.3957	0.4641	0.5140	0.5543
100	0.0097	0.0442	0.0792	0.1298	0.1648	0.2139	0.2942	0.3509	0.3944	0.4308
150	0.0079	0.0360	0.0647	0.1063	0.1354	0.1766	0.2451	0.2941	0.3327	0.3655
200	0.0068	0.0312	0.0561	0.0923	0.1177	0.1537	0.2144	0.2583	0.2934	0.3234
500	0.0043	0.0197	0.0355	0.0586	0.0750	0.0984	0.1386	0.1685	0.1928	0.2140
1000	0.0030	0.0140	0.0252	0.0416	0.0532	0.0699	0.0989	0.1206	0.1385	0.1542

In Table 3 some results of the comparison between the correlation proposed here and the analogous one given by equation (6), on the common basis of both the numerical results given here and by Coney are finally reported.

It should be noted, furthermore, that, while equation (9) provides a maximum error of 6.6% the correlation (6) reaches a maximum error of about 25%.

5. CONCLUSION

A simple and reliable correlation for the prediction of the quench front velocity in the rewetting of hot dry surfaces by a falling water film has been presented.

This correlation is valid in the full range of practical

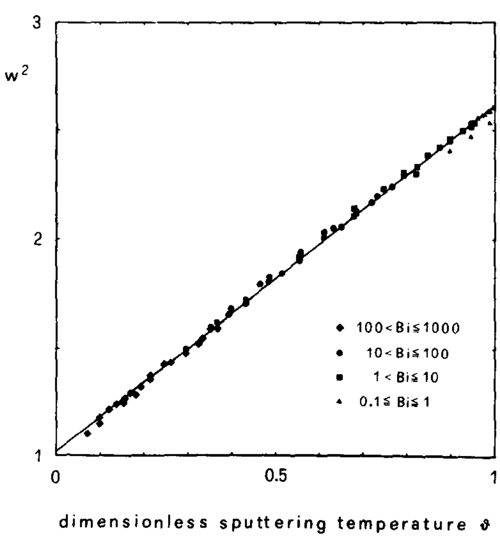

FIG. 1. Plot of w^2 vs θ, for Bi from 0.1 to 1000 and for $u > 5$.

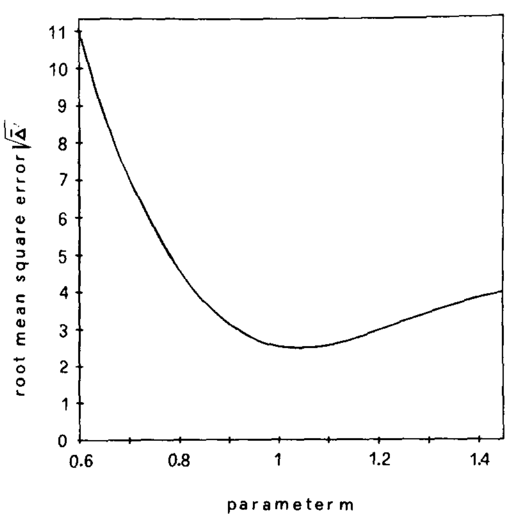

FIG. 2. RMS error on u vs m, on the basis of the equations (7) and (8) and of the data in Table 2.

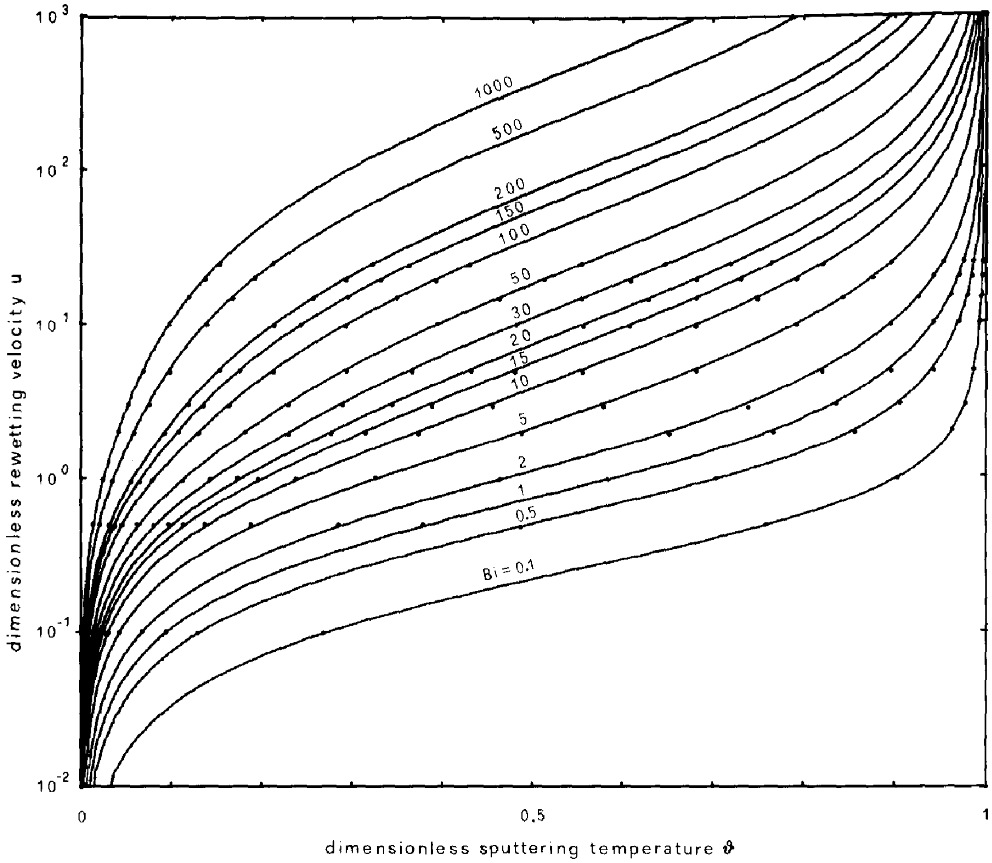

FIG. 3. Comparison between the numerical data of Table 2 and the correlation (9).

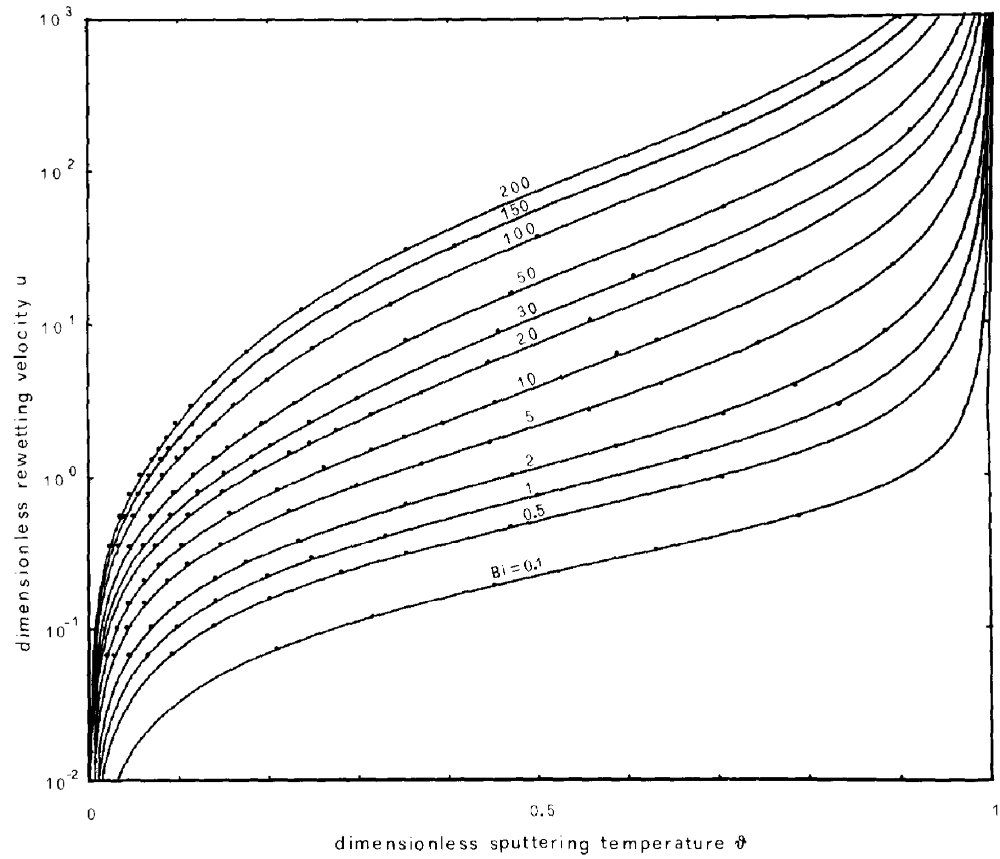

FIG. 4. Comparison between the numerical results of Coney and the correlation (9).

Table 3. Results of the comparison between equations (9) and (6)

	Equation (9)	Equation (6)
Mean error (%)	−0.42	−3.48
RMS error (%)	2.44	8.51

interest, where it gives a RMS error of about 2.5% with respect to the numerical results obtained previously (Table 2) and those of Coney.

As for the values of the parameters w and m which appear in the correlation we note, finally, that a more accurate procedure could be adopted in their determination with some additional effort. However, such a small increase in accuracy seemed to us to be unnecessary in view of the large uncertainties in the values of the sputtering temperatures and the Biot numbers under actual operating conditions.

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UNE NOUVELLE FORMULE POUR LA VITESSE DU FRONT DE TREMPE

Résumé—Le but de cet article est de présenter une nouvelle formule pour la prévision de la vitesse du front de trempe dans le remouillage des surfaces chaudes et sèches par des films d'eau tombants.

Cette formule est valable dans le domaine complet des paramètres opératoires, avec une erreur quadratique moyenne de 2,5% par rapport aux solutions numériques précises du problème mathématique.

EINE NEUE BERECHNUNGS-GLEICHUNG FÜR DIE GESCHWINDIGKEIT EINER ABSCHRECK-FRONT

Zusammenfassung—In dieser Arbeit wird eine neue Beziehung zur Bestimmung der Geschwindigkeit der Abschreck-Front bei der Wiederbenetzung von heißen, trockenen Oberflächen durch Wasser-Fallfilme vorgestellt.

Diese Beziehung ist im gesamten Parameter-Bereich gültig und erweist sich als sehr erfolgreich; im Vergleich mit den genauen numerischen Lösungen des entsprechenden mathematischen Problems ergibt sich ein mittlerer quadratischer Fehler von rund 2,5%.

НОВОЕ ОБОБЩЕННОЕ СООТНОШЕНИЕ ДЛЯ ОПРЕДЕЛЕНИЯ СКОРОСТИ ФРОНТА ЗАКАЛКИ

Аннотация—Представлено новое обобщенное соотношение для расчета скорости фронта закалки нагретых сухих поверхностей стекающими пленками воды. Соотношение справедливо во всем диапазоне рабочих параметров. Сравнение с точными численными решениями рассматриваемой математической задачи показывает, что среднеквадратичная погрешность расчета по предложенному соотношению не превышает 2,5%.