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Analyses of Precooling Parameters for a Bottom Flooding ECCS Rewetting Velocity Model

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Abstract

An extension work of the previous paper on the rewetting velocity model is presented. Application of the rewetting velocity model presented elsewhere requires a priori values of ϕ. In the absence of ϕ values, film boiling heat transfer coefficient (h_{df}) and fog-film length (l) data are needed. To provide these informations, a modified Bromley's correlation is first derived and used to obtain h_{df} values at higher pressure conditions. In addition, the analysis of the precooling parameters, such as ϕ and l is further extended using much more expansive PWR FLECHT data. Thus, the applicable range of the rewetting velocity model is further expanded in this work.

요　　약

지난번 이미 다른곳에 발표한 재침수속도공식(rewetting velocity model)에 관한 논문을 더 확충하였다. 앞서 발표한 재침수속도 공식을 사용하려면 ϕ의 값을 미리 알고 있어야한다. ϕ 값을 모를 때에는 film boiling 열전달계수 (h_{df})와 fog-film 길이 (l)의 자료가 있어야 한다. 이러한 자료를 제공하기 위해서, 먼저 브롬리(Bromley)의 공식을 수정하여 보다 높은 압력조건하에서의 h_{df} 값을 구하였다. 그리고, 지난번 사용한 자료보다 훨씬 더 충실한 PWR-FLECHT 자료를 사용하여 ϕ와 l과 같은 precooling 계수들의 값을 더 확충하여 놓았다. 이리하여, 재침수속도공식의 응용 가능한 영역을 더 확대하였다.

Nomenclature

A_l=coolant flow area per fuel rod, m^2

b=clad surface breadth or rod perimeter, m

c=clad specific heat, Kcal/Kg-°C

c_g=specific heat of vapor, Kcal/Kg-°C

D=outside diameter of tube, m

g=acceleration of gravity

h_c=heat transfer coefficient of the wetted region, Kcal/hr-m^2-°C

h_{co}=heat transfer coefficient which accounts only for the heat conduction through the vapor film and by boiling convection from the surface of the film to the surrounding liquid, Kcal/hr-m^2-°C

h_{df}=heat transfer coefficient of the unwetted fog rigion, Kcal/hr-m^2-°C

h_{ds}=heat transfer coefficient of the unwetted superheated vaper region, Kcal/hr-m^2-°C

h_r=radiation heat transfer coefficient, Kcal/hr-m^2-°C

H_{fg}=latent heat of vaporization, Kcal/Kg

k=thermal conductivity of clad, Kcal/hr-

m-°C

k_v=thermal conductivity of saturated vapor, Kcal/hr-m-°C

l=fog length which denotes the distance between the wet front and the fog front, m

m_c=reflooding flow rate flowing upward per unit fuel rod, kg/hr

p=system pressure, k_{gf}/cm^2

T_1, T_2=temperature of surface 1 and 2 respectively, °K

T_0=effective Leidenfrost temperature (or sputtering temperature) at which the hot surface may wet, °C

T_{sat}=saturation temperature of coolant, °C

T_{vf}=average temperature of the film defined by

$$T_{vf}=\frac{T_w+T_{sat}}{2}, \ °C$$

T_w=initial hot clad surface temperature, °C

U=wet front velocity, m/hr

U_c=reflooding velocity, m/hr

α_{12}=absorptivity of radiation of surface 1 for radiation from surface 2

α_{21}=absorptivity of radiation of surface 2 for radiation from surface 1

δ=clad thickness, m

$\epsilon_1(T_1)$=emissivity of surface 1 at T_1

$\epsilon_1(T_2)$=emissivity which is equal to the absorptivity of surface 1 at T_1 for black radiation at T_2, α_{12}, by semi-gray assumption.

$\epsilon_2(T_1)$=emissivity which is equal to the absorptivity of surface 2 at T_2 for black radiation at T_1, α_{21}, by semi-gray assumption

$\epsilon_2(T_2)$=emissivity of surface 2 at T_2

λ'=a symbol defined as $\lambda'=H_{fg}+C_g(T_{vf}-T_{sat})$

μ_v=viscosity of saturated vapor, kg/m-hr

ρ=clad density, kg/m^3

ρ_l=liquid density, kg/m^3

ρ_v=vapor density, kg/m^3

σ=Stefan-Boltzmann constant, 5.6697×10^{-8} $W/m^2-°K^4$

ϕ=fraction of unevaporated water particles in fog flow

1. Introduction

PWRs are provided with an emergency core cooling system (ECCS) designed to deliver cooling water to the reactor core in the event of a postulated loss of coolant (LOCA) resulting from a pipe rupture up to and including the double ended failure of a main reactor coolant system pipe. The ECCS, consisting of pressurized accumulators and high and low pressure injection pumps, ensures that essential heat transfer geometry is preserved in the core, and also it prevents the maximum fuel clad temperature from reaching the prescribed maximum permissible temperature.

A large break LOCA has four characteristic stages; blowdown, refill, reflood and long term circulation. Blowdown starts with the assumed initiation of the LOCA and ends when the reactor system pressure falls to essentially that of the containment atmosphere. Refill starts at the end of blowdown and ends when the addition of emergency core cooling water fills the bottom of the reactor vessel and reaches the elevation of the bottom of the fuel rods. Reflood is defined as the time from the end of refill until the reactor vessel has been filled with water to the extent that core temperature rise has been terminated and core temperatures subsequently have been reduced to their long term steady-state levels associated with dissipating residual heat[1].

The quench phase, where rewetting of hot fuel cladding surfaces take place, is one of the most important physical process that must be modeled in a reactor safety systems code and this phase falls within the reflood phase of a LOCA. Cooling an overheated reactor fuel rod by the application of water requires that the water be in contact with the surface of the rod. However, if that surface is too hot, no contact is possible because of the presence of a steam film or calefaction effect that prevents the water from wetting the surface. The temperature at which the hot surface may wet has been called Leidenfrost, Calefaction, Sputtering, or Quench temperature.

And the velocity at which the quench front moves as a result of bringing the hot surface temperature below the sputtering temperature by the reflooded water has been variously called in the literatures, such as rewetting velocity, quench front velocity, and wet-front velocity.

Many investigations have been carried out to develop an analytical model that predicts the rewetting velecity by various workers[2–10] in the past. Close examinations of some analytical and experimental works[2,3,5,7], large-scale bottom flooding tests such as PWR Full Length Emergency Cooling Heat Transfer (PWR-FLECHT)[11], and the German work as reported by Blank et al.[12] show that precooling in the unwetted film-boiling region by the rising vapor and dispersed water droplets plays a dominant role during the transient period of reflooding. In the rewetting analysis of emergency core cooling, therefore, emphasis should be given to the precooling heat transfer in the unwetted region rather than simple liquid film cooling. For this purpose, the previous work was carried out and obtained a general explicit correlation that assigns a characteristic heat transfer coefficient to the unwetted film boiling region, as presented elsewhere[9].

The purpose of the present work is to extend the previous analytical work[9] : that is, the analysis of ϕ, which reflect the critical precooling mechanism for the wet-front velocity, is further extended using much more expansive PWR-ECCS (FLECHT) data[11] gathered by Westinghouse for U.S. Nuclear Regulatory Commission (NRC).

In addition, a modified Bromley's correlation[13] for the fog film boiling heat transfer coefficient, h_{df}, is derived and applied to the case of higher pressure conditions. Thus, the pressure range to which the rewetting velocity model[9] is applicable is also further expanded in this work.

2. Outline of the Rewetting Velocity Model

An attempt was made to obtain a general explicit correlation that assigns a characteristic heat transfer coefficient to the unwetted film boiling region as reported elsewhere[9]. The model is discussed in Ref. 9, and is not presented here in detail. Rather, the model is outlined as applied to the present extension work.

In the previous work[9], one-dimensional analysis of rewetting a vertical hot surface was carried out without neglecting heat transfer in the unwetted region and an explicit formula for the wet front velocity was presented.

The physical model consists of an infinitely extended vertical thin slab whose initial surface temperature is higher than the Leidenfrost point. During rewetting, three different regions of constant heat transfer coefficients are assumed : (1) the surface of the wetted region as characterized by a higher constant heat transfer coefficient (h_c), (2) the two regions of unwetted surface i.e., the fog-film region which is precooled via a lower heat transfer coefficient (h_{df}), and the superheated vapor film region which has a negligible heat transfer coefficient (h_{ds}).

The correlation employs a precooling parameter ϕ, which is the fraction of unevaporated water particles that constitutes the precooling fog-film ahead of the wet front. The wet front velocity, U, is given as[9]

$$U=\frac{b(h_c k\delta)^{\frac{1}{2}}(T_0-T_{sat})}{b\rho c\delta(T_w-T_{sat})-\phi[\rho_l A_l H_{fg}-b\rho c\delta(T_0-T_{sat})]} \quad (1)$$

Equation (1) may also be expressed in terms of fog-film length, l, as

$$U=\frac{1}{\rho c}\left(\frac{h_c k}{\delta}\right)^{\frac{1}{2}}\left(\frac{T_0-T_{sat}}{T_w-T_{sat}}\right)+\frac{h_{df}l}{2\rho c\delta}\left(\frac{T_w+T_0-2T_{sat}}{T_w-T_{sat}}\right) \quad (2)$$

Equation (2) conveys the physical meaning of each term more explicitly than other expressions. The first term on the right-hand side of Eq (2) represents the contribution of the heat transfer in the wetted region, while the second term denotes the precooling effect of the fog-film region on the wet-front velocity U. Thus, one may obtain the precooling effect on the rewetting velocity U in terms of percentage as follows:

$$\left(\begin{array}{l}\text{Percentage of Con-}\\ \text{tribution of Precool-}\\ \text{ing on the Wet-Fro-}\\ \text{nt Velocity } U\end{array}\right)=100\times\frac{\frac{h_{df}l}{2\rho c\delta}\left(\frac{T_w+T_0-2T_{sat}}{T_w-T_{sat}}\right)}{U} \quad (3)$$

Equation (3) is used to examine the precooling effect on the wet-front velocity.

The fog-film length, l, in Eqs. (2) and (3) is given by

$$l=\frac{2\phi[\rho_l A_l H_{fg}-b\rho c\delta(T_0-T_{sat})]U}{bh_{df}(T_w+T_0-2T_{sat})} \quad (4)$$

Also, note that Eq. (1) may be solved for ϕ as

$$\phi=\frac{b\rho c\delta(T_w-T_{sat})}{[\rho A_l H_{fg}-b\rho c} \frac{\left[U-\frac{1}{\rho c}\left(\frac{h_c k}{\delta}\right)^{\frac{1}{2}}\left(\frac{T_0-T_{sat}}{T_w-T_{sat}}\right)\right]}{\delta(T_0-T_{sat})]U} \quad (5)$$

3. Quantitative Analyses of Precooling Parameters

3.1 Precooling Parameters

In the above equations (1) and (2), one notes that the values of ϕ (or l and h_{df}) are needed in addition to T_0 and h_c to find the wet front velocity U. The values of k, ρ, c and δ may be deduced from the clad or tube material used and its thickness. T_w and T_{sat} are known from test parameters, while ρ_l and H_{fg} can be obtained from coolant properties. A_l may be obtained from the geometry of the coolant passage.

Notice that h_{df} appearing in Eqs. (2), (3) and (4) corresponds to the film boiling heat transfer coefficient. The knowledge of film boiling heat transfer coefficient is required to find fog-film lengths (l) from Eq, (4). This is also required to obtain the wet-front velocity if one wants to use Eq. (2) instead of Eq. (1).

Thus, prediction of the wet-front velocity from Eq. (1) requires a priori values of ϕ, whereas h_{df} and l are needed to obtain U from Eq. (2). However, l can be estimated from Eq. (4) if ϕ and h_{df} values are available.

3.2 A Formula for Film Boiling Heat Transfer Coefficient

The choice of a formula to be used in the evaluation of h_{df} depends largely on the fluid conditions that exist in the unwetted region. Amm and Ulrych[14] compared their measured heat transfer coefficients during reflooding a 340-rod bundle and those calculated from the existing heat transfer correlations. They found that the film boiling heat transfer coefficient is independent of length, but with a characteristic dimension about equal to the rod diameter substituted into the horizontal tube correlation, Bromley[13] equation gives a film boiling heat transfer coefficient for vertical tubes which is close to what is observed.

In the present work, to improve its accuracy Bromley's correlation[13] is modified as follows:

$$h_{df}=h_{co}+h_r \quad (6)$$

where

$$h_{co}=0.62\left[\frac{k_v 3\rho_v(\rho_l-\rho_v)g\lambda'}{D\mu_v(T_w-T_{sat})}\right]^{\frac{1}{4}} \quad (7)$$

and

$$h_r=\frac{\sigma}{(T_w-T_{sat})}\left[\frac{T_1^4}{\frac{1}{\epsilon_1(T_1)}+\frac{1}{\epsilon_2(T_1)}-1}-\frac{T_2^4}{\frac{1}{\epsilon_1(T_2)}+\frac{1}{\epsilon_2(T_2)}-1}\right] \quad (8)$$

λ' in Eq. (7) is defined as

$$\lambda'=H_{fg}+C_g(T_{vf}-T_{sat}) \quad (9)$$

where T_{vf} is the average temperature of the film given by

$$T_{vf}=\frac{T_w+T_{sat}}{2} \quad (10)$$

Equation (8) is obtained considering the radiation between two infinite semi-gray parallel plates. A semi-gray approximation is based on the assumption that the "absorptance of a surface" is equal to the emittance of that surface evaluated at the approximate black-body temperature of the incoming radiation. In terms of the properties used in Eq. (8), the "semi-gray" assumption is equivalent to $\alpha_{12}=\epsilon_1(T_2)$ and $\alpha_{21}=\epsilon_2(T_1)$.

To examine the applicability of Eqs. (6), (7) and (8) h_{co} and h_r are first computed using the experimental parameters at one atmospheric pressure conditions as reported by Case et al.[15]. The results are

$$h_{co}=136 \text{ Kcal}/hr\text{-}m^2\text{-}^\circ\text{C} \quad (11)$$

$$h_r=12 \text{ Kcal}/hr\text{-}m^2\text{-}^\circ\text{C} \quad (12)$$

and

$$h_{df}=148 \text{ Kcal}/hr\text{-}m^2\text{-}^\circ\text{C} \quad (13)$$

This value is then found slightly lower than the value reported by Case et al.[15] who obtained $h_{df}=172$ Kcal/hr-m^2-°C.

3.3 h_{df} at Higher Pressure Conditions

Since no experimental data for h_{df} in the range of 6.7 atmosphers (~100 psia) to 67.8 atmosphers (1,000 psia) are available, computational analyses of h_{co}, h_r and h_{df} at high pressure conditions were carried out using the above equations for selected experimental conditions used by Bennett et al.[16]. The results of analyses are shown in Table 1.

As can be seen in Table 1, the values of h_{co}, h_r and h_{df} evaluated from Eqs. (6), (7) and (8) are quite consistent and reasonable. These data may be used for h_{df} values at high pressure conditions in the absence of experimental data. It may be noted here that h_r values, in particular, are obtained under the following assumptions;

(1) The fog-film and the liquid envelope that exists between the concentric cylinders is transparent to the thermal radiation. That is, only the radiations between the two surfaces of the tube walls are considered.

(2) Both walls are assumed to be at constant temperatures of T_1 (heater rod initial temperature) and T_2 (outer tube is assumed to be at the saturation temperature corresponding to the system pressure).

3.4 Quantitative Analyses of ϕ, l and Precooling Effect Using PWR-FLECHT Data.

Previous analyses of precooling parameters[9] were carried out using the experimental data for bottom flooding at atmospheric pressure conditions as reported by Case et al.[15]. In the present work, analyses of precooling parameters are further extended using much more expansive data collected by Westinghouse for U.S. NRC[11].

Table 1. Results of Analyses for h_{co}, h_r, and h_{df}

Run No. (Ref. 16)	Presure (atm)	m_c (kg/hr)	T_w (°C)	T_o (°C)	T_{sat} (°C)	U (m/hr)	h_{co} (Kcal/hr-m^2-°C)	h_r (Kcal/hr-m^2-°C)	h_{df} (Kcal/hr-m^2-°C)
5609	67.8	38.6	454	392	285	208.5	635.6	7.7	643.3
5613	67.8	38.3	441	392	285	241.4	637.4	7.4	644.8
5612	67.6	38.1	428	392	285	307.2	638.8	7.0	645.8
5607	67.7	38.6	423	392	285	340.2	640.4	7.0	647.4
5598	33.8	36.1	463	357	242	120.7	442.6	7.1	449.7
5596	33.8	36.1	439	357	242	153.6	447.0	6.6	453.6
5595	33.8	36.3	430	357	242	175.6	448.8	6.4	455.2
5594	33.9	36.3	416	357	242	208.5	452.0	6.2	458.2
5593	33.9	35.8	409	357	242	219.5	453.7	6.0	459.7
5592	34.0	35.8	393	357	242	296.3	458.5	5.7	464.2
5558	20.6	37.4	439	321	214	109.7	354.7	6.2	360.9
5602	20.4	38.6	427	321	214	120.7	357.2	6.0	363.2
5556	20.8	37.6	417	321	214	131.7	359.7	5.8	365.5
5584	20.4	36.3	404	321	214	153.6	362.9	5.5	368.4
5616	20.4	38.8	392	321	214	175.6	366.1	5.3	371.4
5582	20.4	36.3	373	321	214	230.4	372.4	5.0	377.4
5630	13.6	37.6	390	292	194	120.7	312.6	5.0	317.7
5631	13.8	37.4	385	292	194	142.7	314.1	5.0	319.1
5635	13.6	37.4	379	292	194	142.7	315.8	4.8	320.6
5629	13.6	37.6	355	292	194	186.5	324.3	4.5	328.8
5634	13.6	37.4	337	292	194	230.4	331.7	4.2	335.9
5623	6.8	37.9	367	259	164	109.7	259.2	4.4	263.6
5622	6.8	37.9	352	259	164	131.7	263.5	4.1	267.6
5621	6.8	37.9	329	259	164	164.6	270.7	3.8	274.5

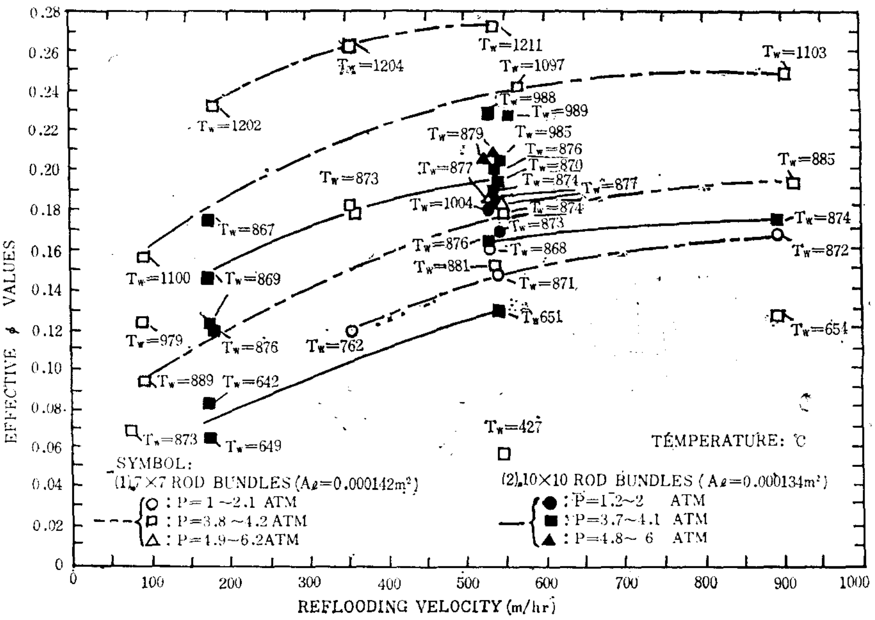

Fig. 1. Variation of Effecitve ϕ with Reflooding Velocity (U_c)

Table 2. Results of Analyses for ϕ, l, and Effect of Precooling on U (PWR-FLECHT Data for Bundle size 7×7)

Run No. (Ref.11)	T_w (°C)	P (atm.)	T_0 (°C)	T_{sat} (°C)	U_c (m/hr)	U (m/hr)	Effective ϕ	l (m)	Precooling Per Cent
0610	761.7	1	487	100	530.4	63.1	0.120	0.20	71.3
0711	871.1	1	500	100	539.5	63.1	0.147	0.22	74.5
0812	1003.9	1	449	100	539.5	63.1	0.180	0.26	80.5
0913	871.7	1	541	100	896.1	107.9	0.167	0.41	83.7
1615	867.8	2	446	121	530.4	63.1	0.160	0.21	79.0
0105	427.2	3.8	387	142	548.6	87.8	0.056	0.20	70.2
1002	873.9	3.8	431	142	548.6	86.9	0.179	0.33	86.2
1314	873.3	3.9	533	143	530.4	101.5	0.179	0.34	84.0
6155	1211.1	3.9	483	143	539.5	84.1	0.272	0.35	88.5
6047	1096.7	3.9	456	143	566.9	86.9	0.241	0.36	88.5
7057	872.8	3.9	516	144	73.2	22.9	0.068	0.03	32.0
5948	888.9	3.9	498	144	91.4	25.6	0.094	0.05	43.4
0307	654.4	3.9	442	144	896.1	131.7	0.126	0.44	86.5
0509	1102.8	3.9	425	144	905.3	103.3	0.249	0.45	91.4
6351	979.4	4.0	490	144	91.4	25.6	0.123	0.06	50.7
6553	1100.0	4.0	497	144	91.4	25.6	0.156	0.06	56.1
408	885.0	4.0	425	144	914.4	128.9	0.192	0.52	91.0
6658	1201.7	4.1	482	145	182.9	40.2	0.232	0.14	75.8
6256	1203.9	4.1	448	145	356.6	64.9	0.263	0.27	86.6
1720	880.6	4.2	423	145	539.5	40.2	0.150	0.13	71.4
1116	877.2	5.0	462	152	548.6	87.8	0.181	0.32	85.2
1417	877.2	6.1	439	160	530.4	90.5	0.185	0.35	86.9

The variation of effective ϕ with U_c for various T_w, as obtained from selected exprimental points from PWR-FLECHT[11] data, is shown in Fig. 1. Following observations may be made from Fig. 7 : (1) An excellent correlation exists between ϕ and U_c for a given T_w, A_t and cladding material. (2) ϕ increases as U_c increases for a given T_w, A_t and cladding material.

The results of analyses for ϕ, l and precooling effect, on the other hand, are presented in Tables 2 and 3. The data used were for runs with stainless-steel cladding at constant flooding rates and without flow blockage.

Effective ϕ values listed in Tables 2 and 3 are obtained using Eq. (5), while fog-film lengths (l) are found employing Eq. (4) and computed ϕ values. Precooling effect on the wet front velocity is obtained from Eq. (3).

4. Discussion of the Results

4.1 Conclusions Deduced from Table 1

Following results may be deduced from the results of Table 1 :

(1) In general, for a given initial hot clad surface temperature (T_u) and the reflooding flow rate (m_c), both the values of heat transfer coefficients (h_{co}, h_r and h_{df}) and the wet-front velocity increase as the system pressure increases.

(2) For the initial hot clad surface temperature ranges between 329°C and 454°C, the contribution of radiation heat transfer coefficient (h_r) is less than two percent of the film-boiling heat transfer coefficient (h_{df}).

4.2 Remarks on the Precooling Parameters Analyses

Quench front velocities shown in Tables 2 and

Table 3. Results of Analyses for ϕ, i, and Effect of Precooling on U (PWR-FLECHT Data for Bundle Size 10×10)

Run No. (Ref. 11)	T_w (°C)	P (atm.)	T_0 (°C)	T_{sat} (°C)	U_c (m/hr)	U (m/hr)	Effective ϕ	l (m)	Precooling Per Cent
5231	872.8	1.2	284	106	539.5	38.4	0.169	0.16	81.6
5332	873.3	1.9	392	119	539.5	68.6	0.180	0.26	83.9
5123	875.0	3.7	432	142	173.7	26.5	0.121	0.06	54.5
3920	875.6	3.7	396	142	530.4	40.2	0.162	0.14	73.7
3440	651.1	3.7	416	142	540.0	101.5	0.129	0.34	83.9
4718	876.7	3.7	401	142	540.0	64.0	0.183	0.24	83.2
5019	873.9	3.7	415	142	896.1	55.8	0.175	0.20	79.6
4027	866.7	3.9	378	143	173.7	50.3	0.174	0.19	80.3
3823	648.9	3.9	415	143	173.7	28.4	0.064	0.05	42.2
3724	641.7	3.9	421	143	173.7	37.5	0.082	0.08	54.7
3541	870.0	3.9	400	143	540.0	92.4	0.193	0.37	88.3
4526	875.6	3.9	454	143	540.0	121.6	0.200	0.47	89.4
3642	985.0	3.9	429	143	540.0	75.9	0.220	0.30	86.4
4321	873.3	4.0	434	144	356.6	64.9	0.180	0.23	81.3
4225	868.9	4.0	426	144	173.7	34.8	0.145	0.10	65.9
4442	989.4	4.0	429	144	530.4	88.7	0.227	0.36	88.4
4628	874.4	4.0	458	144	540.0	92.4	0.192	0.34	85.8
4129	868.9	4.1	454	145	173.7	29.3	0.123	0.07	55.5
5642	988.3	4.1	408	145	530.4	87.8	0.228	0.37	89.2
5433	878.9	4.8	431	151	540.0	107.9	0.201	0.43	89.2
5534	878.9	5.7	468	157	540.0	121.6	0.205	0.47	89.2

3 are the average velocities computed from the quench time of the hot rod midplane elevation (6-foot) listed in the Table 3-1 of the PWR-FLECHT report[11]. With respect to the PWR-FLECHT data analyses, it is important to note the following:

(1) The wet front velocity formula Eq. (1) is applicable for axially uniform initial wall temperature distribution. In the case of PWR-FLECHT test, however, the axial peak to average power varied from 1.6 (at 6-foot elevation) to zero (at both ends). On the other hand, examination of the available data in the PWR-FLECHT report shows that ratios of the average initial wall temperature $(T_w)_{avg}$ to the maximum initial wall temperature $(T_w)_{max}$ vary from 1.28 to 1.47.

(2) An approximate method of taking the effect of axial cosine power distribution into account is to use the average initial wall temperature $(T_w)_{avg}$ as a uniform initial wall temperature T_w. However, T_w values shown in Fig. 1 are the initial wall temperature of the midplane. Also, values of T_w used in the analyses of ϕ are the initial temperatures of the hot rod midplane elevation which correspond to the points of axial peak power. Hence, in order to obtain a proper ϕ values for any uniform initial wall temperature T_w from Fig. 1 it is necessary to reduce the T_w values shown in the figure by dividing by the ratio of $(T_w)_{at\ 6ft}/(T_w)_{avg}$.

(3) The temperature rise, ΔT_{rise}, in the PWR-FLECHT report is defined as the difference between the intial clad temperature (i.e, the clad temperature at the start of flooding) and the first peak temperature, and /or the second peak temperature. FLECHT

data shows that the first temperature rise varies from 5 to 296°C and that this temperature rise decreases in magnitude with increase in flooding flow rate (m_c). To take the effect of this temperature rise into account, one may use the higher initial wall temperature by an amount of ΔT_{rise} than the actual T_w. This factor may offset the effect to be considered for the cosine power distribution.

Table 4. Physical Properties and Test Parameters for Each Bundle Size [11]

Bundle Size	7×7	10×10
Inside Dimensions of Square Flow Housing, m	0.11×0.11	0.15×0.15
Heater Diameter, *m*	0.01	0.01
Approximate Coolant Flow Area Per Unit Heater Rod (A_l), m^2	1.4×10^{-4}	1.3×10^{-4}
Perimeter of the Heater (b), *m*	3.4×10^{-2}	3.4×10^{-2}
Thickness of the wall (δ), *m*	6.1×10^{-4}	6.1×10^{-4}
ρ(for Type 347 S.S), kg/m^3	7818	7818
C, Kcal/kg−°C	0.11	0.11
k, Kcal/*hr-m*-°C 19.05	19.05	19.05

(4) The physical properties and test parameters used in the analyses of ϕ, l and others are summarized in Table 4.

4.3 Indications of Fig. 1 and Tables 2 and 3

Following observations may be made from Fig. 1 :

(1) ϕ increases with increase in the reflooding velocity U_c for a given T_w which is in complete agreement with the previous results[9].

(2) For a given U_c, ϕ increases with increase in T_w. This result agrees with the physical reasoning. The rate of vaporization depends on T_w and the system pressure.

For a given pressure, the rate of vaporization increases with increase in T_w. Hence, ϕ is a strong function of T_w and it increases with increase in T_w since the greater amount of vapor is produced at higher T_w to form an effective precooling fog-film.

With respect to the results of analyses of various precooling parameters using PWR-FLECHT data[11] shown in Tables 2 and 3 the following interpretations may be made:

(1) The range of computed effective ϕ values varies from 0.056 to 0.272. In general, ϕ increases as U_c increases.

(2) Computed fog-film length (l) also increases with increase in reflooding rate U_c.

(3) Percentage of the contribution of precooling effect on the wet-front velocity increases with increase in U_c and T_w.

5. Conclusions

Application of the rewetting velocity model presented elsewhere[9] requires a priori values of ϕ. In the absence of ϕ values h_{df} and l data are needed.

To provide these informations, a modified Bromley's correlation is first derived, and h_{df} values at higher pressure conditions are obtained using the modified Bromley's equation for selected experimental conditions reported by Bennett et al.[16].

In addition, the precooling parameters of the rewetting velocity model, such as ϕ and l are determined using PWR-FLECHT data[11] which agree well with the previous results[9] based on the data of Case et al.[15]. Thus, it is concluded that Eq(1), which assumes a significant precooling effect in the fog-film region immediately ahead of the rewet (quench) front, may now be used to compute the rewetting velocity with the fuller knowledge of precooling parameters such as ϕ, h_{df} and l.

That is, the applicable range of the rewetting velocity model presented elsewhere[9] is further expanded in the present work.

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