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Dryout in annular flow – theoretical analysis

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Abstract In the paper a two-equation model of mass balance of liquid in the film and in the core for calculation of dryout at high vapour quality is modified from the earlier version presented by Sedler and Mikielewicz [1]. Additionally, the mass balance equation for the liquid film contains a modified evaporation term. Modified is the heat flux density applied in evaporation of liquid film which now is variable within film thickness. The solution of such equations requires prior knowledge of rates of deposition and entrainment. The theoretical determination of there quantities involves serious difficulties. The relations for determination of deposition and entrainment rate are taken therefore from Okawa et al. [3]. The results of calculations are validated against experimental data of Sedler and Mikielewicz [1], showing a satisfactory consistency.

Keywords: Dryout; Annular flow; Flow boiling

Nomenclature

C	–	droplet concentration in core
d	–	tube diameter
D	–	deposition, diffusion coefficient
E	–	entrainment
f	–	friction factor
g	–	gravitational constant
G	–	mass velocity

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h – enthalpy
J – superficial velocity
k – mass transfer coefficient
P – pressure
Re – Reynolds number, (G d)/μ
Sc – Schmidt number, ν/D
q – heat flux
z – length
x – quality

Greek symbols

δ – thickness of liquid film
ρ – density
μ – dynamic viscosity
ν – kinematic viscosity
π – non-dimensional number
σ – surface tension

Subscripts

b – boiling
cr – critical
d – deposition
e – entrainment
eq – equilibrium
g – gas
i – interface
l – liquid
LF – liquid film
LE – liquid droplets
lv – liquid-vapour
t – initial
w – wall

1 Introduction

The phenomenon of critical heat flux occurs in different technical applications just to mention nuclear reactors, steam generators, evaporators in refrigeration technology or air-conditioning. Recently a huge area for possible applications can be found in micro-channel heat sinks, Qu and Mudawar [4]. From amongst a number of mechanisms triggering the critical heat flux the two can be named more precisely, namely the first one when the vapour film can be formed between the continuous liquid phase and the heating wall. Such case is often called the departure from nucleate boiling (DNB). The second mechanism is the disappearing liquid film at the wall due to its evaporation. In the latter case the wall surface is exposed to vapour phase and such a mode of critical heat flux is named the dryout. That type of critical heat flux will be a topic of considerations in the paper. In both mentioned above cases wall temperature suddenly increases and a severe impairment of heat transfer coefficient is observed as the wall is covered merely by vapour, Kandlikar [5].

Annular flow is one of the most often encountered two-phase flow patterns in which a wide range of vapour quality can be found. Transition from annular flow to the mist flow in most cases involves passing through the dryout conditions. For that reason accurate method of prediction of the dryout process is of particular importance from the engineering point of view. Detailed measurements of entrainment and deposition processes enabled development of theoretical models for the above process and eventually the models based on the mass balance equations, which found significant appreciation in engineering practice.

The film flow analysis is one of the successful prediction methods of the dryout in flow boiling. Most approaches so far used the mass balance equation for the liquid film with appropriate formulations for the rate of deposition and the rate of entrainment. The first approach to such modeling was postulated by Whalley et al. [2]. Other implementations of that approach have been described by Okawa et al. [3, 8] and Celata [9]. The one equation model for balance of mass in the film constitutes from the contributions coming from deposition of droplets on the film, entrainment of droplets from the film and evaporation of liquid from the film. Such equation can be integrated from the point of the onset of annular flow (assumed arbitrarily). It must be acknowledged that any discrepancy in determination of deposition and entrainment rates, together with cross-correlations between them, renders loosing of accuracy of model predictions. There are no direct methods for calculation of deposition and entrainment rates and only empirical correlations are available. Sedler and Mikielewicz [1] postulated a two-equation analytical model where the balance equation in the film is supplemented with the mass balance equation for entrained droplets in the core. Such approach is more general, as two variables, namely the mass velocity of film and mass velocity of droplets are solved by two independent equations. In many approaches to modeling dryout, which are basing on a mass balance equation of the film, there can be found a term in which the ratio of entrained droplets with respect to the amount of liquid is used. Such parameter is adjusted based on experimental data. The approach presented by Sedler and Mikielewicz can, amongst the others, model directly such term. The original model due to Sedler and Mikielewicz [1] provided analytical solutions of liquid film distribution, whereas in the present case more complex solutions have been obtained. Originally it was assumed that the rate of deposition D is proportional to the flow rate of entrained droplets in the core, whereas the rate of entrainment E was also proportional to the flow rate of liquid in the film. Such assumption enabled to find very simple analytical solution of liquid film flow rate distribution. That distribution was similar in form to the relation determined experimentally by Silvestri, which agreed very well with experimental data, Cumo et al. [10]. In the present paper a two-equation model, developed earlier by Sedler and Mikielewicz [1] is revisited with new correlations for deposition and entrainment rates of liquid. Additionally, in the present work the amount of heat used for evaporation of film has been modified to yield a more precise distribution as only the interface heat flux takes part in the evaporation process. The predictions using the model have been compared with experimental data due to Sedler and Mikielewicz [1].

2 The two-equation model of dryout

Let's consider a two-phase annular flow with a specified mass flow rate in the circular channel with inner diameter d. The liquid film covers the channel wall whereas vapour flows in the core with entrained droplets of liquid (Fig. 1). The beginning of the annular flow pattern is assumed to be known. Entire disappearance of liquid film on the wall is assumed as a criterion for the occurrence of flow boiling crisis. It ought to be however noted that experimental observations point out that prior to complete evaporation of liquid film the dry patches are formed on the wall and liquid is split into rivulets. Heat transfer is deteriorated despite the fact that some liquid is still present on the wall. In the present study, however, only an abrupt change of liquid film disappearance will be considered, i.e. without rivulets.

The process under scrutiny here is accompanied by the droplet entrainment from the film surface, E, and the droplet deposition onto the film surface, D. In a simple case of steady state with constant properties, the axial variation of film flow rate and droplets flow rate in the core assumes the form:

$$\frac{dG_{LF}}{dz} = \frac{4}{d}\left(D - E - \frac{q_i}{h_{lv}}\right), \tag{1}$$

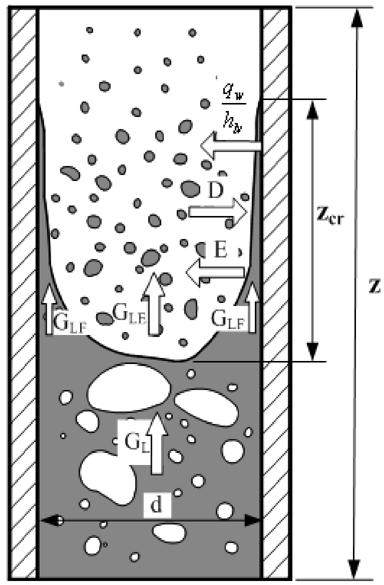

Figure 1. Schematic view of annular flow with boiling.

$$\frac{dG_{LE}}{dz} = \frac{4}{d}\left(-D + E\right). \tag{2}$$

Additionally, the balance of mass gives:

$$G = G_{LF} + G_{LE} + G_g. \tag{3}$$

Equation (3) is included here to make sure that the total mass balance is conserved, and enabling in such way calculation of the flow rate of gas, G_g. Additionally, the interface mass flux due to evaporation from the film surface is modified. In all up to date theoretical studies the mass flux taking part in the evaporation process was equal to:

$$m_v = \frac{q_w}{h_{lv}}. \tag{4}$$

In Eq. (4) q_w denotes the heat flux at the wall. Such approach is not exactly true, as the core of the flow is supplied with vapour produced by an action of interface heat flux. In case where the thickness of the liquid film is larger that effect can be of significance. Only in cases of very thin films such assumption that the wall heat flux is responsible for entire evaporation is allowable. Therefore in the present study the modified value of heat flux is used, which can be obtained from the solution of energy equation:

$$u\frac{\partial T}{\partial z} = \frac{1}{\rho c_p}\frac{\partial q}{\partial r}. \tag{5}$$

That leads to the following distribution of heat flux, yelding the interface heat flux:

$$q_i = q_w\left(1 - \frac{2\delta}{d}\right). \tag{6}$$

The set of equations (1-3) can be integrated from the commencement of annular flow to the location where liquid evaporates completely. That corresponds to dryout. The film flow at any axial point can be calculated, provided initial values of all parameters are known. In order to carry out such calculations with reasonable precision we require correlations for the vapour quality and entrainment fraction at the starting point of annular flow, rates of deposition, entrainment and vaporization and finally the film flow rate at the onset of dryout. Correlations for modeling of deposition and entrainment rated for that purpose have been taken from Okawa et al. [3]. The closure relations used for the calculations have been briefly outlined below.

Denoting the concentration of droplets in the gas core by C and the deposition mass transfer by k_d, the rate of droplet deposition, D, can be calculated from:

$$D = k_d \cdot C. \tag{7}$$

The concentration of droplets can be determined from:

$$C \cong E_{eq}\rho_l \frac{J_l}{J_g}^n, \tag{8}$$

where n is an experimentally fitted constant (assumed in the present study as unity) and E_{eq} denotes the entrainment in the equilibrium state, Okawa et al. [8].

The mass transfer coefficient, k_d, can be determined from the empirical correlation presented by Sugawara (Okawa et al. [3]):

$$\frac{k_d}{J_g} = 0.009 \cdot \left(\frac{C}{\rho_g}\right)^{-0.5} \cdot \mathrm{Re}_g^{-0.2} \cdot \mathrm{Sc}^{-\frac{2}{3}}. \tag{9}$$

Most of contemporary approaches assume that droplet entrainment (E) consists of the breakup of roll waves due to interfacial shear force (E_{ew})

and boiling in the liquid film (E_{eb}). Okawa [11] developed the following correlation for the rate of entrainment due to breakup of roll waves:

$$E_{ew} = k_E \cdot \rho_l \pi_E \cdot \left(\frac{\rho_l}{\rho_g}\right)^n , \tag{10}$$

where

$$\pi_E = \frac{f_i \cdot \rho_g \cdot J_g^2 \cdot \delta}{\sigma} . \tag{11}$$

Relation (10) has coefficients k_E and n developed for different values of parameter π_E. According to Okawa et al. [8] values of coefficients k_E and n assume following values:

- for $\pi_E < 0.0675$, $k_E = 3.1 \cdot 10^{-2}$ and $n = 2.3$,
- for $0.0675 < \pi_E < 0.295$, $k_E = 1.6 \cdot 10^{-3}$ and $n = 1.2$,
- for $\pi_E > 0.295$, $k_E = 6.8 \cdot 10^{-4}$ and $n = 0.5$.

The term E_{ew} in Eq. (10) is "active" in cases when Re_l >320 as the roll wave cannot be formed in the case of smaller Reynolds numbers. The film thickness δ present in Eq. (11) can be estimated from the force balance between interfacial shear force and wall friction force acting on a liquid film, Okawa et al. [3]:

$$\delta = \frac{1}{4} \cdot \sqrt{\frac{f_w}{f_i} \cdot \frac{\rho_l}{\rho_g}} \cdot \frac{J_l}{J_g} \cdot d \, . \tag{12}$$

Values of wall and interface friction factors are determined from relations:

$$f_i = 0.005 \cdot \left(1 + 300 \cdot \frac{\delta}{d}\right) , \tag{13}$$

$$f_w = \max\left(\frac{16}{\mathrm{Re}_f}, 0.005\right) . \tag{14}$$

Entrainment rate due to boiling, E_b, is estimated using the empirical correlation due to Ueda, Okawa et al. [3]

$$E_{eb} = c_{eb} \left(\frac{q_w}{h_{lv}}\right)^{2.5} \left(\frac{\delta}{\sigma \rho_g}\right)^{0.75} , \tag{15}$$

where the proportionally factor c_{eb} depends on fluid and the value of 477 is recommended for water.

As little is known about the non-linear relation between the shear and boiling induced entrainments and hence the total entrainment rate is constituted using the linear superposition:

$$E = E_{ew} + E_{eb}. \tag{16}$$

Tests were also attempted on geometric superposition of entrainment contributions, however it did not lead to improvements in predictions of dry-out [13].

An important issue is appropriate determination of initial parameters in the calculation procedure. In one of the most popular approaches to detect that moment is the expression suggested by Celata et al. [9] where the beginning of the annular flow starts at the location where the superficial velocity of vapour exceeds a value given by the following relation:

$$J_g \geq \left(\frac{\sigma \cdot g \cdot \Delta\rho}{\rho_v^2}\right)^{0.25} N_{\mu_l}^{-0.2}, \tag{17}$$

where

$$N_{\mu_l}^{=} \left(\frac{\rho_l \cdot \sigma}{\sqrt{\sigma / g \cdot \Delta\rho}}\right)^{-0.5}. \tag{18}$$

The initial entrainment rate, E_t, is calculated from, Okawa et al. [3]:

$$\frac{E_t}{1 - E_t} = \frac{1}{4} \frac{k_E}{k_d} \cdot \frac{\sqrt{f_i f_w} \sqrt{\rho_g \rho_l} J_g^2 d}{\sigma} \cdot \left(\frac{\rho_l}{\rho_g}\right)^n. \tag{19}$$

Recommended value for the exponent n is 0.111.

Calculations were carried out using the fourth order Runge-Kutta scheme for solving a system of ordinary differential equations implemented in Mathcad11. A constant stepsize version of the procedure has been chosen. At each marching step of the length dz the values of mass velocity are calculated and consequently values of deposition and entrainment rates were updated.

3 Results and calculations

The verification of the model was performed based on the comparison with experimental data obtained by Sedler and Mikielewicz [1]. These experiments were performed with R21 as a working fluid. Measurement section was made of stainless steel with internal diameter of 8 mm and a length of 4.22 m. The tests were performed with initial pressures of 5.5, 10.6 and 15.0 bar and mass flows ranging from 1000 to 3500 kg/(m^{2}s). As a result of data reduction the relation between critical vapour quality x_{cr} and the boiling length z_{cr} was established. The duration of boiling was determined from the heat balance since the initiation of annular film boiling. The data is presented in Tab. 1.

Good consistency of the results obtained from the model proposed by the authors with the experimental data can be observed, see Figs. 2 and 3.

It is also worth noting, that suggested correction for the distribution of the heat flux also contributes to a better consistency between theoretical results and those from the experiments. For the sake of comparisons, Tab. 1 contains the results obtained from calculation using the single-equation model, where only the balance equation of liquid in the film was considered, and all other correlations were used in the two-equation model considered here.

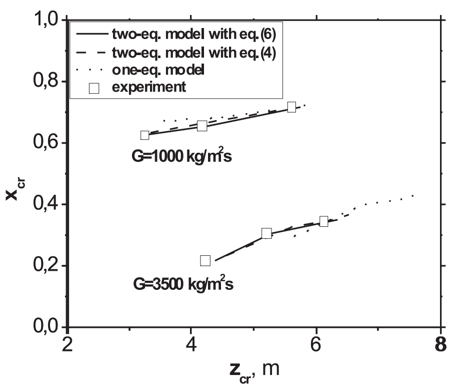

Figure 2. Calculation and experimental results for pressure $P = 5.5$ bar.

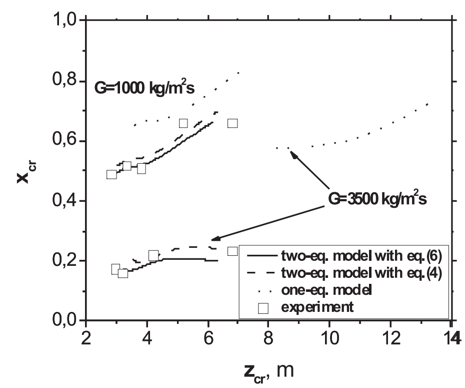

Figure 3. Calculation and experimental results for pressure $P = 15$ bar.

The results of calculation lead to a conclusion that the two-equation model with variable interface heat flux density is superior to all other models, i.e. the two-equation model without variable heat flux distribution and one-equation model. The assumption of a constant heat flux density applied to the evaporation term is only justified in the case of very thin films. In all other cases the amount of heat taking part in evaporation process varies with respect to the liquid film thickness, which is revealed in

Table 1. Input data and calculation.

P	G	q_w	Calculation based on two-equation model with Eq. (6)		Calculation based on two-equation model with Eq. (4)		Calculation based on one-equation model		Experiment [1]	
			x_{cr}	z_{cr}	x_{cr}	z_{cr}	x_{cr}	z_{cr}	x_{cr}	z_{cr}
bar	kg/(m^{2}s)	W/m^2	–	m	–	m	–	m	–	m
5.5	1000	79720	0.62	3.319	0.637	3.337	0.673	3.538	0.63	3.24
		65050	0.66	4.246	0.667	4.283	0.685	4.459	0.66	4.16
		52710	0.72	5.739	0.725	5.749	0.728	5.909	0.72	5.60
	1750	82860	0.44	3.926	0.450	3.976	0.501	4.419	0.44	3.81
		86700	0.59	5.057	0.605	5.113	0.642	5.474	0.595	6.40
	3500	74990	0.22	4.387	0.233	4.555	0.297	5.659	0.22	4.21
		85550	0.31	5.294	0.325	5.571	0.395	6.685	0.31	5.20
		82070	0.35	6.340	0.366	6.540	0.431	7.668	0.35	6.12
10.6	1000	80670	0.51	2.412	0.531	2.466	0.641	2.843	0.51	2.32
		65690	0.61	3.380	0.623	3.557	0.708	3.921	0.605	3.38
		43910	0.67	5.812	0.683	5.833	0.722	6.062	0.670	5.60
		40500	0.64	6.017	0.652	6.034	0.688	6.258	0.64	5.89
	1750	80790	0.40	3.325	0.425	3.451	0.551	4.223	0.40	3.18
		71520	0.49	4.594	0.515	4.733	0.630	5.524	0.49	4.40
		81300	0.44	3.634	0.467	3.769	0.595	4.558	0.44	4.61
		44010	0.45	6.950	0.477	7.118	0.567	8.013	0.455	6.64
	3500	72850	0.24	4.595	0.277	4.996	0.507	7.896	0.245	4.32
		77440	0.29	5.102	0.327	5.547	0.568	8.461	0.290	4.81
		52260	0.26	6.846	0.298	7.480	0.628	12.746	0.260	6.39
15.0	1000	58730	0.49	2.953	0.517	3.023	0.652	3.591	0.49	2.82
		52840	0.52	3.482	0.546	3.554	0.675	4.167	0.52	3.32
		45360	0.51	3.989	0.536	4.061	0.658	4.749	0.51	3.80
		38580	0.66	6.070	0.695	6.194	0.840	7.147	0.66	5.19
		37760	0.66	6.206	0.696	6.340	0.843	7.326	0.66	6.81
	1750	50740	0.35	4.381	0.394	4.666	0.674	7.255	0.35	4.08
		48310	0.41	5.388	0.459	5.723	0.736	8.340	0.41	5.02
		47600	0.51	6.721	0.554	7.008	0.750	8.626	0.515	6.40
	3500	69940	0.17	3.222	0.205	3.518	0.578	8.266	0.175	2.95
		59330	0.16	3.493	0.187	3.794	0.579	10.685	0.160	3.19
		61970	0.22	4.548	0.257	4.995	0.723	13.232	0.220	4.20
		41000	0.20	6.330	0.235	6.887	0.998	27.620	0.235	6.78

the modified model. This indicates that the suggested two-equation model offers much wider possibilities than the single equation model. It is, however, very important in the calculations to appropriately split the quantity of liquid into film and droplets in the core. In the calculations presented here, the initial ratio of the liquid in the film was established by trial and error in such a way as to achieve the same critical quality as in the Sedler and Mikielewicz experiment. All other remaining parameters resulted from calculations. As presented, the estimated length at which the liquid film dries out is only slightly higher than the experimental value confirming the fact that deposition and entrainment rates are correctly calculated. When compared to the results of the model, where the distribution of the heat flux is not considered, the results from the model with the heat flux distribution are better. In addition, when compared to the one-equation model, the two-equation model with the heat flux distribution in the equation of liquid balance in the film gives much better results. This is especially visible when analysing series of measurements performed at the highest mass flow velocities. In these cases the discrepancies can reach even two hundred percents.

In the course of examination of the model carried out were also sensitivity studies of the influence of the splits between the amount of liquid film and entrained liquid droplets. For that purpose a case at a total flow rate $G = 1000$ kg/m^{2}s was selected. The results of calculations of respective mass flow rates of liquid in the film with respect to quality are presented in Fig. 4. We can see from the graphs that in the initial length there is a sudden drop in the liquid film flow rate, much steeper than in further flow development. That is due to variable distribution of the interface heat flux, the distribution of which has been presented by Eq. (6). As a result we can justify the fact that appropriate selection of the split between the amount of liquid film and entrained liquid droplets leads to more accurate calculation of dryout, namely the critical quality. The dependence between the liquid film flow rate and resulting quality after complete evaporation ($G_{LF} = 0$) is quite strong.

In the frame of this paper the comparisons have also been made with a well established empirical correlation due to Katto and Ohno [12] for the prediction of dryout. The results of comparisons have been presented in Figs. 5 and 6. A very good consistency between the results obtained using a postulated model and correlation can be seen.

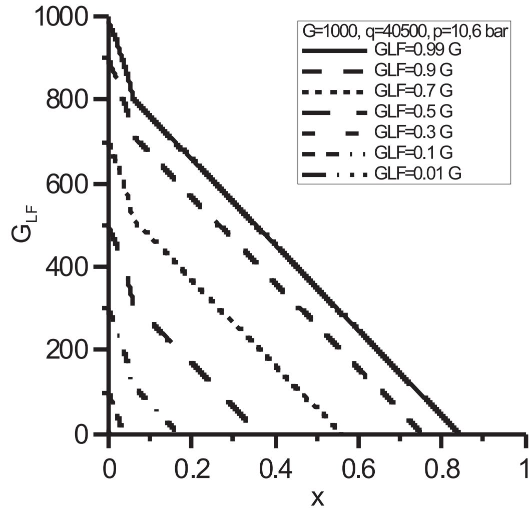

Figure 4. Simulation of experimental data for a mass flow rate of liquid $G = 1000\ \mathrm{kg\,m^{-2}s^{-1}}$.

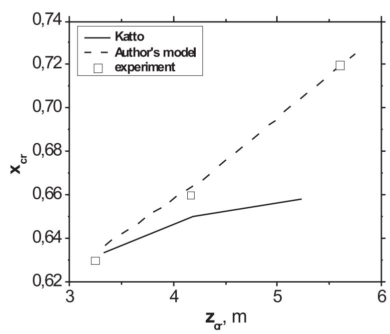

Figure 5. Calculation, experimental data and Katto and Ohno formula [12] for pressure $P = 5.5$ bar.

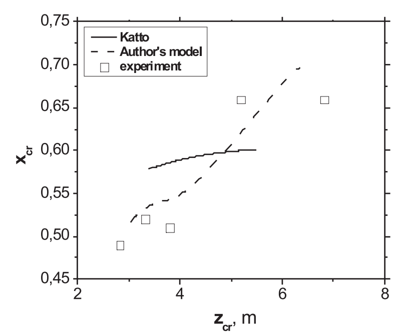

Figure 6. Calculation, experimental data and Katto and Ohno formula [12] for pressure $P = 15$ bar.

4 Conclusions

In the paper a model of dryout in annular flow which is based on a solution of two balance equations of liquid film and entrained droplets is presented. The mass balance equation for the film contains also a modified evaporation term. The solution is obtained in a numerical way by integration of arising balance equation. The results of calculations have been compared against experimental data for R21 due to Sedler and Mikielewicz [1]. The critical issue in determination of the dryout process is appropriate optimal initial split of the flow into the film flow and entrained liquid droplets flow. Much more efforts are required into modelling of such split of liquid flow to devise appropriately the beginning of annular flow, which is crucial for subsequent calculations. The criterion provided by Celata et al. [6] described by Eq. (17) does not predict the beginning of annular flow correctly, however is of a great indicative value. Manual adjustments are required to set correct values of G_{LE} and G_{LF}. Another crucial issue is modelling of distribution of liquid film thickness in the flow. Also here the simple and accurate models of devising the film thickness are required. It ought to be noted that correlations describing rates of entrainment and deposition were developed for the case of water and applied here to the case of refrigerant R21, which in the light of satisfactory results confirms generality of the model.

It should be mentioned that initial model of Sedler and Mikielewicz [1] was verified by the experiments provided in the channel of large diameter (d = 8 mm). Recently the authors have new aims related to adaptation of two-equations model to the dryout process in the small diameter tubes. In parallel there are conducted the experimental investigations with tubes of 5.2, 2.3 and 1.15 mm inside diameter. The results will be presented in due time. The two-equation model of dryout can be further modified. That can be done by incorporation of momentum equation into analysis. That would provide a better distribution of the film thickness instead of using empirical correlations in calculations of film thickness, whilst still preserving a relatively simple form of the model, i.e. the form of ordinary differential equations.

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