PERGAMON

International Journal of Heat and Mass Transfer 46 (2003) 139–148

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Boiling curve in temperature wave region

B.A. Gabaraev [a], S.A. Kovalev [b], Yu.S. Molochnikov [a], S.L. Soloviev [a,*], S.V. Usatikov [b]

[a] *Research and Development Institute of Power Engineering (RDIPE), P.O. Box 788, Moscow 101000, Russia*

[b] *Institute for High Temperatures, RAS, Moscow 127412, Russia*

Received 15 June 2001; received in revised form 4 April 2002

Abstract

Heat transfer was studied for the case of autowave transition from metastable to stable boiling regimes. The boiling curves classification was proposed in dependence on the direction of the vectorial parameters, such as temperature gradient, flow and temperature wave velocity. According to the proposed hypothesis, considerable changes in heat transfer relationships in the regions affected by temperature waves can be explained by local non-equilibrium near-to-wall layers.

The experiments were conducted to study heat transfer in case of autowave change of boiling conditions in tubes in the pressure range from 3 to 10 MPa and in the broad range of steam quality and mass velocity. It was demonstrated that the change of boiling regimes in tubes in the form an autowave could be observed if the steam quality was less than its boundary value.

The paper also discusses possible application of the obtained data for simulation of abnormal processes in the reactor core.

Keywords: Equilibrium heat flux; Boiling curve; Temperature wave

1. Introduction

The change-over of boiling regimes is often accompanied by appreciable and sometimes dangerous variation of the fuel element temperature. A reliable mathematical description of the boiling regimes change-over is of prime importance for the safety of power steam generators. The regimes of boiling are changed as a result of *gradual temperature* wave travelling along the surface of the fuel elements. It is possible to calculate whether the boundaries of the boiling regimes would remain fixed or would move (and the velocity of such movement), provided the heat transfer mode is known. In nuclear power this problem was named *rewetting* and related studies have been performed for many years. The techniques used for the analysis of temperature wave velocities in boiling systems are of significant interest for the specialists in nuclear power, superconductivity and other technical fields. Numerous publications on this subject are available. It is reasonable to specify two associated tasks in the rewetting problem study.

1.1. Numerical studies of fuel element temperature distribution in off-normal conditions

The accident and subsequent short-term loss of coolant cause heatup of the reactor core. Fuel element temperature goes up as high as 1000 °C. Afterwards the core re-flooding begins. The heat release rate may decrease with time. Fuel element temperature will gradually decrease along its full length. The final stage of cooling can be simulated as a change from film to nucleate boiling in the form of a travelling temperature wave. The detailed analysis and methods for calculation

* Corresponding author. Tel.: +7-95-263-7328; fax: +7-95-263-7491.

E-mail addresses: ocrk@entek.ru, ssl@ocrk.ru (S.L. Soloviev).

0017-9310/03/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S0017-9310(02)00213-2

Nomenclature

c	specific heat, kJ/(kg K)
d	tube diameter, m
I	electric current, A
l	length, m
P	pressure, MPa
q	heat flux density, W/m^2
q_{cr1}	the first critical heat flux, W/m^2
q_{cr2}	second critical heat flux, corresponding to Leidenfrost temperature, W/m^2
q_{eq}	equilibrium heat flux, W/m^2
q_{tv}	boiling curve in the temperature wave region, W/m^2
q_w	heat flux density on a wall, W/m^2
$q(\theta)$	boiling curve, W/m^2
R	specific electric resistance of a material, Ω m
s	sectional area of a specimen, m^2
T	temperature, °C
u	perimeter, m
v	temperature wave velocity, cm/s
x	Cartesian coordinate, m
X	flow steam quality
X_b	boundary steam quality
Greek symbols	
α	heat transfer coefficient, W/(m^2 K)
$\lambda(T)$	heat conductivity of wall material, W/(m K)
ρ	density, kg/m^3
θ	temperature head, $T - T_s$, K
θ_{cr1}	the first critical temperature head, K
θ_{cr2}	Leidenfrost temperature, K
θ_w	temperature head on a wall, K
ρw	mass flow, kg/(m^2 s)
τ	time, s
Subscripts	
in	inlet
s	saturation
sub	subcooled boiling
1,2,3	nucleate, transient and film boiling

of fuel element temperature conditions (such as heatup, gradual decrease followed by a sudden drop in temperature as nucleate boiling becomes dominant) are stated in a general formulation [1,2].

1.2. Autowave change of boiling conditions

This problem is more specific if compared to the previous one. It is assumed that a relatively long fuel element is put into a large volume of liquid. On one half of the fuel element the surface liquid boils in a nucleate regime, while on the other half, the film boiling takes place. Transition from nucleate-to-film boiling and vice versa happens in the form of a travelling temperature wave. Stationary metastable regime of boiling is replaced by stationary stable one. The heat flux density q_w falls in the range q_{cr2}–q_{cr1}. The rate of temperature wave propagation has to be determined. This problem is often raised in nuclear power [3] and superconductivity [4,5]. Some complex of autowave processes investigations during pool boiling was done by Zhukov et al. [6,7].

Though both problems are similar in their physical nature, different mathematical tools will be required for their solution. Certain achievements have been made in the studies of both problems. However, many aspects have to be clarified as yet. One of those unclear aspects can be formulated as follows. Can the heat transfer data obtained under steady-state boiling on isothermal heating surface be used in the calculations of travelling temperature waves?

Problem 2 can also be formulated in a somewhat different way. The temperature field of the heating surface is often non-uniform because of the non-uniform heating or complex geometry of a fuel element. As a result, nucleate and film boiling regimes may co-exist on the same wall. Boiling occurs in the area of a stopped temperature wave, $v = 0$. Hence an obvious question whether the heat transfer relationships of isothermal surface boiling are also applicable to the area of a stopped temperature wave.

In this article the authors made an attempt to clarify these aspects. The heat transfer in the area of temperature waves (i.e. problem 2) becomes a subject of interest and analysis. The obtained results may prove to be useful for the numerical studies of accident conditions (problem 1).

2. Velocity of temperature wave propagation

Let us focus on the transition of the boiling regimes taking as an example a horizontal cylinder assumed as infinite and submerged in a large pool of liquid. Heat sources are placed uniformly in the cylinder body. A nucleate boiling regime characterized by wall temperature $\theta_1 = q_w/\alpha_1$ is found on one half of the fuel element, while a film boiling regime at temperature $\theta_3 = q_w/\alpha_3$ occurs on the other half. The transition from nucleate-to-film boiling and vice versa is accompanied by a change in wall temperature in the form of temperature wave motion. The schematics of hot and cold tempera-

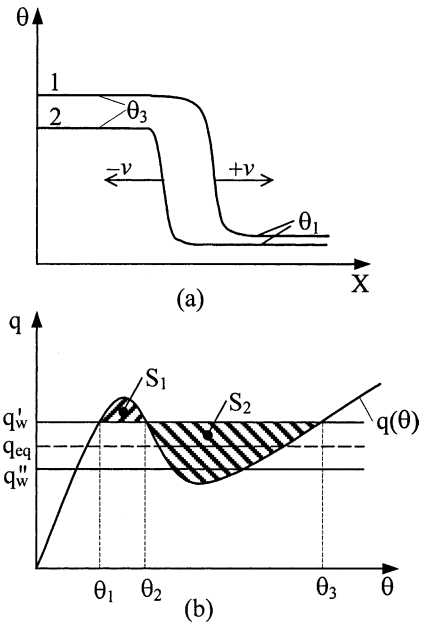

Fig. 1. Temperatures waves in case of rod boiling: curve 1—propagation of hot wave, $q'_w > q_{eq}$, $v > 0$ and curve 2—propagation of cold wave, $q''_w < q_{eq}$, $v < 0$ (a); $S_1 - S_2 = \int_{\theta_1}^{\theta_3} [q_w - q(\theta)]\,d\theta$—difference of areas that determines the wave velocity (b).

ture wave movements are shown in Fig. 1a. Since wave motion is a self-sustaining process, let us define it as *autowave motion*.

Let us consider a stabilized steady-state autowave process. The temperature wave moves at a constant velocity v, and the wave profile does not change its shape with time. Let us assume that the heat flux removed by boiling liquid depends only on the temperature head θ and can be described by the boiling curve $q(\theta)$ (a typical N-shaped Nukijama boiling curve). Then a temperature field of a thin horizontal cylinder with a cross-sectional can be described by the equation:

$$c\rho\frac{\partial\theta}{\partial x} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right) + [q_w - q(\theta)]\frac{u}{s}, \tag{1}$$

where $\theta = \theta(x,\tau)$ is the temperature head to be found. If electrical heating is used, then $q_w = I^2R/(us)$ describes the average heat flux on the wall. The boundary conditions for the wall are as follows:

$$\begin{aligned} &\frac{\partial\theta}{\partial x} \to 0 \quad x \to \pm\infty, \\ &\theta \to \theta_1 \quad \text{if } x \to +\infty, \\ &\theta \to \theta_3 \quad \text{if } x \to -\infty. \end{aligned} \tag{2}$$

Eq. (1) is based on the relationship $q(\theta)$ obtained under steady-state boiling on a uniformly heated specimen with an *isothermal surface*. If necessary, the relationship can be corrected to account for the specific features of a given specimen (i.e. surface roughness and impurity, properties of wall material, etc.).

Under the N-shaped function $q(\theta)$, the problem (1) and (2) can be solved as $\theta = \theta(x - v\tau)$ with a single value of v (temperature wave velocity) [8]. To calculate autowave velocities in the entire interval $q_{cr2} < q_w < q_{cr1}$, an approximate expression can be derived for v from Eq. (1) and (2) as the second Picard approximation [9]:

$$v \approx \left\{ \int_{\theta_2}^{\theta_3} \frac{Q(\theta)\lambda\,d\theta}{\sqrt{2\lambda S(\theta,\theta_3)} - v_{min}c\rho(\theta_3-\theta)} + \int_{\theta_1}^{\theta_2} \frac{Q(\theta)\lambda\,d\theta}{\sqrt{-2\lambda S(\theta_1,\theta)} + v_{min}c\rho(\theta-\theta_1)} \right\} \Big/ c\rho(\theta_3-\theta_1). \tag{3}$$

Here v_{min} is the modulus lower bound for v (the first Picard approximation):

$$v_{min} = \left\{\sqrt{2\lambda S(\theta_2,\theta_3)} - \sqrt{-2\lambda S(\theta_1,\theta_2)}\right\}/\{c\rho(\theta_3-\theta_1)\},$$

$$S(A,B) = \int_A^B Q(\theta)\,d\theta,$$

$$Q(\theta) = [q_w - q(\theta)]\frac{u}{s}. \tag{4}$$

It is clear from the relationship (3) and (4) that velocity depends essentially on Q, i.e. the difference between the heat supplied to the surface and the heat removed by the boiling liquid. The integral

$$S = \int_{\theta_1}^{\theta_3} Q(\theta)\,d\theta \tag{5}$$

is the difference of the shaded areas shown in Fig. 1b. As the figure indicates, S is dependent on the heat flux density on the wall q_w. It is important here to introduce a definition of an equilibrium heat flux q_{eq}.

The definition of the equilibrium heat flux has been introduced in [10,11]. These studies were focused on the boiling on the surface of a uniformly heated horizontal rod. It was found that if one half of the rod surface is characterized by film boiling and the other half by nucleate boiling, there exists a certain equilibrium heat flux which could maintain the boundary between the boiling regimes in a motionless state. In [10] the method for calculation of q_{eq} was proposed. The results of q_{eq} measurements under water boiling are summarized in [11].

The equilibrium heat flux draws a boundary between the steady-state regions of nucleate and film boiling regimes. The region of heat fluxes $q_{eq} < q_w < q_{cr1}$ is a region of metastable nucleate boiling and stable film boiling, while the area $q_{cr2} < q_w < q_{eq}$ is a region of metastable film boiling and stable nucleate boiling regimes. *Under autowave transition of the boiling regimes, the steady-state metastable regime is replaced with a steady-state stable regime*.

In case of an equilibrium heat flux $q_w = q_{eq}$, $S = 0$, $v = 0$ and the autowave does not move; under $q_w > q_{eq}$, $v > 0$ which means the beginning of film boiling. If $q_w < q_{eq}$, then $v < 0$ and nucleate boiling starts (Fig. 1a).

Eq. (3) turned to be somewhat complicated, though, if compared with the experimental data [9], it seems to be more accurately describing autowave velocities under boiling on horizontal rod surfaces in a large amount of liquid than other available relationships [7,12].

3. A disturbance of local equilibrium in the temperature wave

In spite of the satisfactory agreement between Eq. (3) and the measurement data for pool boiling on the surfaces of horizontal wires, there is a question whether the boiling curve obtained under steady-state conditions on an isothermal heating surface could be used for calculation of temperature wave velocity.

In case of a pool boiling of liquid on a horizontal uniformly heated plate, the boiling process is isotropic, i.e. the averaged characteristics of boiling do not change in any direction. In case of an autowave transition of the boiling regimes the vector values should be dealt with. In the region covered by the travelling temperature wave, liquid boils on a non-isothermal surface in non-steady conditions, the derivatives $\partial\theta/\partial x$ and $\partial\theta/\partial\tau$ take the values different from zero. When deriving Eq. (3), it was assumed that the boiling curve did not depend on these derivatives

$$q(\theta) \neq f\left(\frac{\partial\theta}{\partial x}, \frac{\partial\theta}{\partial\tau}\right), \tag{6}$$

i.e. on $\mathrm{grad}\,\theta$ and on v. It was assumed that the boiling curve $q_{tv}(\theta)$ measured in the region covered by a temperature wave and the curve $q(\theta)$ obtained for steady-state boiling regime on isothermal heating surface, coincide. Is this condition always fulfilled?

Pool boiling. Let us assume that the liquid is boiling on the surface of a horizontal cylinder heated by electricity. A temperature wave is moving along the axis and upon the cylinder surface. In a certain section of the cylinder of δx length, which is located in the area affected by the wave, the wall temperature will change by $\pm\delta\theta$ in a time period $\delta\tau$. To restore the heat balance on the wall, new centers of steam generation should be switched on (if $\delta\theta > 0$) or off (if $\delta\theta < 0$) within the section δx. Following the temperature changes, the near-to-wall layers of liquid should be transformed (i.e. the velocities and phases across its depth should be redistributed). If the time period required for boiling conditions relaxation on the heating surface is long enough as compared with the duration of a transient heat process in the wall, then the condition (6) could not be met and the boiling curve in the area of the temperature wave $q_{tv}(\theta)$ will differ from the relationship $q(\theta)$ measured under steady boiling regime on an isothermal surface.

Boiling in tube. In case of tube boiling the boundary between nucleate and film boiling regimes can remain motionless or can move. The boiling conditions will be somewhat different.

Stopped temperature wave, $v = 0$, $\rho w \neq 0$. In the region affected by the wave, the temperature head along the tube length will be changed in a monotonous way. The near-to-wall layer shall be transformed (i.e. phases and velocities distributed across its depth) in accordance with θ variation in the steam–water flow. If changes along the tube are significant and time period needed for near-to-wall layer transformation is large enough, then the heat transfer relationships in the area affected by the wave $q_{tv}(\theta)$ will differ from the relationship $q(\theta)$ obtained under steady boiling regime in a tube with an isothermal surface. Sometimes it is so called "memory" effect.

Autowave, $v \neq 0$, $\rho w \neq 0$. The balance upsets found in the previous case, are complemented with a time period required for the restoration of the surface conditions (switching boiling centers on/off during wall temperature variation). It is necessary to consider that v and ρw are *vectorial values*. Each of the vectors may be directed either *in coincidence* with the temperature gradient, or *opposite* to it. If the directions of $\mathrm{grad}\,\theta$ and ρw coincide, then the temperature head along the tube will grow, if these directions are opposite, then θ will decrease. Will the boiling curves be similar in both cases? As it will be shown below, the reciprocal direction of $\mathrm{grad}\,\theta$ and ρw vector produces a significant impact on heat transfer relationships in the region affected by the temperature wave.

It is clear from the above arguments that local non-equilibrium boiling in an area affected by the temperature wave, may upset the condition (6). The first stage of this model development consists in the collection of the data on boiling in the area affected by the temperature wave. To describe boiling under local non-equilibrium conditions, let us present Eq. (1) in the following way:

$$c\rho\frac{\partial\theta}{\partial\tau} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial\theta}{\partial x}\right) + \frac{u}{s}[q_w - q_{tv}(\theta)]. \tag{7}$$

Here $q_{tv}(\theta)$ is the boiling curve in the region of the temperature wave, which is found either by direct measurements of local heat transfer, or is adjusted so as to describe the autowave motion in the best way [13].

4. Boiling in tubes

Because of the importance of the rewetting problem for a nuclear reactor core, a great number of theoretical and experimental studies were performed to investigate the velocity of nucleate boiling propagation in hot tubes and channels [1–3,14,15]. The studies in the heat transfer in the region affected by the temperature waves, are scarce and the available data are contradictory. No systematic data have been collected yet on the boiling curves under conditions of forced movement. In some studies [16,17], the boiling curve was investigated under the pressure close to atmospheric, in short channels, under low subcooling and mass velocities. According to these data, the boiling curves under conditions of forced movement were N-shaped. The boiling curve diagram gives a clear indication of a nucleate boiling branch, departure from nucleate boiling, downcoming branch of transition boiling and film boiling regime. The ratio q_{cr1}/q_{cr2} reaches 10. These results give an insight into the phenomena of an equilibrium heat flux in case of boiling in tubes. It can be argued that an autowave transition of boiling will take place.

4.1. Directions of grad θ and ρw coincide

Let us consider the conditions for achieving an equilibrium between the nucleate and film boiling regimes in case of tube boiling. Let us assume that a subcooled water is supplied to the tube inlet. The tube is heated by electrical current passing along the tube wall. The electrical resistance of the wall material is assumed to be constant. The supplied electric power is being gradually increased. The departure from nucleate boiling (DNB) will occur at the tube outlet where the flow steam quality is maximum (section I–I, Fig. 2b). A hot spot will appear on the wall as a result of DNB. Additional heat will be transferred from the region of film boiling to the region of nucleate boiling owing to heat conductivity. Since in case of nucleate boiling the heat flux could not exceed the value of q_{cr1}, the wall temperature will grow with time and film boiling will be propagating across the wall towards the flow (it should be mentioned here that film boiling in tube usually means dispersed flow). The process will last until the temperature wave reaches the area of low steam quality, and until the heat transfer in the region of nucleate boiling compensates the heat influx due to the heat conductivity from the region of film boiling (q_{cr1} variations along the tube are shown in Fig. 2a).

As demonstrated in Fig. 2c, the propagation of film boiling is stopped and the nucleate boiling boundary is stabilized in a certain cross-section II–II. The amount of heat supplied from the region of film boiling will be equal to that transferred to fluid in the region of nucleate boiling, and the heat balance (dashed areas are the same) will be maintained for the wall. In a new regime, the film and nucleate types of boiling will remain in a stabilized co-existence which is called *equilibrium regime or equilibrium heat flux* q_{eq}. Similarly to q_{cr1}, equilibrium

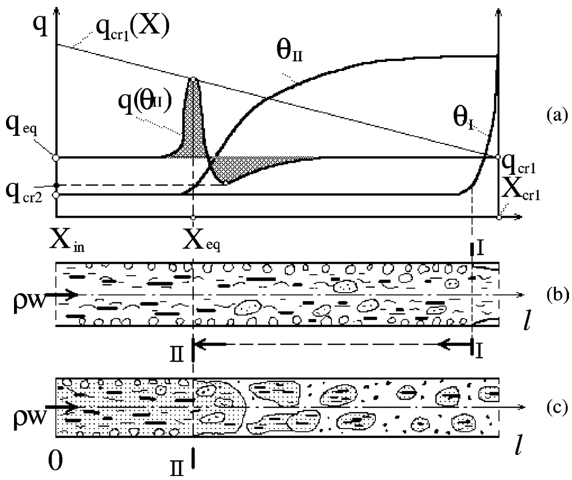

Fig. 2. Model of transition to regime of equilibrium heat flux in a tube: (a) profiles of wall temperature (θ_I, θ_{II}), local heat flux ($q(\theta)$) and relationship $q_{cr1}(X)$; (b) beginning of DNB at the tube outlet; (c) equilibrium between nucleate and film boiling regimes. I → II, propagation of film boiling; θ_I, temperature profile at the moment of DNB onset; θ_{II}, steady-state temperature wave; II–II, quench front.

heat flux is a function of pressure, flow rate and steam quality, $q_{eq} = f(P, \rho w, X_{eq})$, where X_{eq} is measured in section II–II.

Doroschuk [18] has investigated equilibrium heat flux under water boiling in a 8 mm diameter tube at 21.6 MPa. The measurement techniques were similar to those described above. Heat flux and steam quality at the tube outlet were measured at the moment of DNB occurrence. These values were taken as q_{cr1} and X_{cr1} (marked with triangles in Fig. 3). Once temperature wave has propagated towards the flow and its position has stabilized measurements were made on the heat flux averaged along the tube and local steam quality at the nucleate boiling regime boundary (in section II–II quench front, Fig. 2c). These values of q and X were taken as

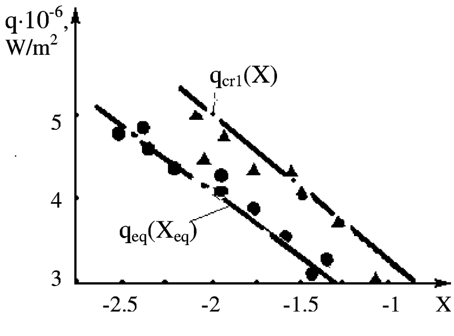

Fig. 3. The results of q_{cr1} and q_{eq} measurements under water boiling in a tube [18]: $d = 8$ mm, $P = 21.6$ MPa, $\rho w = 2500$ kg/(m^2 s).

equilibrium $q_{eq}(X_{eq})$. The results of measurements are presented in Fig. 3. The figure demonstrates that the values of q_{eq} (circles) are about 20% lower than q_{cr1}.

Thus, the ratio q_{cr1}/q_{eq} is equal to 1.2. The actual difference between q_{cr1} and q_{eq} is within the uncertainty of an experiment. Such similarity of q_{cr1} and q_{eq} values is probably caused by the specific features of boiling in the region of stopped temperature wave in a tube.

Let us divide heat transfer investigations under tube boiling into the following stages. At first, we shall look into the relationship $q(\theta)$ in case of boiling in a tube with an isothermal surface ($\mathrm{grad}\,\theta = 0$) and assume it as "the main boiling curve". Next we shall explore the effect of local non-equilibrium, caused by anisothermic nature of the heating surface and by the velocity of the temperature wave, upon the main boiling curve.

Boiling on isothermal heating surface (*the main boiling curve*). The techniques developed in RDIPE [19] allows studying the heat transfer under film boiling of water in a quasi-stable regime. The experiments were performed on the working sections of tubes with 4 mm i.d., wall thickness of 1 mm and length of 800 mm. An independent electrical wall heating was provided for two sections 600 and 200 mm long, placed immediately one after the other. A shorter section was used for the experiments, while the longer tube was meant for thermal flow stabilization at the inlet to the test section. During the experiments the values of the heat flux density in the preliminary part and in the test section were very similar. Thermocouple beads were welded to the outer surface of the tube.

The experiments were conducted as follows. Pre-set pressure, flow rate and heat flux density q_w were obtained in the preliminary section. Steam quality of the flow was set at the inlet to the test section. Next, a short energy pulse (not exceeding ~0.5 s) was applied for the test section. As a result of a sharp rise of the wall temperature, a film boiling regime was established in the test section. By varying the pulse value, it became possible to heat up the tube wall to the pre-set temperature T_w ($T_w \approx 450$–700 °C), after which the energy release was reduced and the pre-set heat flux was obtained (Fig. 4). In the preliminary experiments the value of θ_w had been chosen so as to maintain the heat balance ($q_w = \alpha_3\theta_w$) for the tube wall and establish a steady-state film boiling regime. The control system allowed maintaining the pre-set value of the heat flux density or the current at a constant level until the experiment was over. The duration of the experiment was limited (~10/12 s) because cold temperature wave started to move from the inlet to the test section. Wall temperature measurements were made at a distance of 70/200 mm from the inlet. Stable film boiling could be observed in this place. At the end of the experiment, the thermocouples registered the passage of a cold wave (curves 3–5, Fig. 4). We almost succeeded in reaching the point of $q_{cr2}(\theta_{cr2})$. A detailed

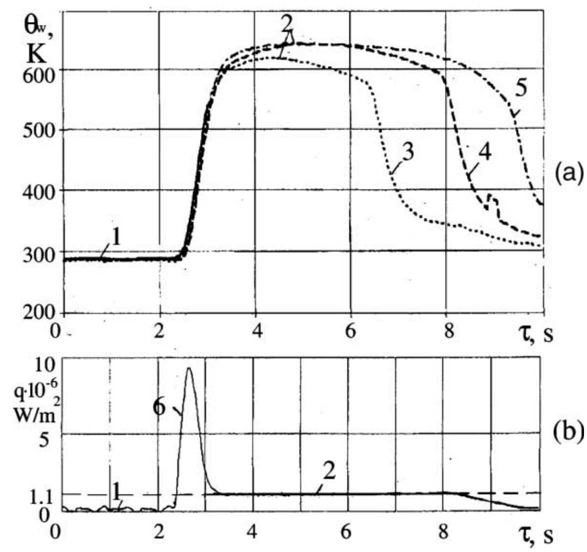

Fig. 4. Technique of quasi-steady heat transfer investigation under film boiling in a tube: (a) changes in wall temperature; (b) variation of heat flux density as a function of time; curve 1—nucleate boiling; curve 2—quasi-steady film boiling; curves 3, 4, 5—drop of wall temperature at a distance of 10, 13 and 16 cm from the inlet to the test section, respectively; curve 6—pulse heatup of wall.

description of the technique is given in [19]. Under nucleate boiling, the relationship $q(\theta)$ was determined using the standard technique.

The results of measurements are shown in Fig. 5 (squares) as relationship $q(\theta)$. This figure gives a clear indication of the branches of nucleate and film boiling. The temperature head and heat flux at the second crisis point are equal to $\theta_{cr2} \sim (150/160)$ °C, $q_{cr2} \sim (1.3/1.5) \times 10^6$ W/m^2. The ratio of q_{cr1}/q_{cr2} is equal to 1.4.

A heat flux increase was observed as θ was getting higher. For example, if $\theta \sim 300$ °C, q will be equal to $\sim(1.8/2) \times 10^6$ W/m^2. The boiling curve is N-shaped.

Boiling with a stopped temperature wave (*equilibrium heat flux*). In the region of high pressure and high steam quality, DNB will not cause the risk of tube wall burnout. After the occurrence of DNB and establishment of an equilibrium regime, nucleate boiling at the inlet and film boiling at the outlet will co-exist in a stable way. This case is illustrated in Fig. 2a by a monotonously ascending profile of the temperature head along the tube length (temperature wave θ_{II}). The temperature profile along the tube length was measured at RDIPE test rig for equilibrium regime. The obtained profile was used to calculate local temperature head as a function of temperature head $q_{tv}(\theta)$ using Eq. (7) [20]. The results of the calculations are shown in Fig. 5 as relationship $q_{tv}(\theta)$ (circles). As shown in the figure, DNB takes place at $\theta = 30$ °C and amounts to $q_{cr1} \sim 1.85 \times 10^6$ W/m^2. At $\theta = 150$ °C, heat flux is minimum,

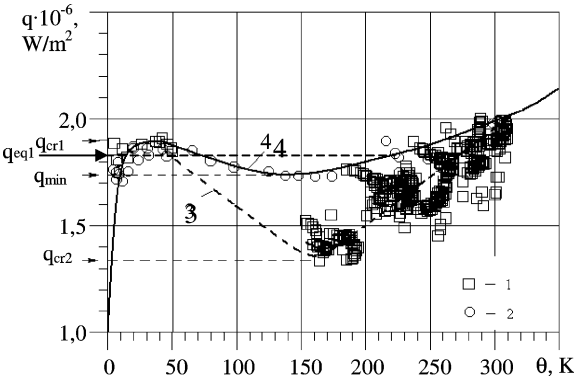

Fig. 5. The results of $q(\theta)$ measurements under boiling on an isothermal surface (1) and in equilibrium heat flux regime, $q_w = q_{eq}$ (2); boiling curves on isothermal surface (3) and under equilibrium boiling regimes (4); $P = 10$ MPa, $\rho w = 2000$ kg/(m^2 s), $X = 0.28$.

$q_{min} = 1.75 \times 10^6$ W/m^2 and is followed by a slow increase of q as a function of θ. The N-shaped profile observed during the experiments with the "main" boiling curve, almost disappeared, and the relationship $q(\theta)$ became flattened, $q_{cr1}/q_{min} = 1.05$.

This significant change of the heat transfer law can probably be attributed to local non-equilibrium boiling. θ rises in a monotonous way along the tube (profile θ_{II}) and the steam–water flow should be transformed accordingly. Transformation of the near-to-wall layer is a long process covering a significant section of the tube length ($l/d \approx 50$). If the near-to-wall layer cannot follow the changes in tube wall conditions the flow is said to process a "memory" ($l/d \ll 50$). In this case, the memory effect manifests itself in the flow ability to remove q at the level of q_{cr1} in the tube sections with a higher wall temperature.

It can be concluded that under boiling on an isothermal tube surface, the relationship $q(\theta)$ is clearly of an N-shape. If the temperature wave is stopped, i.e. there is a significant temperature gradient and the direction of grad θ coincides with the direction of ρw, the boiling curve is flattened (shown by circles). In this regime, the difference between q_{cr1} and q_{min} is negligible, $q_{cr1} \sim q_{min} \sim q_{eq}$.

Since q_{cr1} is almost equal to q_{eq} in value, it is the engineering practice not to distinguish them. In DNB investigations they often measure average heat flux over the tube length and steam quality in a section corresponding to the beginning of the temperature wave (quench front, Fig. 2c). The heat flux measured in this way is called the critical heat flux $q_{cr1}(X_{cr1}) \approx q_{eq}(X_{eq})$.

4.2. Grad θ and ρw are directed to the opposite sides

Let us analyze the impact of local non-equilibrium on heat transfer in the case when boiling regimes exist in the reverse sequence: film to nucleate boiling. This sequence rarely happens in tubes. It may occur, for example, if the cold wave propagates from the outlet in the channel with hot walls.

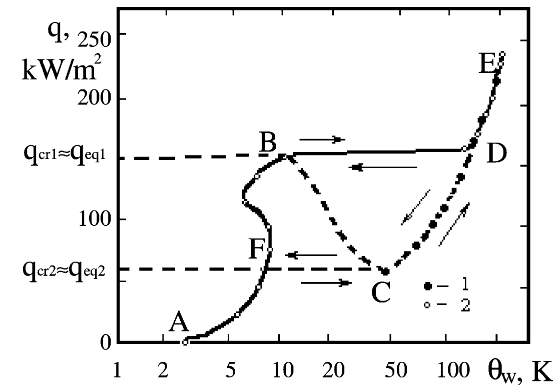

Fig. 6. The effect of boiling regime sequence along the channel length on the relationship $q(\theta)$: (curve 1) film boiling at the tube inlet; (curve 2) nucleate boiling at the tube inlet [21]; BD—transition without additional heater $q_{cr1} \sim q_{eq1}$; CF—transition with additional heater $q_{cr2} \sim q_{eq2}$; freon-12, $P = 1.07$ MPa, $\rho w = 4074$ kg/(m^2 s), $X_{in} = 0.152$, $d = 11.1$ mm.

In Groeneveld's study [21], an additional heater was installed at the tube inlet and a heat flux with high density was produced in a short section. The additional supply of heat made it possible to prevent the propagation of nucleate boiling from the tube inlet side, so that the steady-state film boiling could exist along the full length of the test section. By varying the value of the current that passed along the tube wall, the authors could investigate heat transfer under film boiling. Fig. 6 shows the results of the measurements on the relationship $q(\theta)$ in case of freon-12 boiling. For the case of the reverse sequence of the regimes along the tube (i.e. film-to-nucleate boiling), the authors managed to maintain steady film boiling under the heat flux of about three times lower than q_{cr1} (black dots in the figure). The boiling curve has a pronounced N-shape, $q_{cr1}/q_{cr2} = 3$.

For comparison, Fig. 6 also shows the boiling curve for the standard sequence of the regimes (nucleate-to-film boiling). The sections AB, CD, DE depict boiling (in our terminology) on an isothermal surface, grad $\theta = 0$. A BD transition corresponds both to q_{cr1} and q_{eq1} (equilibrium heat flux if the regimes exist in a nucleate-to-film boiling sequence). Similarly to BD transition, FC transition can be regarded both as a second crisis (q_{cr2}) and as an equilibrium heat flux q_{eq2}.

4.3. Replacement of film boiling with nucleate boiling

It is of great importance for the engineering practice to know whether the boiling curves obtained in Section 4.1 above are applicable for the analysis of a moving temperature wave. The answer can be found only by means of an experiment.

The propagation of nucleate boiling in a tube was investigated at the test rig described in Section 4.1. According to the above-mentioned technique, film boiling was obtained in the test section. After some time, nucleate boiling in the form of a cold wave began propagating from the test section inlet (Fig. 4). The indications of the microthermocouples were used to calculate temperature wave velocity. The boiling curve in the region covered by the wave was plotted using Eq. (7). Root-mean-square error of the measurements does not exceed 20%. The measurements were taken at $P = 3$, 7 and 10 MPa. The results of the measurements for the relationship $q_{tv}(\theta)$ are presented in Fig. 7 dimensionless coordinates $q/q_{cr1} - \theta/\theta_{cr2}$. Here $\theta_{cr2} = 230$, 170 and 150 °C for $P = 3$, 7 and 10 MPa; q_{cr1} was defined from table data [22].

Fig. 7a shows the boiling curves at different pressures and the same mass velocity. Fig. 7b and c illustrate a comparison of the boiling curves under different steam quality if $P = 10$ MPa and mass velocities are 2000 and 3000 kg/(m^2 s), respectively. As may be seen, the shape of the boiling curves is almost symmetrical. As the temperature front reaches the cross-section under analysis, the heat fluxes being removed will gradually increase. When the heat flux reaches its maximum (q_{max}), nucleate boiling is stabilized on the wall. It should be pointed out that the peak heat flux shifts to the region of high temperature head (where $\theta \cong \theta_{cr2}$). If steam quality is low, $q_{max}/q_{cr1} < 1$. If $X = 0.25$ and higher, the peak heat flux on the boiling curve exceeds q_{cr1}. The q_{cr1} data for a tube of 4 mm diameter [22] are compared in Fig. 8 with the experimental q_{max} and q_w data in traveling autowave. As it is shown in the figure, $q_{max} = 0.4q_{cr1}$ at $X = -0.05$, $q_{max} = 1.7q_{cr1}$ at $X = 0.26$.

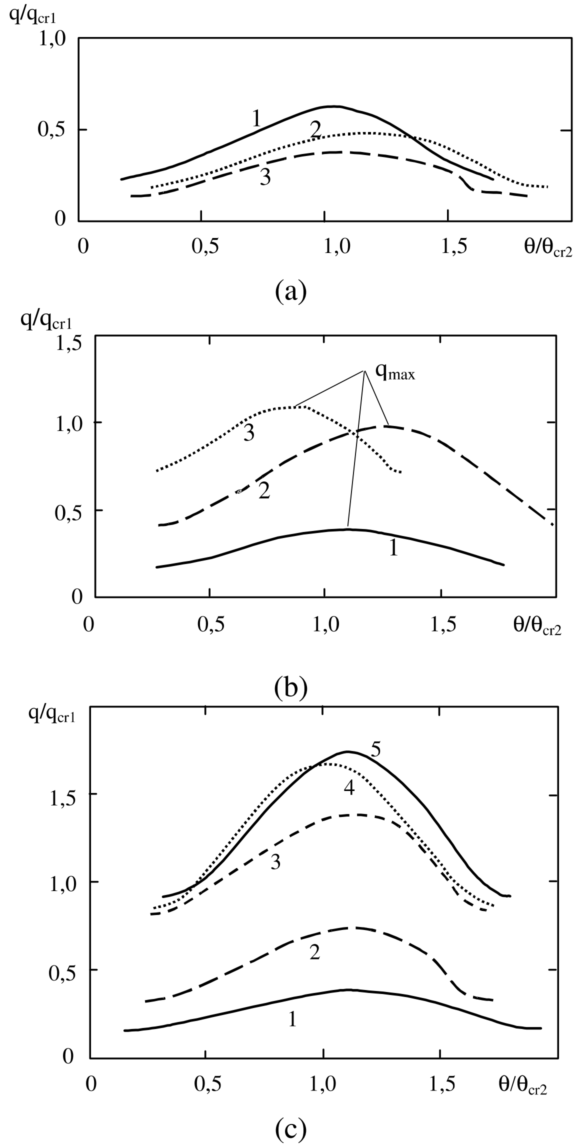

Fig. 7. Boiling curves in the area of the temperature waves under different pressures and steam qualities: (a) $\rho w = 1000$ kg/(m^2 s): curve 1—$P = 10$ MPa, $q_w = 0.94 \times 10^6$ W/m^2, $X = 0.21$; curve 2—$P = 7$ MPa, $q_w = 1.1 \times 10^6$ W/m^2, $X = 0.17$; curve 3—$P = 3$ MPa, $q_w = 1.2 \times 10^6$ W/m^2, $X = 0.22$. (b) $\rho w = 2000$ kg/(m^2 s): ($P = 10$ MPa) curve 1—$X = 0.21$, $q_w = 1.48 \times 10^6$ W/m^2; curve 2—$X = 0.14$, $q_w = 1.45 \times 10^6$ W/m^2; curve 3—$X = 0.28$, $q_w = 1.35 \times 10^6$ W/m^2. (c) $\rho w = 3000$ kg/(m^{2}s) ($P = 10$ MPa): curve 1—$X = -0.03$, $q_w = 0.9 \times 10^6$ W/m^2; curve 2—$X = 0.1$, $q_w = 1.07 \times 10^6$ W/m^2; curve 3—$X = 0.26$, $q_w = 1.62 \times 10^6$ W/m^2; curve 4—$X = 0.26$, $q_w = 1.68 \times 10^6$ W/m^2; curve 5—$X = 0.26$, $q_w = 1.8 \times 10^6$ W/m^2.

4.4. The region of an N-shaped boiling curve in tubes

For the autowave motion to take place, the boiling curve should be of an N-shape, in other words, nucleate and film boiling regimes shall be present and the inequality $q_{cr2} < q_{cr1}$ shall be met. Under boiling of subcooled fluid in tubes as well as under low steam quality, a thick enough film of fluid flows along the tube wall. The differences in the boiling mechanisms for the thick film in tubes and in a large pool are not so significant and, as shown in Section 4.1 above, the boiling curve is N-shaped. If the steam quality values are higher, the differences in the mechanisms of the boiling in tubes and in a large pool become more pronounced. The question is: what is the steam quality range in which the boiling curve remains N-shaped or, rephrasing, what is the steam quality range in which an autowave motion can take place.

Let us compare the values of q_{cr1} and q_{cr2} under different steam qualities of the flow. To this end, we shall use the results of the heat transfer measurements under

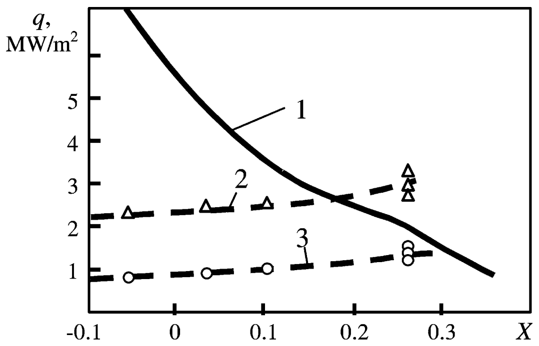

Fig. 8. Dependence of q_{cr1} and q_{max} on X in travelling autowave at $P = 10$ MPa, $\rho w = 2000$ kg/(m^2 s). curve 1, q_{cr1}; curve 2, q_{max}; curve 3, q_w.

dispersed flow regime in a tube with an isothermal surface (Section 4.1). Heat transfer was measured in the wall temperature T_w range $T_s + \theta_{cr2} < T_w < 700$ °C. No special investigations of q_{cr2} were performed in this study. According to the measurements, at 7 MPa, θ_{cr2} amounts to ~170 °C. The results of $q = f(\theta)$ measurements under film boiling at $\theta < 220$ °C were chosen from the entire set of the experimental points. These data can be regarded to be fairly close to the dryout point. The results of q_{cr2} determination in the above method are shown in Fig. 9 in the coordinates q–X. The same figure shows the relationship $q_{cr1}(X)$ plotted from the table data recalculated for a 4 mm diameter tube (solid line) [22]. The measured values of q_{cr2} lie much lower than the q_{cr1} line.

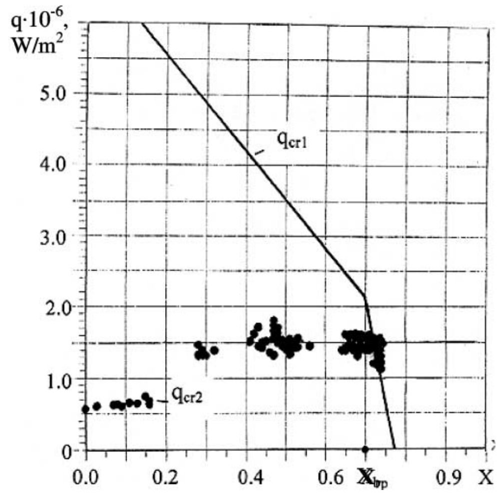

Fig. 9. The region of autowave transition under water boiling in a tube, $d = 4$ mm; the points—results of q_{cr2} measurements, $P = 7$ MPa, $\rho w = 1000$ kg/(m^2 s); q_{cr1}—calculated on the basis of [22].

The lines representing the relationships $q_{cr1}(X)$ and $q_{cr2}(X)$ intersect in a section where the relationship $q_{cr1}(X)$ is characterized by a very sharp decline. In Russian terminology, this section is called "boundary steam quality X_b". The data provided in Fig. 9 allow concluding that if $X < X_b$, the boiling curve should remain N-shaped and an autowave transition can be observed here.

5. Boiling curves for tubes

The above results give an overview of an autowave transition of boiling regimes in tubes. The heat flux absorbed by the fluid in the region affected by the temperature wave, depends on many parameters:

$$q_{tv} = f(\theta, \mathrm{grad}\,\theta, \rho\vec{w}, \vec{v}, P, X). \quad (8)$$

Isothermal surface, *grad* $\theta = 0$. The main boiling curve is clearly N-shaped. The regions of nucleate and film boiling as well as the points of q_{cr1} and q_{cr2} are distinct in the curve (Fig. 5).

Equilibrium heat flux, q_{eq}, $v = 0$. In a stopped temperature wave, the N-shape of the boiling curve is gradually flattened. The relationship q_{tv} is smoothed; nucleate boiling gradually transforms into film boiling, $q_{cr1} \sim q_{min} \sim q_{eq1}$ (Fig. 5).

Opposite directions of grad θ *and* ρw. The regime sequence in the direction of flow motion is as follows: film to nucleate boiling. In case of a hot section with local heat flux q_{cr1} present at the tube inlet, the transition to film boiling can occur if $q_w = q_{eq2}$ and at the same time $q_{cr1} \gg q_{cr2}$ (Fig. 6).

Autowave, *grad* $\theta \neq 0$, $v \neq 0$. The peak of the relationship q_{tv} is shifted towards the region of high temperature head; q_{max} can be both above and below q_{cr1} (Fig. 7).

Fig. 10 depicts the findings of the investigations into the temperature wave velocity dependence on q_w. Points A and B correspond to q_{cr1} and q_{cr2} values for $\rho w = 2000$ and 3000 kg/(m^2 s) with $X = 0.28$. The CDE curve was plotted based on the data obtained in velocity calculations using Eq. (3) for the "main" boiling curve (curve 3, Fig. 5). The experimental data are pooled in groups (1–8), featuring similar flow rates and approximately the same steam qualities. Averaged curves are constructed by the groups of points. It can be seen in the figure that temperature wave velocity (absolute) increases with steam quality increase from −0.1 to +0.3. X decrease from −0.1 to −0.2 also causes a certain growth of v (cf. curves 7 and 8). It can be concluded from the comparison of curves 1 and 5 that temperature wave velocity grows with ρw increase. A curve is constructed by point 5. With an equilibrium heat flux, this curve crosses the x-axis (to the left of point A). Curve 1 crosses the x-axis in about the same point. The dotted lines plotted by points

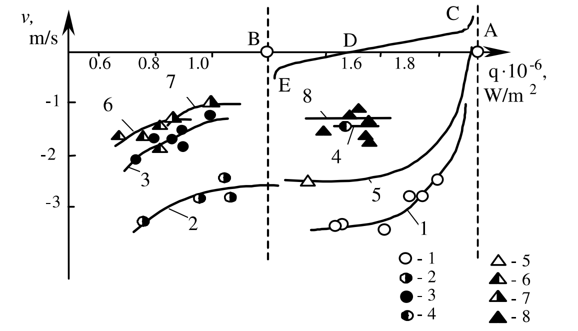

Fig. 10. Heat transfer and temperature waves velocities under boiling in the tube $d = 4$ mm ($P = 10$ MPa); CDE—calculation of $v(X)$ by the curve 3 (Fig. 5); the points and approximating curves—the results of $v(X)$ measurements under $\rho w = 3000$ kg/(m^2 s): curve 1, $X = 0.25$; curve 2, $X = 0.1$; curve 3, $X = 0.04$; curve 4, $X = -0.12$. $\rho w = 2000$ kg/(m^2 s): curve 5, $X = 0.28$; curve 6, $X = 0.0$; curve 7, $X = -0.1$; curve 8, $X = -0.2$.

A and B restrict the autowave area for curves 1 and 5. It can be seen that velocity goes down (in terms of an absolute value) as q_w tends to q_{cr1}. To the contrary, wave velocity goes up as q_w approaches q_{cr2}. Curves 1 and 5 give a general idea of wave velocity behavior as dependent on the heat flux in the range from q_{cr2} to q_{cr1}.

It should be pointed out that the "main" boiling curve plays an important role in the autowave process. In fact, the heat flux range where an autowave transition does exist in tubes, is restricted by the first (DNB) and second crisis points in the main boiling curve. However, the core rewetting modeling (problem (1), Section 1) without due regard for the main boiling curve distortion, may results in serious errors.

References

[1] C. Unal, A phenomenological model of the thermal-hydraulics of convective boiling during the quenching of hot rod bundles, Part I: thermal hydraulic model, Nucl. Eng. Des. 136 (1992) 277–298.

[2] R. Nelson, C. Unal, A phenomenological model of the thermal-hydraulics of convective boiling during the quenching of hot rod bundles, Part II: assessment of the model with steady-state and transient post-CHF data, Nucl. Eng. Des. 136 (1992) 299–318.

[3] H. Ohtake, Y. Koizumi, Study on rewetting of vertical-hot-thick surface by a falling film (investigation from the aspect of boiling heat transfer characteristics and modeling), heat transfer, in: Proceedings of the 11th IHTC, vol. 2, Kyongju, Republic of Korea, August 23–28, 1998, pp. 325–330.

[4] B.J. Maddock, G.B. James, W.T. Norris, Superconductive composites: heat transfer and steady state stabilization, Cryogenics 9 (4) (1969) 261–273.

[5] A.Vi. Gurevich, R.G. Mints, Self-heating in normal metals and superconductors, Rev. Mod. Phys. 59 (4) (1987) 941–999.

[6] S.A. Zhukov, L.F. Bokova, V.V. Barelko, Certain aspects of autowave transition from nucleate to film boiling regimes with a cylindrical heat generating element inclined from a horizontal position, Int. J. Heat Mass Transfer 26 (2) (1983) 269–275.

[7] S.A. Zhukov, V.V. Barelko, A.G. Merzhanov, Wave processes on heat generating surfaces in pool boiling, Int. J. Heat Mass Transfer 24 (1) (1981) 47–55.

[8] Ya.B. Zeldovich, G.I. Barenblatt, V.B. Librovich, G.M. Makhviladze, A Mathematical Theory of Combustion and Explosion, Nauka, Moscow, 1980, p. 478.

[9] S.A. Kovalev, S.V. Usatikov, On the calculations of the propagation velocity of the boiling transition wave, High-temp. Therm. Phys. 38 (3) (2000) 477–483.

[10] S.A. Kovalev, Stability of the boiling regimes, High-temp. Therm. Phys. (Teplofiz. Vys. Temp.) 2 (5) (1964) 780–788.

[11] S.A. Kovalev, An investigation of minimum heat fluxes in the pool boiling of water, Int. J. Heat Mass Transfer 9 (1966) 1219–1226.

[12] V.S. Osmachkin, Sudden cooling of the hot rods by boiling water flow, in: Proceedings of the USSR–Canadian Seminar on Thermal Physical Problems of the Nuclear Reactors Safety, M. Institute for Atomic Energy, 1976, p. 37.

[13] S.L. Sobolev, Local nonequilibrium models of transfer processes, Adv. Phys. Sci. 167 (10) (1997) 1095–1106.

[14] G. Yadigaroglu, R.A. Nelson, V. Teschendorff, Y. Murao, J. Kelly, D. Bestion, Modeling of reflooding, Nucl. Eng. Des 145 (1) (1993) 1–35.

[15] X.E. Peng, B.X. Wang, G.P. Peterson, Film and transition boiling characteristics of subcooled liquid flowing through a horizontal flat duct, Int. J. Heat Mass Transfer 35 (11) (1992) 3077–3083.

[16] D.-M. Qiu, Untersuchungen zur Warmeubertragung beim Sieden von stonmendem Wasser an einer lotrechten Heizflache, D.-I. Dissertation, Technischen Universitat, Berlin, 1995.

[17] K. Johannesen, Low quality transition and inverted annular flow film boiling of water: an updated review, in: R.K. Shah et al. (Eds.), Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Elsevier, New York, 1988, pp. 1416–1429.

[18] V.E. Doroschuk, Heat Transfer Crises Under Water Boiling in Tubes, Energoatomizdat, Moscow, 1983.

[19] Yu.S. Molochnikov, V.T. Sytin, Experimental investigation of high-temperature post-dryout heat transfer, in: RDIPE Yearbook, M., RDIPE, 1997, p. 132.

[20] B.A. Gabaraev, S.A. Kovalev, Yu.S. Molochnikov, S.L. Soloviev, S.V. Usatikov, Certain specific features of autowave processes under boiling conditions, A RDIPE preprint, no. ET-99/49, M., RDIPE, 1999, p. 29.

[21] D.C. Groeneveld, S.R. Gardiner, A method of obtaining flow film boiling data for subcooled water, Int. J. Heat Mass Transfer 21 (1978) 664–665.

[22] Recommendations on the analysis of heat transfer crisis under water boiling in round tubes, A preprint 1-57, M., USSR ASIHT, 1980, p. 67.