

BOILING HEAT TRANSFER

INFLUENCE OF THE OPERATING TIME OF A SURFACE HEATED BY ELECTRIC CURRENT ON THE HEAT-TRANSFER COEFFICIENT OF KEROSENE AND WATER BOILING ON IT

S. G. Obukhov and D. S. Obukhov

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Results of experimental investigation of the influence of the operating time of a heating surface on the intensity of heat transfer in the kerosene and water boiling on it are presented. The experimental data on the heat transfer in the indicated liquids boiling on unrun heating surfaces have been generalized using different relations.

The jet fuel used in a high-speed airplane represents a single coolant that provides temperature conditions necessary for operation of its propulsion system and other elements [1]. However, only liquid jet fuels are used for this purpose, which limits the cooling effect. The cooling effect can be enhanced substantially at the expense of the evaporation heat of these fuels. To use a boiling fuel for cooling an engine, it is necessary to solve a number of problems, in particular, to determine the mechanisms of heat transfer in this fuel in the process of its boiling [2].

The cooling capacity of liquid hydrocarbon fuels can be underestimated when it is determined without regard for the influence of the operating time of a heating surface on their boiling coefficient [3].

Many of our works [4–7] were devoted to investigating the influence of the run-in of a heat-release surface contacting with a boiling liquid on the critical density q_{cr1} of the heat flow formed in the process of boiling. In the present work, we consider the boiling coefficient α that represents a no less important integral characteristic of boiling.

It is known that α decreases monotonically with increase in the operating time of a heating surface because of the appearance of a scale (carbon, coke, oxides, etc.) on it. The operation of such a surface can be divided into three stages [7]: 1) run-in (this stage is the most important, Fig. 1); 2) operation of the run-in surface; 3) running. Analysis of experimental data on the influence of the operating time of a heating surface on the boiling process shows that the integral characteristics of boiling change most substantially at the run-in stage, which is scantily known.

At the Kazan Chemical-Engineering Institute (KCEI), the heat transfer in the TS-1 fuel boiling on a heating surface for 227 h at $p_{sat} = 2$ bar and $q = 125$ kW/m² has been experimentally investigated for the purpose of determining the influence of the operating time of a heating surface, on which a jet fuel boils, on its characteristics [8]. Before each experiment, the dissolved oxygen was removed from the fuel. It is seen from Fig. 2 that the decrease in the heat-transfer coefficient caused by the deposition of gummy substances on the surface of the tube does not exceed 8% within 120 h from the beginning of boiling (portion AB of the curve). This can be explained by the fact that, at this stage, heat is transferred between the metal and the liquid, and the deposits on the surface are small. The fuel became complete dark only after 200–210 h of operation of the surface. In the case where the nonoxidized fuel was used, α decreased significantly within the first hours of surface operation. Such behavior of the heat-transfer coefficient within the first 120 h of surface operation (portion BC) was explained in [8] by the fact that, for this time, the thickness of the deposits on the centers of vapor formation reaches a value at which these centers begin to close. The process proceeds for 25–40 h. For this time, heat is transferred between the metal and the liquid as well as between the metal, the pitch, and the liquid in the cavities filled with the pitch. The cavities are filled nonuniformly because they have different dimensions. At point B, the process of closing of boiling centers ceases and the metal–liquid contact

Kama State Polytechnical Institute, 69/18 Mir Ave., Naberezhnye Chelny, Tatarstan, 423810, Russia. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 78, No. 3, pp. 134–140, May–June, 2005. Original article submitted May 14, 2004.

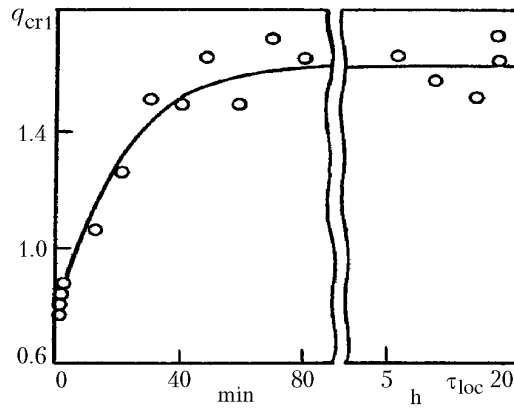


Fig. 1. Dependence of the critical heat flow on the time of local boiling of the TS-1 fuel. $T_{liq} = 20^{\circ}\text{C}$, $q_{loc} = 0.06 \text{ MW/m}^2$. q_{cr1} , MW/m^2 ; τ_{loc} , min, h.

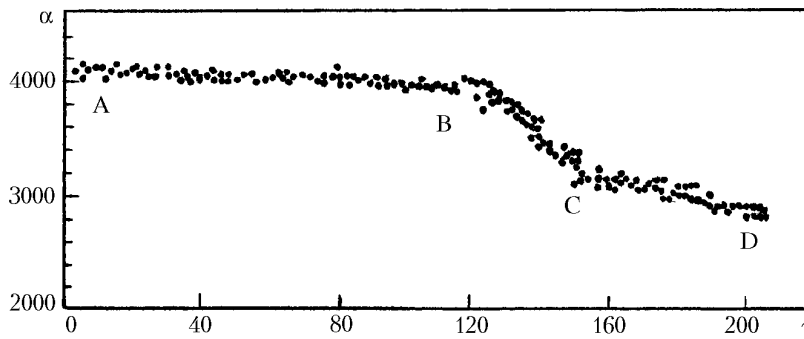


Fig. 2. Dependence of the heat-transfer coefficient on the operating time of a heating surface in the case of boiling of the TS-1 jet fuel on it. $T_{liq} = 160^{\circ}\text{C}$, $p_{sat} = 0.2 \text{ MPa}$, $q = 125 \text{ kW/m}^2$ [8]. α , $\text{W}/(\text{m}^2\cdot\text{K})$; τ , h.

disappears, i.e., the whole heating surface becomes coated with a thin pitch layer and heat is transferred through the metal–pitch–liquid contact. Thereafter, the curve becomes straight once again (portion CD). The heat-transfer coefficient α at point C is 1.4 times smaller than that at point B. The heat-transfer further decreases in interval CD because of an increase in the thickness of the whole deposition layer on the surface of the pipe.

Since the operation of a heat-release surface is divided into three stages [7] and the boiling characteristics depend for the most part on the run-in stage (see Fig. 1), it is interesting to investigate the influence of this stage on the heat-transfer coefficient (this influence was not detected within the first minutes of the experiments conducted in [8]). Therefore, we carried out experiments on the influence of the operating time of a heating surface on the boiling coefficient α . Experiments were conducted with the use of a rectangular duralumin vessel of capacity ~ 64 liters with observation windows in the side walls. The vessel was equipped with electric heaters and a cover-condenser cooled by running water. Kerosene vapor was condensed in the cover-condenser and was then recycled to the experimental vessel. The transparent walls of the vessel allowed us to photograph and take motion pictures of the process studied. An experimental tube of 12Kh18N9T stainless steel with a diameter $d_{out} = 10 \text{ mm}$, a wall thickness $\delta = 0.2 \text{ mm}$, and an operating length $l = 170 \text{ mm}$ was brought into the electric circuit with the use of copper buses. Conductors for measuring the voltage drop were soldered to an experimental sample at a distance of 5 mm (calculated by the method of [9]) from the point of connection of the heater with the busses for preventing the influence of the losses at the ends. To investigate the physics of the processes considered under various heat-transfer conditions, they were filmed with the use of a high-speed motion-picture camera. The speed of filming was 4500 frames/sec. The exposed and developed cinefilm was examined with the use of a Kupava-16 assembly table. The sample was heated by an alternating current generated by a TK-404 welding transformer of power 100 kW through an AOMN-40-220-75 regulating transformer. The liquid was investigated in the large vessel under the conditions of natural convection at a temperature of 160°C . The following quantities were measured in the process of experiments: the pressure and temperature of the ambient air,

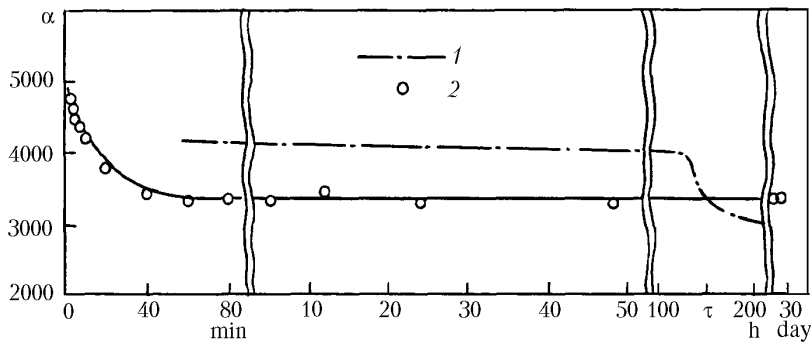


Fig. 3. Dependence of the heat-transfer coefficient on the operating time of a heating surface in the case of boiling of the TS-1 jet fuel ($T_{\text{liq}} = 160^{\circ}\text{C}$) on it: 1) data of [8], $p = 0.2$ MPa, $q = 125$ kW/m²; 2) data of the present work, $p = 0.1$ MPa, $q = 100$ kW/m². α , W/(m²·K); τ , min; h, day.

the pressure of the heat-transfer agent, the temperature of the inner surface of the experimental sample T_{sur} , and the temperature of the heat-transfer agent T_{liq} . The temperature-sensitive elements were chromel-copel thermocouples with thermal electrodes of diameter 0.16 mm. The beads of the thermocouples were soldered to the inner surface of the tube. The above-indicated quantities were measured with the use of oscillographs and electrical measuring instruments. The electromotive-force signals generated by the thermocouples and the voltage and current-strength signals were fed to the input of an N-117 mirror-galvanometer oscillograph (two oscillographs were used). The heat load was determined by the voltage drop across the sample and the current strength. The temperature of the outer surface T_{sur} was determined with account for the temperature drop in the wall.

The heat-transfer coefficient was calculated by the formula $\alpha = q_{\text{sur}}/(T_{\text{sur}} - T_{\text{sat}})$. The current and voltage were simultaneously measured by the electric measuring instruments and the oscillograph. The current strength J was determined by the voltage drop across a noninductive standard resistor connected in the secondary circuit of a UTT-6 current transformer of class 0.2. This voltage was measured by an F 584 voltmeter of class 0.5, the voltage drop was measured by a universal V7-16 voltmeter of class 0.2, and the electromotive force generated by the thermocouples was measured by a universal V7-34A voltmeter of class 0.2.

Estimations have shown that the maximum relative errors in determining the heat-flow density and the heat transfer did not exceed 4 and 11% respectively.

As expected, the coefficient α changed significantly at the run-in stage (Fig. 3). The heat-transfer coefficient of the unrun (new) surface was approximately 1.4 times larger than that of the run-in surface. For comparison, we present data obtained in [8], where this stage was not investigated.

In our experiments, we have not detected a significant influence of the deposits on the intensity of heat transfer in the process of boiling of the TS-1 fuel. After the run-in of the surface, as a result of which the coefficient α decreased by a factor of 1.4 and the critical heat flow increased by two times, the heat-transfer coefficient decreased by no more than 7–8% within 200 h of further boiling under strictly specified conditions. This is evidently explained by the fact that the experiments were conducted under low pressure (atmospheric). It was suggested in [3] that, at atmospheric pressure, deposits are not formed at a temperature close to the boiling temperature. Of course, these data should be verified to be used in calculations.

If the alignment portion is excluded from the dependences obtained (Fig. 4), they agree well with the analogous dependences obtained in other works [10] in both the heat-transfer coefficient (Fig. 4a) and the critical density of the heat flow (Fig. 4b). The total change in many parameters determines the change in the integral characteristics of boiling in the process of run-in of a heating surface. Our data agree well with the data obtained at the Kazan Military Artillery University (KMAU) [3].

The fact revealed is very important for estimating the operation of surfaces with a short operating lifetime, and it can be considered as additional evidence of the three-stage operation of an evaporating heating surface.

The run-in time of the indicated surface depends on many factors, the main of which are the local boiling heat, the pressure, the interaction between the liquid and the wall and the number of virtual centers of vapor formation (i.e., the quality of treatment of the surface, the size and form of the microcracks, and the degree of their saturation

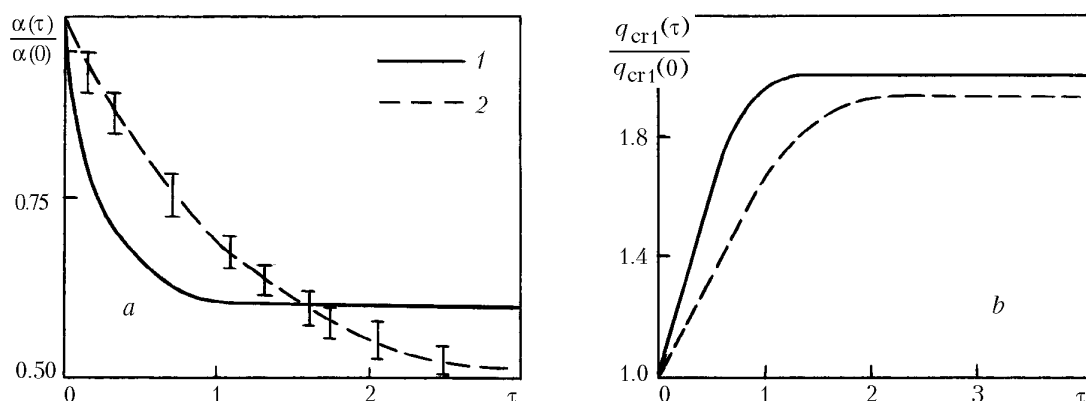


Fig. 4. Dependence of the operating time of a heating surface on the heat-transfer coefficient (a) and the critical heat flow (b) in the case of boiling of fuels in a large vessel: 1) data of the present work (TS-1, 12Kh18N9T); 2) data of [10] (T-6, RT, *n*-octane, C₇-C₁₁ mixture, 12Kh18N9T). τ , h.

with gas). The time of run-in of a heating surface, determined by such a large number of factors, can be estimated only on the basis of experimental data (the proportionality coefficient of q^r) with account for the properties of its material and the technology of its production or, in the first approximation, by the time of deactivation of the vapor-formation centers determined by the calculated adsorption of the vapor-gas inclusions on the heat-release surface. The local instability of the vapor formation and the turbulent heat transfer in the liquid-wall system lead to the formation of local temperatures and heat flows in the near-wall regions of the liquid flow and the solid wall, influencing the boiling process [11]. This influence is characterized by the ratio between the heat-absorption coefficient of the liquid and the wall

$$\Lambda = (c_w \rho_w \lambda_w / (c' \rho' \lambda'))^{1/2},$$

and by the depth of penetration of heat pulsations into the heater material. According to the data of [12], $\alpha \sim \Lambda^{0.4}$ in the first approximation and, according to the data of [13], this dependence for cryogenic liquids is even stronger.

The total influence of various factors on the integral characteristics of boiling can be quantitatively estimated using a traditional method of experimental-data generalization — introduction of the coefficient K_{sur} into the computational relations for α^n or the dimensionless quantities Nu^n :

$$\alpha^n = K_{sur\alpha} \alpha^r \quad \text{or} \quad Nu^n = K_{sur\alpha} Nu^r,$$

where α^r and Nu^r are the heat-transfer coefficient and the Nusselt number of a run-in surface with definite characteristics.

In our opinion, more important parameters (than the run-in time) are the relation between the characteristics of boiling on a run-in surface (i.e., known stable parameters) and the characteristics of boiling on an unrun surface and their dependence on such important factors as the underheating of the liquid to its saturation temperature, the pressure of the liquid, and others. Therefore, we have investigated the characteristics of boiling of the TS-1 fuel on new and run-in heat-release surfaces.

To analyze the influence of the operating time of a heating surface on the boiling characteristics of a hydrocarbon fuel in more detail, we considered works devoted to investigating the influence of the operating time of such a surface on the boiling characteristics of different liquids, water in part.

For any heat-exchange surface, the transfer of heat from it to a boiling liquid becomes stable after a certain time of its operation. The available literature data on the heat transfer in the process of nucleate boiling on run-in and unrun surfaces were obtained for a very narrow range of heat loads and are fragmentary in character [14, 15].

To identify run-in and unrun surfaces, we have experimentally investigated the influence of the run-in time on q_{cr1} and α in the process of boiling of kerosene and water. It has been established that in the process of local boiling

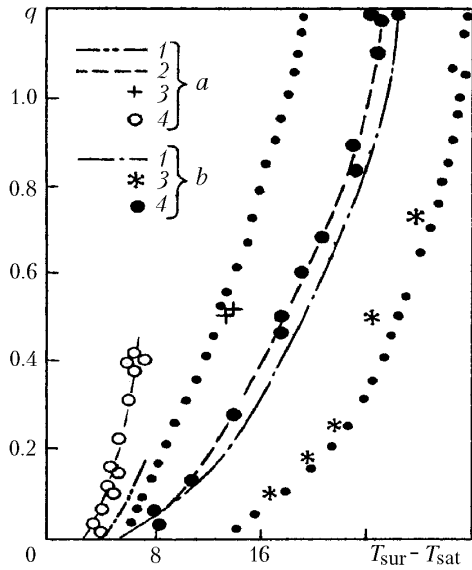


Fig. 5. Temperature dependences of the heat-flow density in the case of boiling of water on new (a) and run-in (b) surfaces: 1) data of [14]; 2) data of [15]; 3) data of [17]; 4) data of the present work. The points denote the dependences for water. q , MW/m^2 ; T , K.

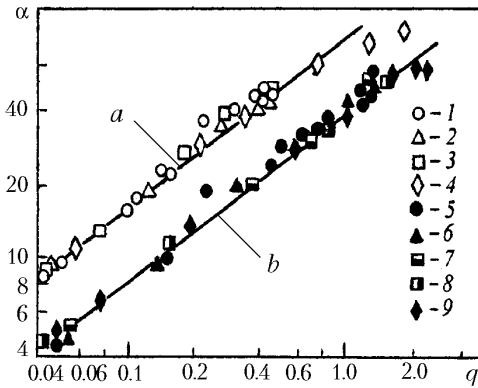


Fig. 6. Dependences of the heat-transfer coefficient on the heat-flow density in the case of boiling of water on new (1–4) and run-in (5–9) heating surfaces: $l = 110$ mm and $F_* = 21.5$ (1–3), 110 mm and 4.59 (4, 5), 110 mm and 21.5 (5–8), and 2.5 mm and 3.25 (9) (1, 2, 4–6, and 9 were obtained for the distilled water; 3, 7, and 8 were obtained for the tap water; 1, 3–5, 7, and 9 were obtained at a horizontal disposition of the tube; 2, 6, and 8 were obtained at a vertical disposition of the tube). $\text{Nu}_* = 0.24 \text{Re}_*^{0.65} \text{Pr}^{1/3}$ (a), $\text{Nu}_* = 0.125 \text{Re}_*^{0.65} \text{Pr}^{1/3}$ (b). α , $\text{W}/(\text{m}^2 \cdot \text{K})$; q , MW/m^2 .

of the TS-1 fuel with $q_{\text{loc}} = 0.06 \text{ MW/m}^2$, the values of q_{cr1} stabilize after 60–70 min (see Fig. 1). The bubbles of absorbed air, gas, and dissolved oxygen arising and collapsing in the fuel and the carbon deposits are responsible for the appearance of a hydrodynamic instability at much lower heat loads. The critical heat load on a new surface is approximately two times lower and its heat-transfer coefficient is 1.4 times higher than those of a run-in surface.

In the process of local boiling of distilled water with $q_{\text{loc}} = 0.2\text{--}0.3 \text{ MW/m}^2$, the values of q_{cr1} and α stabilize after 15–20 min (8–10 min for tap water) and become conventional for these conditions [7]. The critical heat load on a new surface is approximately three times lower and the heat-transfer coefficient is two times larger than those of a run-in surface.

The run-in of a surface and determination of its heat-transfer coefficient were carried out with the use of different vessels. For "purity" of the experiments, each series of experiments was conducted with a new portion of kerosene. These experiments were described in more detail in [5, 6].

Figure 5 shows the curves of boiling of a saturated distilled water on the new (a) and run-in (b) surfaces. This figure also presents the data obtained by other investigators. The experimental data on α of the new and run-in surfaces, generalized with the use of the criterion equation proposed by D. A. Labuntsov in [6], are presented in Fig. 6. He proposed the following criterion equation for the heat-transfer coefficient on a new surface:

$$\text{Nu}_* = 0.24 \text{Re}_*^{0.65} \text{Pr}^{1/3}.$$

The results of our experiments are in good agreement with this dependence.

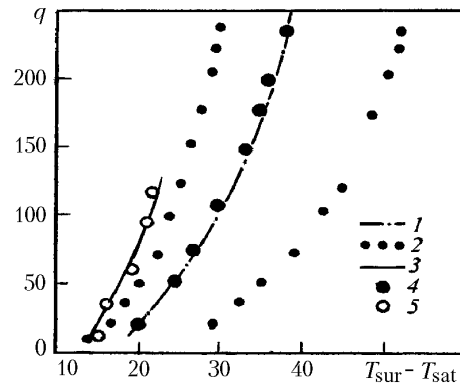


Fig. 7. Temperature dependence of the heat-flow density in the case of boiling of the TS-1 kerosene at atmospheric pressure: 1) equation of [2]; 2) boundary of the Kutateladze equation [14]; 3–5) data of the present work [3] generalizing dependence, $\tilde{\alpha} = 0.197B^{0.106}$; 4) run-in surface; 5) new (unrun) surface]. q , kW/m^2 ; T , K.

Figure 7 presents the experimental data on the heat transfer on the new and run-in surfaces, generalized using the equation proposed in [2]: $\alpha = 0.197B^{0.106}$.

CONCLUSIONS

1. Our investigations have shown that, in the case of boiling of liquids on a heating surface, the values of q_{cr1} and α for the new and run-in surfaces differ significantly due to not a single but a totality of physical effects arising in the process of run-in of the surface. The main of these processes are

(a) removal of the absorbed air from the microcracks (this process is of great importance and manifests itself more pronouncedly at the initial stage of run-in);

(b) appearance of deposits causing a change in the density of vapor-formation centers;

(c) appearance of a scale microlayer decreasing the wetting angle and increasing q_{cr1} .

The run-in time should be determined on the basis of experimental data or, in the first approximation, by the time of deactivation of the vapor-formation centers determined by the absorption of vapor-gas inclusions on the heat-release surface.

2. The values of q_{cr1} and α of the TS-1 kerosene and water boiling on heaters different in shape and size were determined experimentally. Experimental dependences of the boiling characteristics of these liquids on the heat load changing in a wide range (from the onset of boiling to the heat-transfer crises) have been obtained for new and run-in surfaces.

3. The experimental data on the heat transfer in the process of boiling of kerosene on a new surface were generalized using the equation involving dimensionless quantities that was developed for jet fuels in [2], and the analogous data for water were generalized using the criterion equation involving a system of similarity numbers proposed in [16].

NOTATION

a , thermal diffusivity, m^2/sec ; $B = r(\nu\rho'')^{3/2}/(\sigma(\lambda T_{\text{sat}})^{1/2})$, dimensionless quantity; c , specific heat capacity, $\text{J}/(\text{kg}\cdot\text{K})$; d , diameter, mm ; F , area of the heat-release surface, mm^2 ; $F_* = F_{\text{sur}}^{1/2} = (g(\rho - \rho)/\sigma)^{1/2}$, dimensionless area of the heat-release surface; g , gravitational acceleration, m/sec^2 ; J , current strength, A; K , proportionality coefficient; l , working length, mm ; $l_* = c\rho'\sigma T_{\text{sur}}(r\rho)^{-2}$, dimensionless length; p , pressure, MPa; q , heat flow density, W/m^2 ; q_{cr1} , first critical density of the heat flow, W/m^2 ; r , heat of evaporation, J/kg ; T , temperature; K; α , heat-transfer coefficient, $\text{W}/(\text{m}^2\cdot\text{K})$; $\tilde{\alpha} = \alpha(\nu\sigma T_{\text{sur}})^{1/3}/(\lambda q)^{2/3}$, dimensionless coefficient of heat transfer; δ , thickness of the wall, mm ; Λ , ratio between the heat-absorption coefficients of the wall and the liquid; λ , heat-conductivity coefficient, $\text{W}/(\text{m}\cdot\text{K})$;

ρ , density, kg/m³; σ , surface-tension coefficient, N/m; τ , time, sec; ν , kinematic-viscosity coefficient, m²/sec; $Nu_* = \alpha l_* / \lambda'$, Nusselt number; $Re_* = ql_*/(rp''v')$, Reynolds number; $Pr = \nu'/a'$, Prandtl number. Subscripts: cr1, first boiling crisis; loc, local boiling; liq, liquid; sur, surface; sat, saturation; out, outer surface, pr, preliminary; *, dimensionless quantity; w, wall. Superscripts: n, new (unrun); r, run-in; ' and '', quantity for liquid and vapor.

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