# TEMPERATURE CONDITIONS OF DEPARTURE FROM NUCLEATE BOILING AT HIGH PRESSURES

V. P. Skripov and É. N. Dubrovina

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The departure from nucleate boiling is investigated with reference to carbon dioxide boiling on a thin platinum wire. At pressures $p > 0.5\ p_c$ the DNB temperature is close to the maximum superheat temperature.

In describing the departure from nucleate boiling at a hot wall the specific heat flux is usually taken as the controlling quantity. If modeling principles are employed, it can be expressed in terms of the thermophysical parameters pertaining to the saturation line.

In the thermodynamic approach the controlling quantity at a given pressure is the wall temperature $T_w$. The physical premise of the treatment proposed in [1, 2] is the existence of a very sharp temperature dependence of the mean lifetime of the superheated (metastable) liquid [3-5]. If the superheating is sufficient relative to $T_s$, an enormous number of fluctuation vapor nuclei appear in the system. In this sense it is possible to speak of a certain maximum superheat $T_m - T_s$. The temperature of the boiling liquid in the thin boundary layer should not exceed $T_m$. The inequality $T < T_m$ is a necessary, but not sufficient condition of nucleate boiling. Usually, departure from nucleate boiling (DNB) occurs considerably before the maximum superheat temperature can be approached. The reason for this is choking of phase mass transfer near the wall in the presence of a sufficiently large number of active vaporization centers.

The experimenter measures the wall temperature and equates it to the temperature of the liquid adjacent to the wall. This may result in the introduction of errors associated with the difference between mean and local temperatures attributable not only to liquid temperature fluctuations but also to the fact that part of the surface is occupied by vapor.

In [6, 7] a successful attempt was made to describe boiling heat transfer and the maximum heat flux regime by means of the quantity $T_w - T_s$ expressed as a fraction of the difference $T_m - T_s$. In a study of the temperature conditions of DNB in n-pentane and n-hexane it was noted [8] that, as the pressure increases, the DNB temperature $T^*$ and the temperature of developed fluctuation nucleation $T_m$ approach. On the interval $0.6 < p/p_c < 1$ it is found that $T^* \simeq T_m$. Our object was to make a more detailed comparison of the temperatures $T^*$ and $T_m$ for carbon dioxide boiling on a thin platinum wire.

The annealed wire was stretched along the axis of a horizontal channel 40 mm in diameter and 120 mm long in a stainless-steel chamber [9]. The chamber was placed in a constant-temperature water bath. The wires employed were 30 and 50 $\mu$ in diameter and 114, 70, and 37 mm long. The wire served simultaneously as a heater and as a resistance thermometer. The voltage drop across the wire and a standard resistor was measured with a R307 potentiometer. The chamber and the water bath had windows. During the course of the experiments the various boiling regimes were observed and photographed.

At each experimental pressure, determined by the chamber temperature, we recorded the temperature of the wire as the heat flux was raised in small steps. At pressures sufficiently remote from critical DNB develops abruptly. Thus, at $p = 34.8$ bar ($p/p_c = 0.47$, $T_s = 0°C$) the transition to film boiling is accompanied by an increase in wire temperature from 12 to 240°C. DNB was observed visually and registered as a fall in the current in the heater circuit.

Mixed boiling is typical of thin wires with a large length-to-diameter ratio. DNB takes place on individual sections of the wire. Mixed boiling persists as the heat load gradually increases. In this case the

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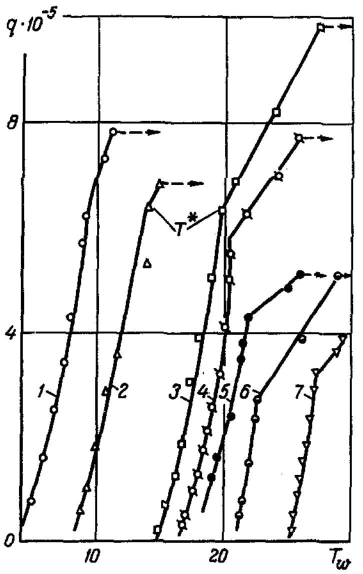

Fig. 1

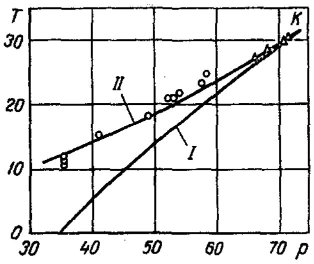

Fig. 2

Fig. 1. Specific heat flux q (W/m$^2$) as a function of wire temperature $T_w$ (°C) for carbon dioxide boiling on the isobars: 1) 34.8; 2) 40.7; 3) 49.2; 4) 51.5; 5) 52.8; 6) 56.6; 7) 63.8 bar. The dashes and arrowheads denote transition to film boiling.

Fig. 2. Comparison of temperatures (°C) of DNB on the isobars (circles and triangles) and the maximum superheat curve (II) at various pressures p in bars [I) saturation line; K) critical point].

mean wire temperature increases more rapidly than in the pure nucleate boiling regime. A characteristic break appears on the $q = q(\Delta T)$, $\Delta T = T_w - T_s$, curves. The abscissa of the break point was taken as the critical temperature head $\Delta T^* = T^* - T_s$ corresponding to DNB. Several experimental curves are shown in Fig. 1. At $T_s = 0$°C the transition to film boiling takes place simultaneously along the entire length of the wire. The results of the experiments are presented in Table 1.

In Fig. 2 the temperatures $T^*$ (points) are compared with the maximum superheat temperatures $T_m$ of liquid carbon dioxide (curve II). The same figure includes the saturation line (curve I). The triangles relate to the experiments described in [10], in which thin wires were employed.

The temperatures $T_m$ for each pressure were calculated from the Döring–Volmer equation (see, for example, [5]) by assigning the spontaneous nucleation frequency $J_1 = 10^6$ cm$^{-3}$ · sec$^{-1}$.

The results presented in Fig. 2 indicate the proximity of the values of $T^*$ and $T_m$ on the investigated pressure range from $p/p_c = 0.5$ to $p/p_c = 1$.

Theoretically, there is reason to anticipate a correlation between the temperature of DNP and the maximum superheat temperature.

There is a known analogy between pool boiling and the vaporization of discrete masses of liquid on a hot plate [11-14]. Experiments on individual-drop heat transfer have shown that the wall temperature T' corresponding to the maximum drop evaporation time is close to the maximum superheat temperature $T_m$ [2, 13]. This agreement is typical only of near-atmospheric pressures. Experiments on the vaporization of drops on a hot plate at saturated vapor pressures up to 10 bar [12] have revealed that the temperature $T_m$ gradually deviates from T' in the direction of lower temperature corresponding to the minimum drop evaporation time. Here, the tendency is qualitatively the same as in pool boiling. The development of a thermodynamic model of DNB has proved more complicated than assumed in [1, 2]. As a result of the prolongation of the effect and depending on the experimental conditions, the reaching of the maximum superheat temperature, as $T_w$ gradually increases, may occur either nearer to the end or nearer to the beginning of DNB. The latter is typical of pressures $p > 0.5\ p_c$. Here a characteristic shortage of vaporization centers may develop.

TABLE 1. Experimental Data on the Boiling of Carbon Dioxide on Horizontal Platinum Wires

| p, bar | $T_s$, °C | $q^* \cdot 10^{-5}$, W/m$^2$ | $\Delta T$, °C | $\alpha^* \cdot 10^{-5}$, W/m$^2$·deg |
|---|---|---|---|---|
| 34,8 | 0 | 7,0 | 10,7 | 0,65 |
| 34,8 | 0 | 7,8 | 11,1 | 0,70 |
| 34,8 | 0 | 7,4 | 11,7 | 0,63 |
| 40,7 | 6,0 | 6,8 | 9,1 | 0,75 |
| 49,0 | 13,3 | 4,7 | 4,8 | 0,98 |
| 51,5 | 15,5 | 5,8 | 5,0 | 1,15 |
| 52,2 | 16,2 | 5,2 | 4,5 | 1,15 |
| 52,8 | 16,8 | 4,2 | 4,7 | 0,9 |
| 56,6 | 19,5 | 2,6 | 3,1 | 0,84 |
| 66,3† | 26,3 | 1,96 | 0,7 | 2,8 |
| 68,4† | 27,7 | 1,56 | 0,7 | 2,20 |
| 70,7† | 29,2 | 0,92 | 0,3 | 3,06 |

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†Data of G. P. Nikolaev and B. A. Kalinin.

Boiling of the liquid begins at the existing centers. These are usually numerous enough to ensure very intense heat transfer and create the conditions for DNB. However, as the pressure increases, changes (increase in vapor density, decrease in bubble break-off diameter) that improve mass transfer in the boundary layer take place in the system. In the presence of a shortage of centers nucleate boiling persists until nuclei of fluctuation origin appear. For this it is necessary to raise the temperature of the heat-transfer surface to $T_m$.

Values of $T^* \cong T_m$ are observed at high pressures for other liquids besides carbon dioxide. They have previously been reported for n-pentane, n-hexane, and sulfur hexafluoride [8]. In [8] the liquid boiled on the outside surface of copper tubes and the temperature $T_w$ was measured with copper – Constantan thermocouples.

The existence of a relation between DNB and maximum superheat is even more definite when the liquid is heated very rapidly [15, 16] as compared with our case of a quasistationary increase in heat load.

## NOTATION

$T_w$ is the wall temperature;
$T_s$ is the saturation temperature at a given pressure;
$\Delta T = T_w - T_s$;
$T_m$ is the maximum liquid superheat temperature;
$T^*$ is the temperature corresponding to departure from stable nucleate boiling;
$q^*$, $\alpha^*$ are the specific heat flux and heat-transfer coefficient corresponding to $T^*$;
$p$ is the pressure;
$p_c$ is the critical pressure;
$q$ is the specific heat flux;
$d$ is the diameter of the wire;
$l$ is the length of the wire;
$J_1$ is the spontaneous nucleation frequency.

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