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THE EFFECT OF PRESSURE ON THE LEIDENFROST POINT OF DISCRETE DROPS OF WATER AND FREON ON A BRASS SURFACE

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Abstract—The Leidenfrost points for freon C51-12, freon 113, carbon tetrachloride and chloroform on a brass surface are determined for pressures ranging to the critical pressure, and curves relating Leidenfrost point and pressure are obtained. The shape of the curve relating Leidenfrost point and pressure, for water, from atmospheric to the critical pressure, and on the same surface, is inferred from experimental determinations up to about 5 atm and beyond that pressure by analogy with the results of the Freon experiments. This shows that, as the pressure increases the Leidenfrost point for water on brass increases to a maximum in excess of the critical temperature, then falls to the critical temperature as the critical pressure is approached.

NOMENCLATURE

T,	initial temperature of drop;
$T_{sat}(T_s)$,	saturation temperature of liquid at ambient pressure;
T_L,	Leidenfrost temperature (surface temperature corresponding to maximum survival time of drop);
T_c,	critical temperature of liquid;
P,	ambient pressure of liquid drop;
P_c,	critical pressure of liquid.

INTRODUCTION

DEPOSITING discrete uniform drops of a liquid of constant temperature on an easily accessible and observable hot surface of controlled temperature, in a controlled atmosphere under pressure, presents many difficulties which have militated against Leidenfrost studies at pressures in excess of atmospheric pressure. These difficulties are greatly increased in the case of water, mainly on account of its high vapour pressure. As in the study of other manifestations of boiling phenomena in which the vapour pressure of water presents insuperable difficulties, it was considered expedient to make the desired experiments on suitable organic liquids of low vapour pressure, Freon in particular. A single heating surface of brass was employed and the Leidenfrost point—defined as the heating surface temperature at which the incident drop of liquid persists longest—was recorded for pressures ranging from atmospheric to the critical. The implications for similar studies on water are interesting.

APPARATUS

A diagram of the arrangement of the apparatus is shown in Fig. 1. The heated surface was brass. Further details may be obtained from [1].

PROCEDURE

At each selected pressure, liquid drops of reproducible size of about 0.029 cm^3 (the average of thirty drops) were deposited on a hot surface of brass through a range of surface temperatures exhibiting the Leidenfrost phenomenon. That surface temperature corresponding to the largest survival time of the drop was taken as the Leidenfrost temperature. The liquids used were—Freon C51–12, Freon 113, carbon tetrachloride, chloroform and distilled water. Experiments on the organic liquids were conducted over the full range of pressures from atmospheric pressure to the critical pressure, while those on distilled water were restricted to a maximum of 100 kN/m^2 for the time being.

Drop uniformity was reasonably maintained after some experience. The lever on the injector had to be depressed gently so that the drop formed easily on the nozzle tip and fell of its own accord on to the hot surface. Any slight variation in drop size, within the limits imposed by this technique, was not a critical matter.

LEIDENFROST POINT AND PRESSURE

Figures 2–5 show that the Leidenfrost points of the fluorocarbon and hydrocarbon liquids examined tend to the critical temperature as the pressure increases and at no time exceed the critical temperature. Freon C51–12 was successfully taken all the way to the critical pressure, but the other organic liquids seemed to be subject to chemical breakdown or the disruptive effect of entrained moisture as the critical pressure and temperature were approached. Perhaps, also, the initial subcooling was not maintained. Nevertheless sufficient data were obtained to show that the Leidenfrost behaviour was similar to that of Freon C51–12. The difference between the Leidenfrost point and the saturation temperation at any given pressure below $\frac{1}{2}$ P_c remained nearly constant for all of the fluids except water. Above that pressure, the difference rapidly decreased, being zero at the critical pressure.

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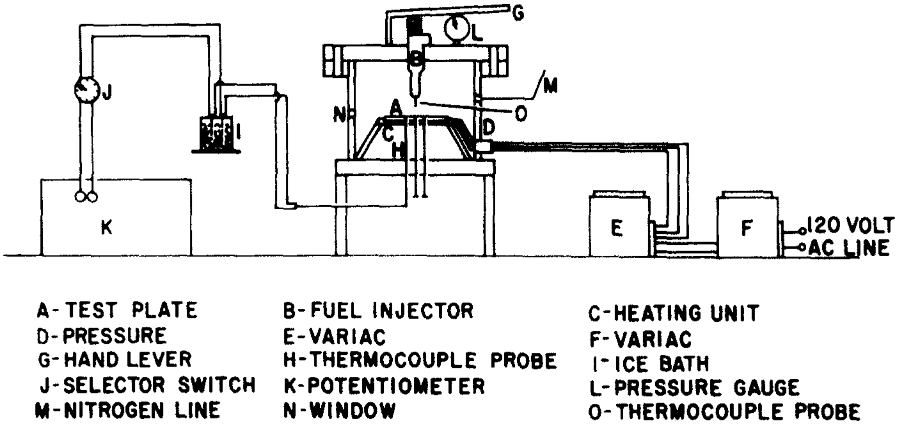

FIG. 1. Schematic diagram of apparatus.

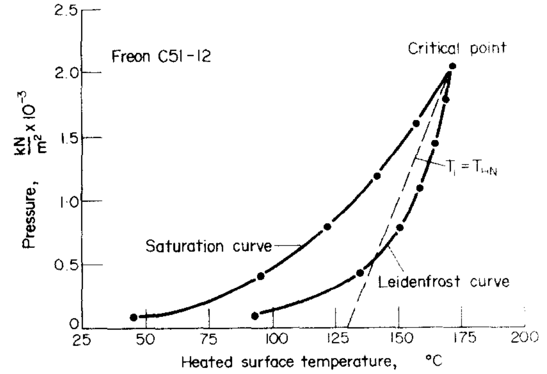

FIG. 2. Effect of pressure on evaporation time and Leidenfrost point for Freon C51-12 on brass.

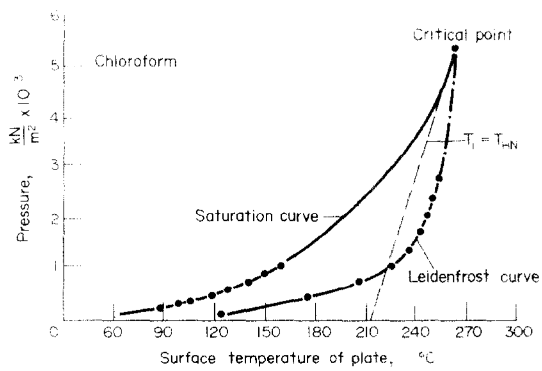

FIG. 5. Effect of pressure on evaporation time and Leidenfrost point for chloroform on brass.

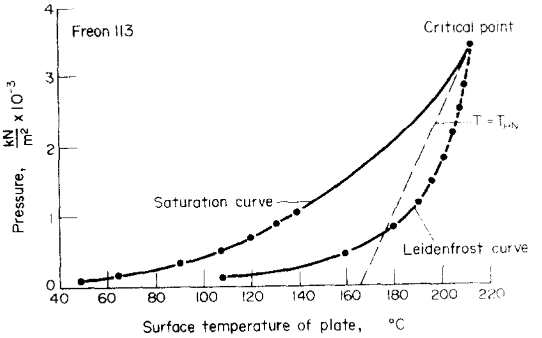

FIG. 3. Effect of pressure on evaporation time and Leidenfrost point for Freon 113 on brass.

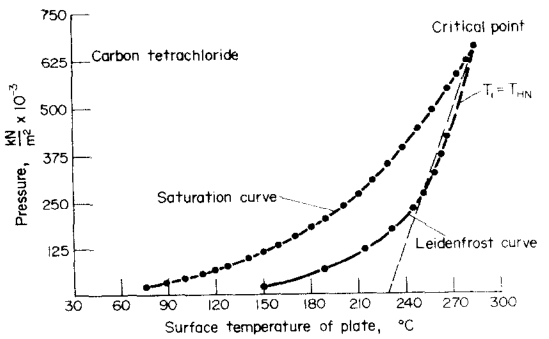

FIG. 4. Effect of pressure on evaporation time and Leidenfrost point for carbon tetrachloride on brass.

In no case—among the organic liquids—did the Leidenfrost point exceed the critical temperature.

An attempt was made to hold the initial temperature of the liquid to 20°C, thus imposing an increasing degree of subcooling as the pressure in the chamber was increased. The subcooled state of the drop made it possible to demonstrate the Leidenfrost point at the critical pressure. In this event an insulating cushion of vapour (or vapour-air mixture) was formed below the drop before sufficient heat had been transmitted to the drop to raise its temperature to an unstable level. It would clearly be impossible to deposit a drop of liquid in the critical condition, i.e. at critical temperature and pressure, on a surface of the same or higher temperature. The slightest exchange of energy from the surface to the drop would, in that case, instantly change the condition of the drop from liquid to vapour. The initial temperature of the drop is therefore important.

The similarities of the Leidenfrost characteristics of the organic liquids (see Figs. 2–5) suggest a dimensionless correlation of the form:

$$\frac{T_{\text{sat}}}{T_L} \text{ vs } \frac{P_L}{P_c}$$

The correlation serves very well for each of the organic liquids considered here and comes close to

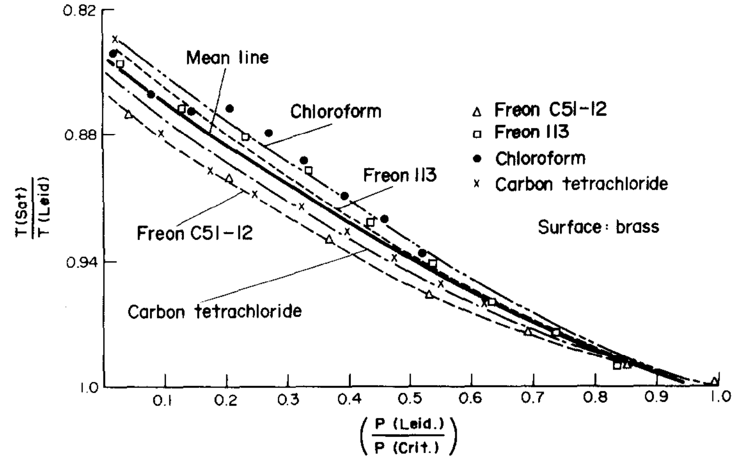

FIG. 6. Dimensionless Leidenfrost correlation for organic liquids.

being a single line as plotted in Fig. 6 with the aid of a root mean square computation.

The results for water, however, do not conform to the correlation suggested for the organic liquids.

The most distinctive difference between the Leidenfrost penomena of water and of the organic liquids studied is that whereas the Leidenfrost points of the latter never exceed the critical temperature, those for water do exceed the critical temperature over a considerable range of pressures. The results of the present experiments suggest that the Leidenfrost curve for water, with drops of a constant initial temperature of 20°C, is of the form shown in Fig. 7.

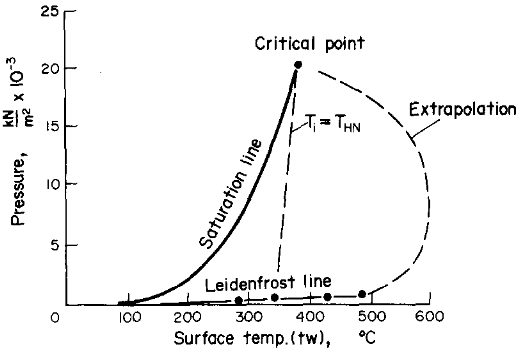

FIG. 7. Predicted Leidenfrost line for water on brass.

Henry and Fauske [2] postulate that when the interface temperature upon contact (T_i) is equal to or greater than what they call the spontaneous nucleation temperature (T_{HN}) of the system, any intimate contacts between the heater surface and the boiling liquid would quickly be interrupted by a vapour blanket formed from a densely packed bubble layer.

T_i is given as:

$$\frac{T_h + T_c(k_c\rho_c C_c/k_h\rho_h C_h)^{\frac{1}{2}}}{1+(k_{cc}C_c/k_{hh}C_h)^{\frac{1}{2}}}$$

It is interesting to plot $T_{HN} = T_i$ on Figs. 2–5 and Fig. 7, from which some correlation is suggested except in the case of water. This raises the question of the reliability of the water data. Perhaps, indeed, contamination of the metal surface has raised the apparent Leidenfrost temperature; but the trend of the data is supported over the same range of pressures (1–5 atm) using monel and stainless steel as well as brass surfaces [1], i.e. in each case the Leidenfrost temperature quickly exceeded the critical temperature as the pressure increased.

THE KEY PROPERTIES

Apart from vapour pressure, the most obvious relevant property difference between the organics and water is the enthalpy of vaporization. This is illustrated in Fig. 8. Also shown in Fig. 8 is the locus of the estimated enthalpy required to change unit mass of liquid from 20°C to dry saturated vapour at each corresponding pressure ratio. The latent heat of Freon is very much less than that of water at all pressures in the range except at the critical point—where both, of course, reach zero.

The relative fractions of heat required to raise the liquid at 20°C to the saturation temperature and to vaporize it are also indicated in Fig. 8. From this it can be noted that the "sensible" fraction of the "total heat" supplied becomes increasingly significant with increase in pressure. In the case of Freon C51–12—and indeed most Freons—the curves are regular and, if not straight lines, gentle curves. This can be said for water

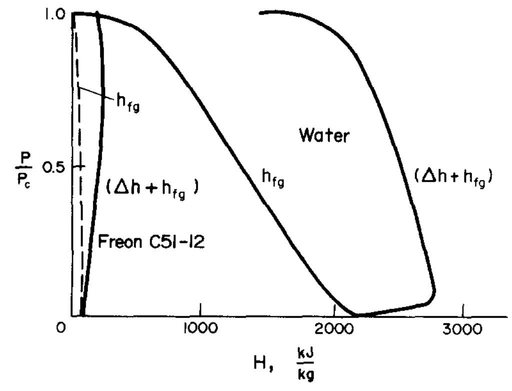

FIG. 8. Comparison of h_{fg} and $(\Delta h + h_{fg})$ for water and Freon C51–12.

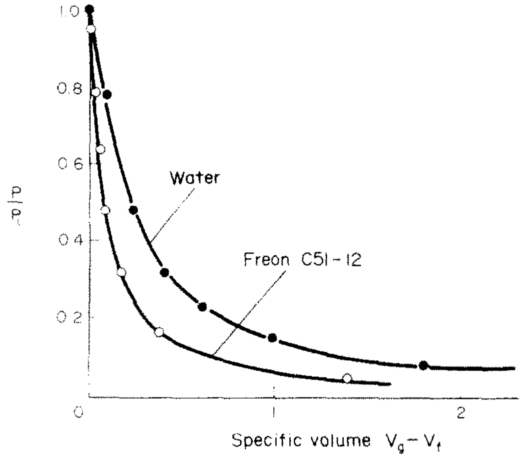

FIG. 9. $(V_g - V_f)$ Correspondence of Freon C51–12 and water.

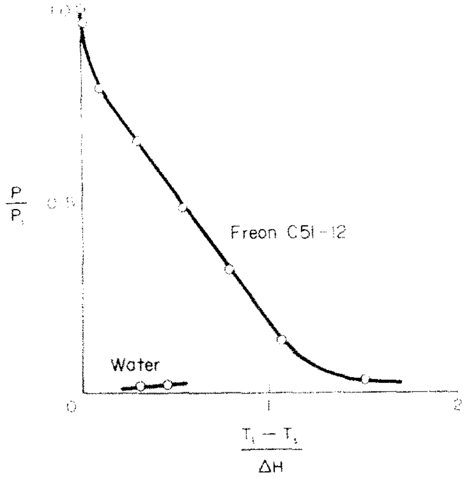

FIG. 10. $P/P_c - (T_L - T_{sat})/\Delta H$ Correlation for Freon C51–12 and water.

only in the range $(0.1 > P/P_c < 0.9)$. In the ranges $(0 > P/P_c < 0.1)$ and $(0.9 > P/P_c < 1)$ there are steep declines in h_{fg} as P/P_c increases. The results of the experiments on water described here fell around $P/P_c = 0.05$, within the region of rapidly declining h_{fg} but rapidly increasing "total heat" (ΔH). The curves of Fig. 8 suggest the kind of differences we may expect in the Leidenfrost curves of water and Freon and hint at a strong influence on the part of latent heat.

A comparison of $(V_g - V_f)$ between water and Freon C51–12 is shown in Fig. 9. This shows that $(V_g - V_f)$ for water greatly exceeds that of Freon between about $P/P_c = 0.08$ and $P/P_c = 0.16$, meeting at zero at $P/P_c = 1$ and tending to infinity at $P/P_c = 0$. The important consideration here, however, is the amount of heat required to establish the requisite thickness of stable vapour cushion against the weight of the drop, and this is taken care of by h_{fg} which includes the term $\int P.\mathrm{d}V$.

The most promising parameters, then, for correlation of Leidenfrost point and pressure are: the saturation temperature (T_{sat}) and particularly the difference between the Leidenfrost point (T_L) and the saturation temperature or the initial temperature of the drop, i.e. $(T_L - T_{sat})$ or $(T_L - T)$; the enthalpy of vaporization (or latent heat) (h_{fg}), or the "total heat"

$$[\Delta H = C_p(T_{sat} - T) + h_{fg}].$$

The dimensionless ratios,

$$\frac{P}{P_c}, \frac{T_L}{T_{sat}}, \frac{T_L}{T_c}, \frac{(T_L - T_{sat})C_p}{h_{fg}} \text{ or } \frac{(T_L - T_{sat})C_p}{\Delta H}$$

are suggestive of fruitful application. All of these were tested in suitable combinations and the best combination proved to be T_{sat}/T_L vs P/P_c as shown in Fig. 6. This correlation had the advantage, of course, of utilizing known properties for all of the liquids considered.

With Freon C51–12, the correlation P/P_c vs $(T_L - T_{sat})/\Delta H$ within the range $(0.15 > P/P_c < 0.8)$ produced a straight line (Fig. 10). The limited results for water are plotted on the same curve and suggest a very different initial trend. The curve $(T_L - T_{sat})$ vs ΔH for Freon (Fig. 11) was very regular and suggested an exponential relationship. The results available for water are too limited to facilitate a similar plot, but do not preclude a curve of like kind.

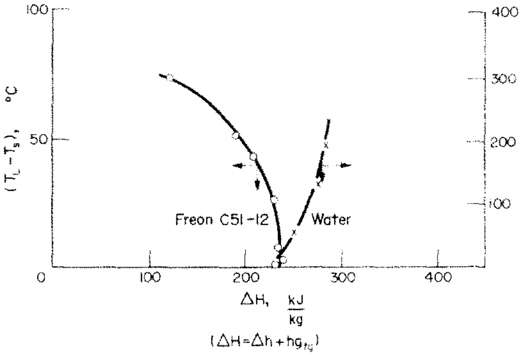

FIG. 11. $(T_L - T_{sat}) - \Delta H$ Correlation for Freon C51–12 and water.

COMMENT ON CORRELATIONS

A general correlation of Leidenfrost points and pressure, applicable to all liquids in common, or even just to Freon and water, seems out of reach, and experience in the related field of boiling heat transfer does not offer any encouragement. The experiments reported here point the direction for future work on water and emphasize the need for it. Much, indeed, could be derived from the determination of Leidenfrost points of water up to pressures of about $\frac{1}{2}P_c$. The superior correlation achieved with $(T_L - T_{sat})$ vs ΔH (Fig. 11) as compared to $(T_L - T_{sat})$ vs h_{fg} (not shown) suggests that subcooling of the drop has to be taken into account and reason would support this at high pressure, as explained below.

SUBCOOLING EFFECTS

In experiments at atmospheric pressure, it has been shown that subcooling of the drop makes little impression on the Leidenfrost point [3–4]. It is likely, however, that this depends upon the enthalpy of evaporation. In the case of water at atmospheric pressure, it is clear that h_{fg} accounts for the major fraction of the heat transmitted to the vapour film. Consequently, the water drop at atmospheric pressure can be expected to be relatively insensitive to subcooling. At higher pressures, however, h_{fg} is markedly reduced and the major fraction of the heat transmitted to the production of the vapour film is employed in raising the temperature of the liquid to the saturation temperature. The influence of subcooling on the Leidenfrost point of water can therefore be expected to be more evident at higher pressures.

The same remarks hold for Freon but to a lesser degree and it is not surprising that the Leidenfrost point of the organic liquids was not found to be particularly sensitive to the degree of subcooling except near the critical pressure. It was, of course, not possible to demonstrate the Leidenfrost phenomenon at the critical pressure unless the drop were subcooled.

The present experiments indicate, therefore, that the initial temperature of the drop has an influence on the Leidenfrost point at higher pressures, particularly if water is the liquid, and that more careful further work has to be done on this.

It is impracticable, however, to deposit uniform drops of liquid of known size at saturation temperature at any pressure. Certainly, the drop deposition apparatus used in the experiments reported here could not be used for this duty. Some subcooling of the drop is necessary in practical experiments—a subcooling which allows of no vaporization of the drop prior to its deposition.

SURFACE FOULING

One uncertain variable in the experiments was the possible contamination of the metal surface either through oxidation or the deposition of residue from the evaporating liquid drops. It has been shown [5], that contamination of the metallic surface raises the Leidenfrost point, as indeed we would expect any insulating film to do. In the experiments reported here, the ambient atmosphere of the drop was air, supercharged with nitrogen. While this could be expected to reduce the rate of oxidation of the hot brass surface, it would not obviate it. The attempt was made to control contamination effects from whatever cause by frequent cleaning of the brass surface and the use of double distilled water in the water experiments; but this, a very impractical procedure in the circumstances, was the best that could be done.

SUMMARY

The Leidenfrost point of Freon C51–12, Freon 113, carbon tetrachloride and chloroform tends to the critical temperature at the critical pressure, and does not exceed the critical temperature. The Leidenfrost point of water on brass appears to exceed the critical temperature as the pressure exceeds about 700 kN/m^2 but can be expected to tend to the critical temperature at the critical pressure. The experiments of [1] indicate that the precise shape of this curve will be influenced by the nature of the surface material. It is suggested that the practical goal, for the prediction of the Leidenfrost point as required for design purposes, is a family of curves relating Leidenfrost point and pressure for a range of surface materials and conditions.

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EFFET DE LA PRESSION SUR LE POINT DE LEIDENFROST DE GOUTTES DISCRETES D'EAU ET DE FREON SUR UNE SURFACE DE LAITON

Résumé—Les points de Leidenfrost du Fréon C51-12, du Fréon 113, du tétrachlorure de carbone et du chloroforme sur une surface de laiton sont déterminés pour des pressions atteignant la pression critique et on obtient des courbes reliant le point de Leidenfrost à la pression. La forme de la courbe pour l'eau, depuis la pression atmosphérique jusqu'à la pression critique, sur la même surface, est déduite des déterminations expérimentales jusqu'à cinq atmosphères et au-delà par analogie avec les résultats relatifs au Fréon. Cela montre que lorsque la pression croît, le point de Leidenfrost pour l'eau sur le laiton croît jusqu'à un maximum supérieur à la température critique, puis décroît jusqu'à la température critique lorsque la pression critique est approchée.

DER DRUCKEINFLUSS AUF DEN LEIDENFROST-PUNKT BEI EINZELNEN TROPFEN VON WASSER UND FREON AUF EINER MESSINGOBERFLÄCHE

Zusammenfassung—Die Leidenfrost-Punkte für Freon C51-12, Freon 113, Tetrachlorkohlenstoff und Chloroform auf einer Messingoberfläche wurden für Drücke, die bis zum kritischen Druck reichen, bestimmt. Es wurden Kurven gewonnen, aus denen der Zusammenhang zwischen Leidenfrost-Punkt und Druck ersichtlich ist. Die Form der Kurve für den Zusammenhang zwischen Leidenfrost-Punkt und Druck für Wasser, von Atmosphärendruck bis zum kritischen Druck und auf derselben Oberfläche, ergibt sich aus experimentellen Bestimmungen bis zu 5 Atmosphären oberhalb dieses Druckes aus Analogie mit den Ergebnissen der Freonexperimente. Es zeigt sich, daß bei einer Druckerhöhung der Leidenfrost-Punkt für Wasser auf Messing ansteigt zu einem Maximum über der kritischen Temperatur und bei Annäherung an den kritischen Druck bis auf die kritische Temperatur fällt.

ВЛИЯНИЕ ДАВЛЕНИЯ НА ТОЧКУ ЛЕЙДЕНФРОСТА ДЛЯ КАПЕЛЬ ВОДЫ И ФРЕОНА НА ЛАТУННОЙ ПОВЕРХНОСТИ

Аннотация — Определены точки Лейденфроста для фреона C51-12, фреона 113, тетрахлорметана и хлороформа на латунной поверхности при давлениях вплоть до критического и получены кривые, связывающие точку Лейденфроста с давлением. По аналогии, на основе экспериментальных данных для фреона при давлении от пяти атмосфер и выше, построен такой же график для воды на той же поверхности при давлении от атмосферного до критического. Делается вывод, что с ростом давления точка Лейденфроста для воды на латунной поверхности растёт до максимального значения, при этом значительно превышая критическую температуру, а затем, с приближением давления к критическому, падает до критической температуры.