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# THE EFFECT OF PRESSURE AND SURFACE MATERIAL ON THE LEIDENFROST POINT OF DISCRETE DROPS OF WATER

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**Abstract**—The maximum evaporation time and Leidenfrost point for discrete drops of water deposited on smooth surfaces of stainless steel, brass and Monel, at pressures ranging to 75 lb/in$^2$ are obtained and compared. The results suggest that, contrary to expectation, thermal diffusivity of the hot surface is not the controlling factor. The evaporation time–surface temperature correlation due to Baumeister *et al.* is substantially confirmed.

## INTRODUCTION

IT HAS long been known that the Leidenfrost point of a discrete drop of liquid varies with the nature of the hot surface on which the drop is deposited. It has also been expected that the Leidenfrost point would vary with pressure, just as the saturation temperature varies although few experiments concerned with this have been reported; the difficulty of conducting Leidenfrost studies at pressure is sufficiently forbidding. With regard to the nature of the hot surface, apart from its roughness, it has been suspected that the thermal diffusivity of the material is the greatest factor influencing the Leidenfrost point of a given liquid drop. For a given liquid on a given surface, therefore, it was to be expected that an increase in ambient pressure would produce a change in Leidenfrost point on account of the change in saturation temperature and the change in thermal diffusivity of the hot surface with temperature. The determination of the Leidenfrost point of water at pressures up to about 70 lb/in$^2$ on three surfaces of different material was expected to confirm these preconceptions, but did not.

## APPARATUS

The principal details of the apparatus are shown in Figs. 1–3, comprising a pressure vessel, a heating surface unit and a drop injector and generator. The more important particulars are as follows:

### *Pressure vessel*

The pressure vessel (Fig. 2) is constructed of carbon steel and water tested to 800 lb/in$^2$. Two 1-in dia pressure glass windows are located 90° apart, the one for the provision of illumination, the other for observation. The interior is coated with aluminium paint.

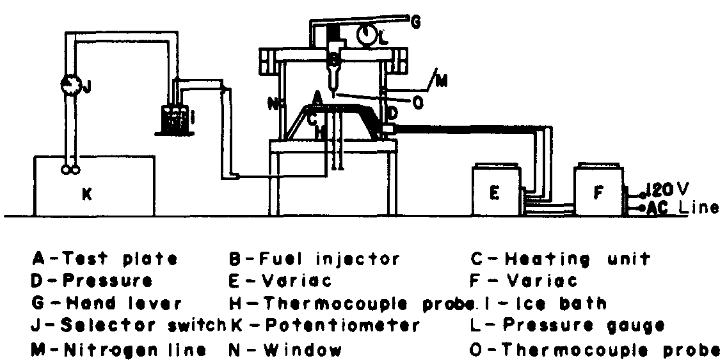


FIG. 1. Schematic diagram of apparatus.

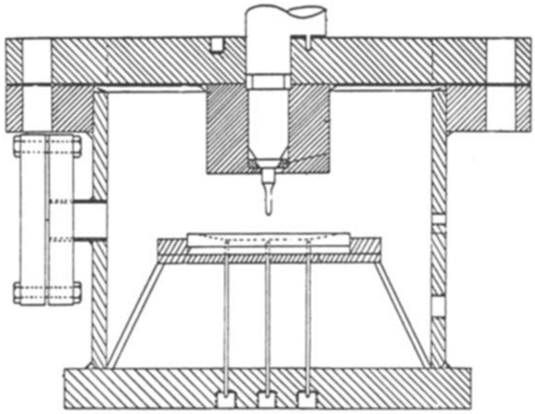

FIG. 2. Pressure vessel and hot plate assembly cross-section.

Pressure is maintained by compressed nitrogen through a pressure regulation valve. Two Heise pressure gauges are used on the vessel with ranges of 1–100 and 1–600 lb/in$^2$ respectively.

*Drop generator and injector*

An 80 mm General Motors oil engine fuel injector was adapted to introduce drops of the selected liquid under pressure. The atomizer was replaced by specially designed brass nozzles of selected diameter. The complete injector unit is shown in Fig. 3.

The injector unit was fitted and sealed to the bolted flange cover of the pressure vessel. It was actuated by depressing the spring-held plunger at the top of the injector body until a drop formed at the tip of the nozzle. A lever was attached to facilitate this and was hand operated. The distance from the nozzle tip to the heating surface was 7/8 in.

To prevent contamination, parts of the injector were "electroless" nickel-plated. Electroless nickel plating is a chemical process by which only a very thin (0·003 in) layer of nickel is deposited.

*Heating unit and heating surface*

The heating unit was designed to raise the temperature of a disk of selected material, which served as the hot surface (Fig. 3), to 1000°F (538°C). The heater comprised a flat spiral of 22 gauge nichrome resistance wire (1·005 Ω/ft) inlaid upon a transite board and covered with a layer of Sauereisen DW30 insulating cement. The thickness of this layer was machined to 0·0625 in, presenting a smooth surface. The element was separated into an inner and outer circuit so that adjustments could be made to flatten the temperature gradient across the surface plate. Each circuit was controlled by means of voltage regulators.

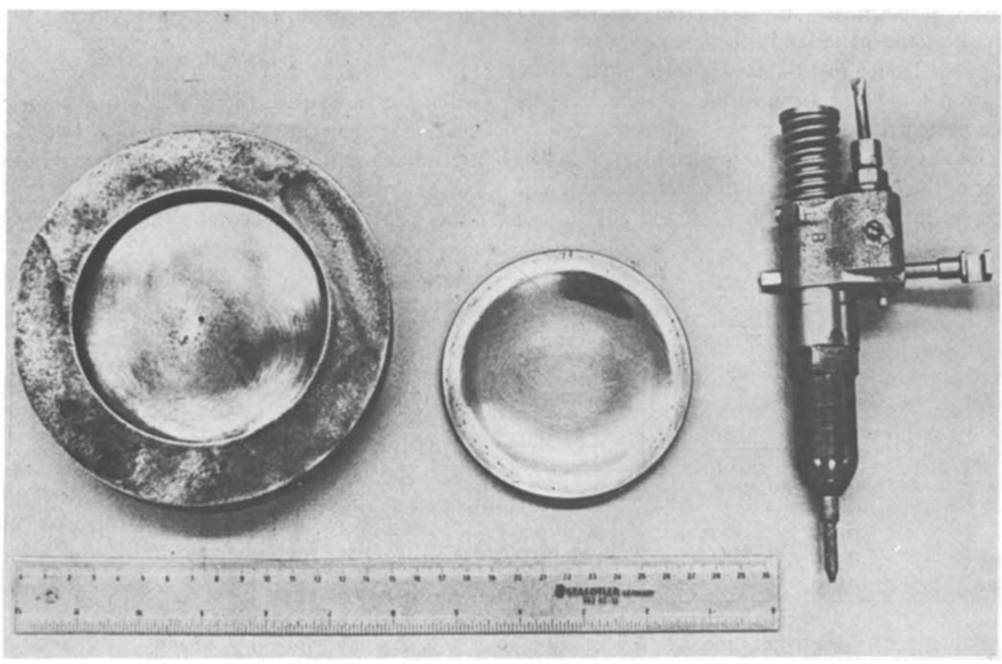

FIG. 3. Heater, disk surface, drop injector.

*Temperature measurement and control*

Five thermocouples were inserted to within 0·0625 in of the surface of the hot surface plate. Each thermocouple lead was protected by an insulating cover of fibreglass and metallic ribbon braid and passed through the heating unit by way of a 0·0625 in O.D. stainless steel tube. Teflon inserts were used in swagelock fittings through which the thermocouples were introduced into the pressure vessel. A sixth thermocouple probe was introduced horizontally one inch above the surface plate, and protected from direct radiation from the plate, to record the ambient temperature.

## PROCEDURE

At each selected pressure, drops of distilled water of constant size were deposited on the heated surface over a range of surface temperatures. The specific pressures selected were: Atmos., 30, 45, 60 and 75 lb/in$^2$, and the surfaces were of stainless steel, brass and Monel. Drop uniformity was sensitive to the manner in which the injector was operated. The lever had to be depressed gently so that the drop formed and fell from the nozzle simply of its own accord. A degree of expertise was necessary to achieve the desired reproducibility.

## EXPERIMENTAL DATA AND DISCUSSION

The effect of pressure on evaporation time and Leidenfrost point, on surfaces of stainless steel, Monel and brass, is illustrated in Figs. 5–7. It is clear from these results that the evaporation time is reduced as the pressure is increased. This is to be expected, the latent heat of vaporization decreases with increase in pressure. The Leidenfrost point, however, increases with pressure, but, as is shown in Figs. 8–10, within the pressure range considered, the value of $\Delta T_{sat}$ (i.e. the difference between the heating surface temperature and the saturation temperature of the liquid), at the Leidenfrost point, is nearly constant in the case of the brass and Monel surfaces, but in the case of the stainless steel surface, it increases markedly as the pressure rises beyond 30 psia.

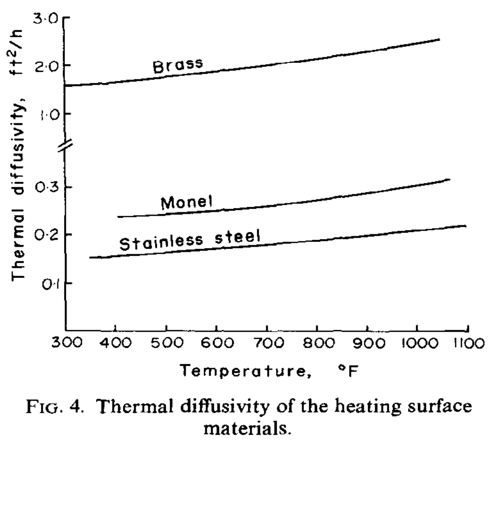


FIG. 4. Thermal diffusivity of the heating surface materials.

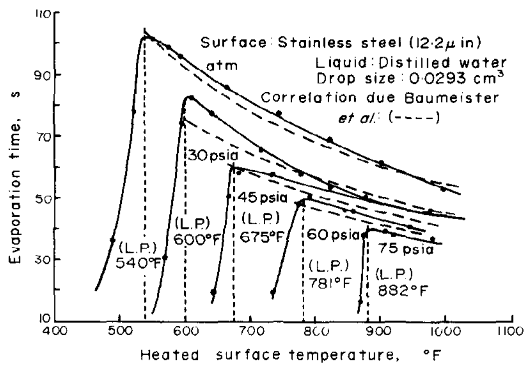


FIG. 5. Effect of pressure on evaporation time and Leidenfrost point for water on stainless steel (roughness 12·2 μin).

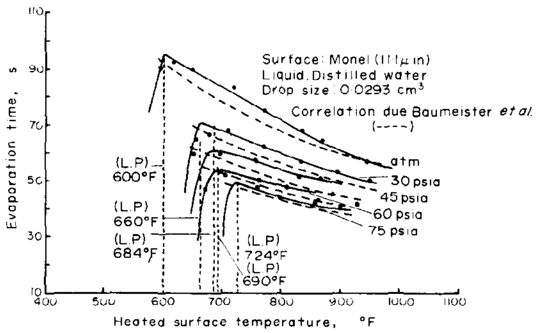


FIG. 6. Effect of pressure on evaporation time and Leidenfrost point for water on Monel (roughness 11·1 μin).

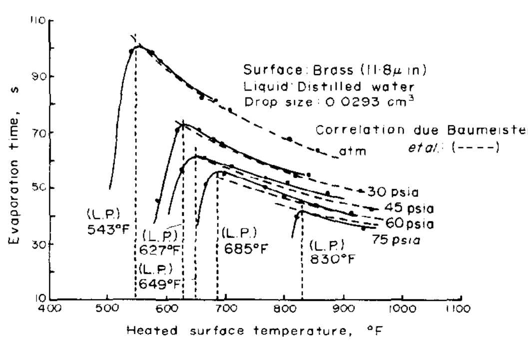


FIG. 7. Effect of pressure on evaporation time and Leidenfrost point for water on brass (roughness 11·8 μin).

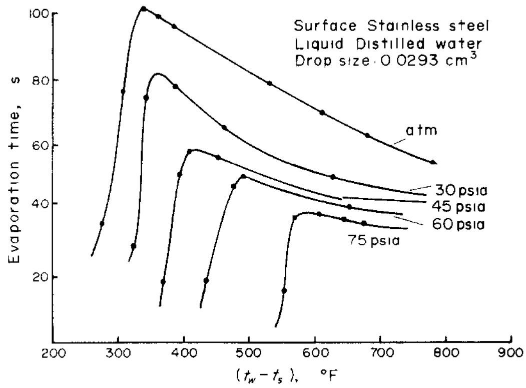


FIG. 8. Effect of pressure [Fig. 5 to abscissa $(t_w - t_s)$°F].

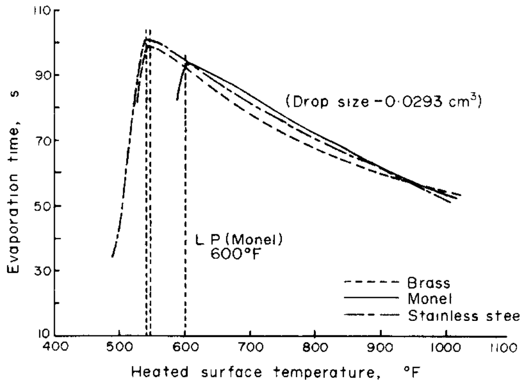


FIG. 11. Effect of heating surface material at atmospheric pressure.

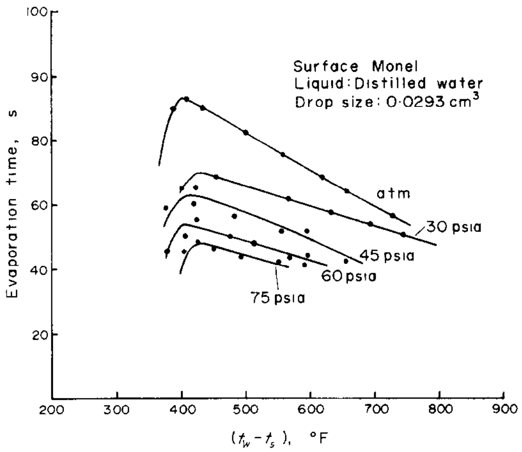


FIG. 9. Effect of pressure [Fig. 6 to abscissa $(t_w - t_s)$°F].

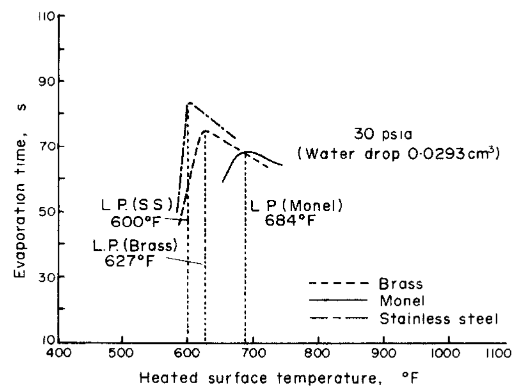


FIG. 12. Effect of heating surface material at 30 lb/in².

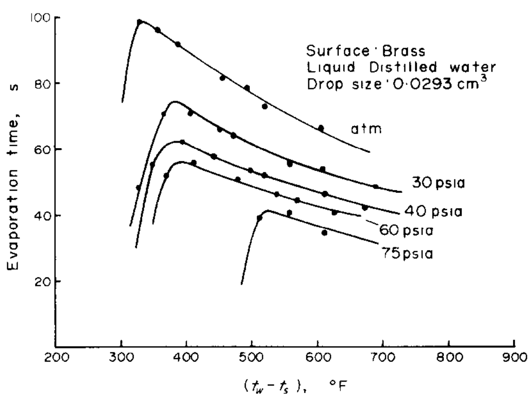


FIG. 10. Effect of pressure [Fig. 7 to abscissa $(\tau_w - \tau_s)$°F].

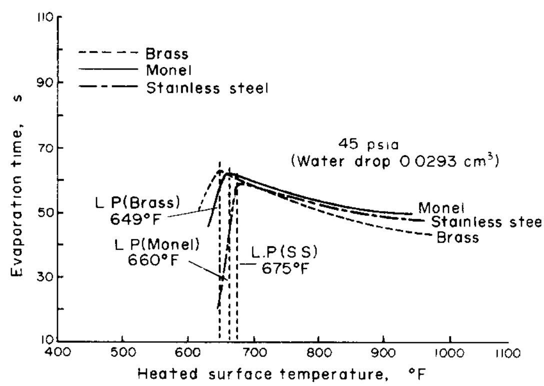


FIG. 13. Effect of heating surface material at 45 lb/in².

Figures 11–15 show a comparison of the Leidenfrost points for the three surfaces at each of the pressures considered. From these it is evident that the Leidenfrost point varies with pressure at a different rate with each of the three materials studied. As the Leidenfrost point increases, however, the maximum evaporation time decreases. Thus at atmospheric pressure (Fig. 11) the ascending order of Leidenfrost points and descending order of maximum evaporation times is: stainless steel, brass and Monel. At 75 lb/in² (Fig. 15) the order is reversed—Monel, brass, stainless steel. The crossover occurs in the range 45–60 lb/in² (Figs. 13 and 14). At

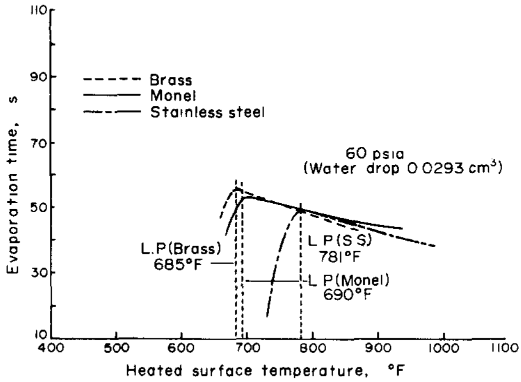


FIG. 14. Effect of heating surface material at 60 lb/in$^2$.

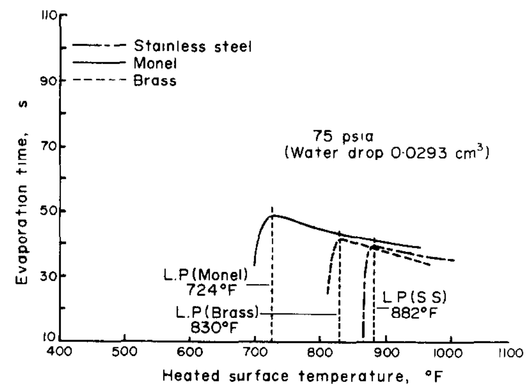


FIG. 15. Effect of heating surface material at 75 lb/in$^2$.

45 lb/in$^2$ (Fig. 13) the Leidenfrost points and maximum evaporation times with the three metals are very close to one another.

The variation in the rate of change of Leidenfrost point with pressure on a given surface could be due to variations in one or other of the following: thermal diffusivity of the metal, emissivity of the metal or of the liquid or both, interfacial tension between the metal and the liquid, and surface tension of the liquid. These variables, with the slight exception of emissivity of the metal and drop, however, are ignored in the evaporation time model developed by Baumeister *et al.* [1] which was found to agree extremely well with the results as shown in Figs. 5–7. The actual Leidenfrost point, however, is not predicted by the Baumeister correlation.

A comparison of the thermal diffusivities of stainless steel, brass and Monel (Fig. 4) and the results illustrated in Figs. 11–15 do not support thermal diffusivity as a controlling factor on the Leidenfrost point. If thermal diffusivity were the controlling factor, one would expect stainless steel and Monel to give similar results for evaporation time and Leidenfrost point, and brass to give significantly higher or lower values than either, at all pressures. This is not the case, pressure alters their relative positions on the evaporation time–surface temperature graph. It must be remembered, too, that the drop often did not remain at any one location on the surface.

This leaves wettability, roughness of the surface, and oxidation of the surface as suspects, with the addition of emissivity in the case of evaporation time. Oxidation of the surface would affect surface finish as well as emissivity and it is possible that some microscopic perturbations of surface finish occurring variously according to the metals involved is the source of the apparent irrationality.

In considering the influence of emissivity of both the surface and the drop, Gorton [2] estimated that in his experiments (at atmospheric pressure) equal heat-transfer coefficients were obtained for the same liquid on different plates after radiation was subtracted. Baumeister *et al.*, however, were disposed to disregard radiation at surface temperatures below 1000°F (538°C). The relevant emissivities for polished surfaces are presented in the following table:

| | Emissivity* | | |
|---|---|---|---|
| Temp. | Stainless Steel (301) | Brass | Monel |
| 500°F | 0·18 | 0·03 | 0·17 |
| 1000°F | 0·25 | 0·035 | 0·18 |

*G. G. Gubareff *et al.*, Thermal radiation properties survey, Minneapolis Research Center, Minneapolis-Honeywell Regulator Co. (1960).

From the table it can be seen that within the metal temperature range concerned in the present case, only stainless steel shows a marked variation in emissivity with temperature. This, however, ignores the effect of oxidation which is reported to be able to raise the emissivity of Monel to about 0·4 (oxidized at 1100°F) and of brass to about 0·6 (oxidized at 1110°F). Likewise that of stainless steel can be raised to about 0·4 or 0·7 depending on the period of exposure to oxygen at temperature. Here again, however, the results of the present experiments seem to preclude emissivity as a controlling factor although it doubtless is a factor. Assuming the heating surface were not oxidized and radiation controlling, then the evaporation times from highest to lowest would be in the order—brass, Monel, stainless steel—stainless steel and Monel would be close together and brass decidedly different. Assuming a degree of oxidation, the order could be Monel, brass, stainless steel, with the Monel and brass further apart than stainless steel to either. This reasoning is not easily reconciled with Figs. 11–15. The oxidation of the heating surface was minimized with frequent cleaning and in the experiments at pressure the drop atmosphere was predominantly nitrogen.

The Baumeister equation, which exhibits close correspondence with the results of the present experiments (see Figs. 5–7), does include a radiation term, but, as mentioned above, Baumeister considers this of little significance below surface temperatures of 1000°F.

Wettability is an even more intractable property. The variation of interfacial tension with temperature is an obscure topic. Certainly, in bulk boiling, the "departure from nucleate boiling" depends a great deal upon the wettability of the heating surface. The less wettable the surface, the lower the D.N.B. point, hence the more readily the liquid enters the film boiling phase. The increasing reluctance of water drops to enter the film boiling stage when placed on stainless steel at higher temperatures (in comparison with brass and Monel surfaces) could be due to a more rapid decrease in the wettability of the surface, i.e. in the interfacial tension between the drop and the metal. The results could suggest, therefore, that stainless steel and brass become more rapidly wettable with increase in temperature than does Monel. Physical data of this kind for these materials are difficult to find even if they exist. The oxide layer which must develop on these surfaces is not completely controlled by regular cleaning and does introduce a very unpredictable complication.

The results presented here show that no single Leidenfrost point correlation with pressure can embrace all surface materials whatever their roughness. The Baumeister correlation is certainly supported by these results, with an average deviation of only 3·6 per cent. This close correspondence suggests that the conductive–convective heat-transfer mechanism postulated by Baumeister is valid.

## SUMMARY

The Leidenfrost point of water varies with pressure in a way peculiar to any given material of heating surface, is probably dependent on the wettability of the heating surface but is substantially independent of the thermal diffusivity of the heating surface.

The maximum evaporation time of a discrete drop of water deposited on a hot surface decreases as the Leidenfrost point increases at any given pressure. It decreases as the pressure increases in a way peculiar to the material and character of the heating surface, and is substantially independent of the thermal diffusivity of the heating surface.

## REFERENCES

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2. C. W. Gorton, Heat transfer to drops of liquid in the spheroidal state, Ph.D. Thesis, Purdue University (1953).