Leidenfrost transition temperature for stainless steel meshes

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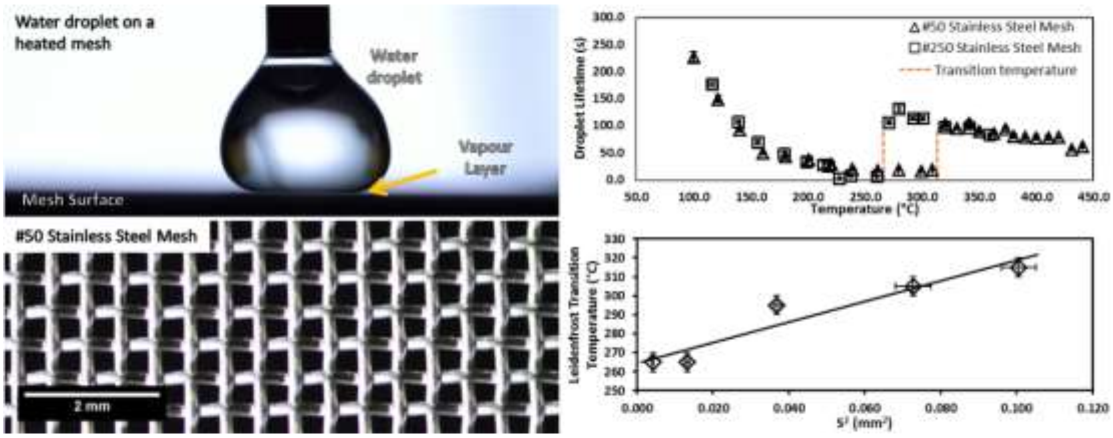
Abstract

On surfaces well above 100°C water does not simply boil away. When there is a sufficient heat transfer between the solid and the liquid a continuous vapour layer instantaneous forms under a droplet of water and the drop sits on a cushion of vapour, highly mobile and insulated from the solid surface. This is known as the Leidenfrost effect and the temperature at which this occurs if known as the Leidenfrost transition temperature. In this report, an investigation of discontinuous surfaces, stainless steel meshes, have been tested to determine the effect of the woven material on the Leidenfrost phenomenon. It was found that with increasing the open area of the mesh pushes up the Leidenfrost temperature from 265°C for an open area of 0.004 mm^2 to 315°C for open area of 0.100 mm^2. This allows suppression of the Leidenfrost effect as it can be increase to over 300°C from 185°C for a stainless steel surface.

Graphical Abstract



1. Introduction

When a droplet of water comes into contact with a surface just above 100°C it will rapidly boil away violently. However, when the temperature of the substrate increases further and the droplet enters the film boiling regime [1], where a vapour layer is produced instantaneously and causes the droplet to levitate on a cushion of its own vapour. The vapour also provides thermal insulation from the surface. The lack of contact with the surface means the droplet no longer boils in the bulk has an extended lifetime; the presence of the vapour layer enables the droplet to become highly mobile. This phenomena, known as the Leidenfrost effect [2], has been studied extensively for rigid solid surfaces [3–5]. Recently, there has been a strong resurgence in interest in the topic, which can be viewed as an example of perfect superhydrophobicity since a levitating droplet can be viewed in some respects as a droplet on a surface with a contact angle of 180^o [5–7]. Examples of recent reports include Leidenfrost-induced drag reduction [8], ratcheted surfaces for droplet self-propulsion [9–14], stabilisation of Leidenfrost vapour layers by superhydrophobic surfaces [15] and a sublimation heat engine [16]. In the majority of these cases, a common aspect is the combination of some form of surface texture or roughness on a substrate, always rigid, with the Leidenfrost effect.

From the perspective of the surface, the Leidenfrost effect can impact negatively on some processes. When the temperature of a solid surface exceeds the Leidenfrost point, the surface exhibits a relatively low heat transfer due to the poor thermal conductivity of the vapour layer. Although this insulation effect extends a droplet's lifetime, it also means a slower rate of cooling of the surface as the dissipation of heat from the surface by the liquid is reduced. Many industries, such as the nuclear industry, rely on the dissipation of heat through contact with cooling liquids and so the ability to increase the Leidenfrost point and delay the onset of the film boiling regime would this process in high temperature systems. Recent studies have shown that an increase in surface roughness can increase the Leidenfrost point [17–19]. There are many potential approaches to achieving a rough surface, such as the use of coatings. However, one alternative method, which has the potential to provide a flexible surface, is to use a simple metallic mesh. Since a hydrophobic mesh with suitable size wires and weave can be superhydrophobic [20], a mesh can be used as a surface in its own right or as an overlay of another surface. However, little is known of the Leidenfrost properties of meshes. In this report the results of experiments to determine the Leidenfrost transition temperature for stainless steel meshes are reported.

2. Transition Temperature Measurement Method

In order to determine the Leidenfrost transition temperature for different surfaces, a custom hot plate was built consisting of a 90 x 90 x 25 mm aluminium block into which two equally spaced 335 W cartridge heaters were inserted horizontally. The heated aluminium block was insulated using a calcium silicate surround and suspended on ceramic posts to prevent heat damage to the surroundings. A surface mount thermocouple connected to a Sestos D1S P.I.D controller was used to regulate the temperature of the hotplate to within ±2 °C. To determine the Leidenfrost transition temperature for the substrates, 75 µL droplets of distilled water, at 98 °C, were observed as they evaporated or boiled off from the surface. The droplets were dispensed using an Eppendorf Multipette® M4. The time taken for the droplets of water to disappear (i.e. the droplet lifetime) was recorded for increasing temperatures of the surface, in 10 °C increments.

Firstly the Leidenfrost point for a polished stainless steel plate was ascertained. The droplet lifetime was recorded 3 times at each temperature, from 80 °C to 300 °C, in 10°C increments. Fig. 1(a) and Fig. 1(b) illustrates the difference between a droplet of water sitting on stainless steel plate of stainless steel at room temperature and that of a droplet levitating above the surface of the plate heated to a temperature above that of the Leidenfrost point. Fig. 1(c) shows droplet lifetime versus temperature. The sharp rise in the droplet lifetime at 185±5°C after the initial fall shows the onset of the film boiling regime and is the temperature at which the Leidenfrost phenomenon is first seen. A static contact angle of 63±2° was measured for the polished stainless steel surface using a Krüss Drop Shape Analyser DSA-30. This result, combined with the transition temperature for the polished stainless steel substrate are consistent with those of Vakarelski *et al* [15], who measured the Leidenfrost transition temperature for stainless steel surfaces with a range of contact angles.

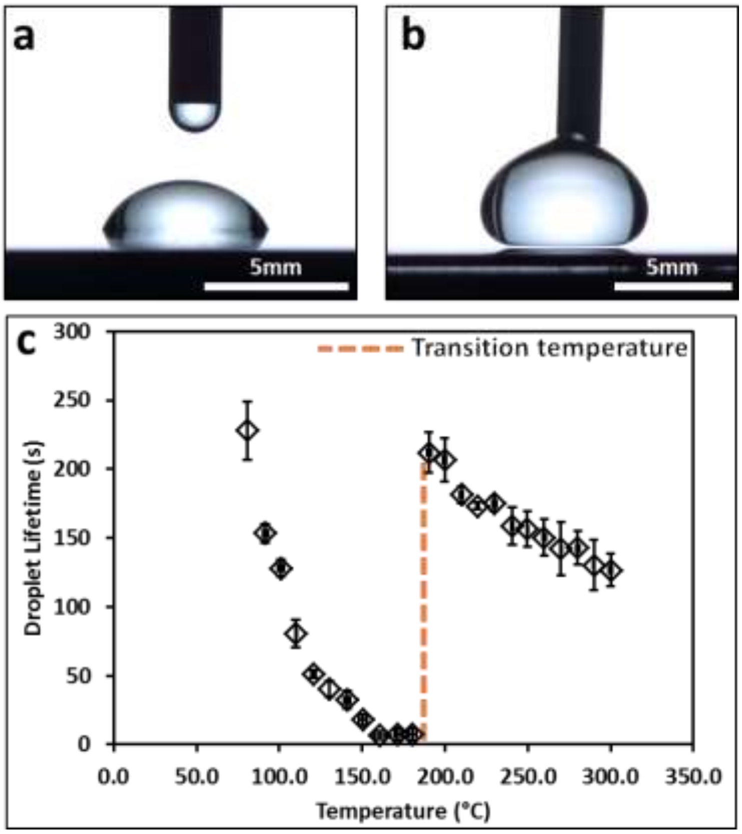


Fig. 1 Images and experimental data for a polished stainless steel surface, where (a) is an image of a droplet of water on a surface at 20 °C and (b) is a droplet of water on the same surface at 250°C. (c) Plot of droplet lifetime for a polished stainless steel surface versus surface temperature. The dashed line indicates the Leidenfrost transition temperature.

3. Stainless Steel Meshes

The stainless steel meshes in this work were plain weaves with square open areas between the wires and with each weft wire passing alternately over and under each warp wire and vice versa (Fig. 2(a)). The meshes are described in Table 1 and range from a #50 gauge stainless steel mesh, which has a wire diameter of 0.193 mm and a wire separation (edge to edge) of 0.317 mm, to a #250 mesh, which has a wire diameter of 0.04 mm and a wire separation (edge to edge) of 0.065 mm. Fig. 2(c) shows an image of a stainless steel mesh showing the pattern of a plain weave of the wires. By using meshes with varying diameter of the wires, *d*, and the separation distance, *s*, between the wires, the Leidenfrost transition temperature was determined for the surfaces of varying dimension.

Mesh Gauge	Material	Weave	Wire Diameter (d) (mm)	Wire Separation (s) (mm)
#50	SS304	Plain	0.193±0.004	0.317±0.010
#60	SS316	Plain	0.145±0.003	0.270±0.013
#98	SS304	Plain	0.077±0.001	0.192±0.004
#150	SS316	Plain	0.065±0.001	0.115±0.004
#250	SS304	Plain	0.040±0.002	0.065±0.002

Table 1. Properties of the stainless steel meshes.

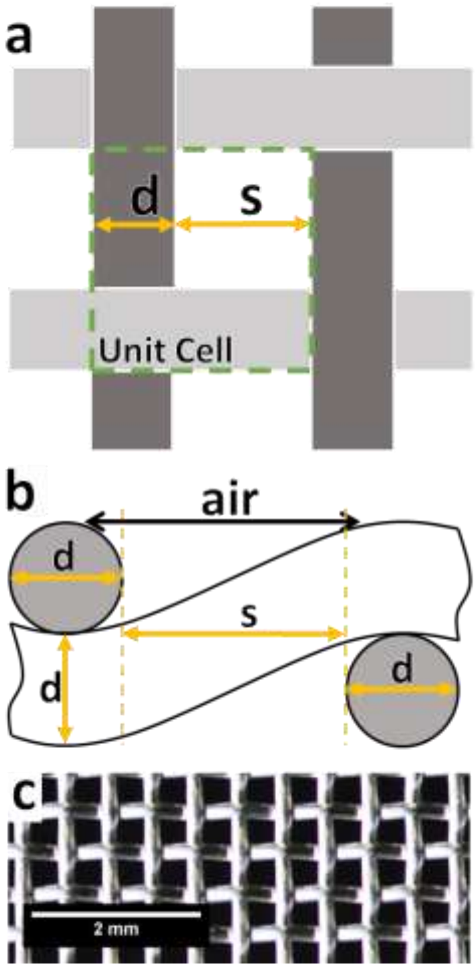


Fig. 2 (a) Illustration of a plain weave mesh. The wire diameter (*d*) and separation (*s*) are indicated. Image (b) side view showing relative contact area (c) image of a plain weave #50 stainless steel mesh.

To determine the Leidenfrost droplet lifetime for the mesh surfaces, a steel frame was made on which a 100 x 25 mm section of mesh could be held taut over a 5 mm high platform which kept the surface flat during the heating process. The mesh together with the frame was placed on top of the custom hotplate and a surface thermocouple was positioned on the top of the mesh surface in order to regulate the average surface temperature of the mesh substrate.

Observations of the droplet lifetime were made in the same manner as for the polished stainless steel, and the temperature range was extended out to 440 °C. Each measurement was repeated three times at each temperature for the five different mesh gauges. An average time was calculated for each temperature step.

A droplet on a polished surface has uninterrupted contact with that surface. Through this contact area the majority of the heat is transferred to the liquid causing it to vaporise. However, when a droplet of water sits on the surface of the mesh, the liquid only makes contact with the wires in the mesh, whilst it bridges the gaps in the wires. This is caused by the surface tension of the liquid and means that the droplet does not penetrate through the mesh. This reduction in solid-liquid contact area means that the heat flux required to generate the supporting vapour layer required for a Leidenfrost state has to be transferred through the reduced contact area between the liquid and the solid wires. This would mean that a higher temperature is needed for the required heat flux to generate a continuous vapour and so produce a Leidenfrost state [21–24].

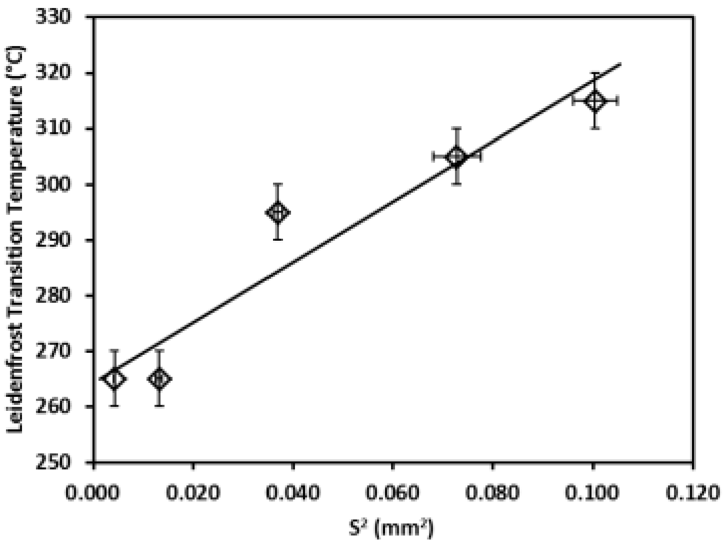


Fig. 3. Graph showing the Leidenfrost transition temperature versus open area (s^2) for five different mesh sizes.

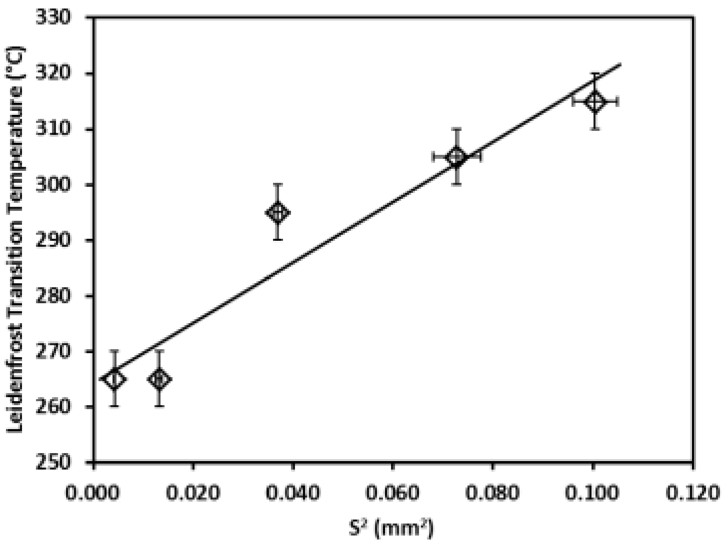


Fig. 3 shows the Leidenfrost transition temperature for the five different meshes with respect to the area in the centre of the mesh (s^2). The increase in the Leidenfrost temperature for the stainless steel meshes follows the increase in the open area. Adding in an additional contribution from the area alongside the wires, as shown in Figure 2(b), degrades the fit, suggesting that this area is not a significant factor. It should be noted that the drops are highly mobile on the surface and so are unlikely to reach a steady state of heat transfer. The results indicate the possibility of tailoring the Leidenfrost point between 245°C and 315°C by selection of an appropriate mesh size. The tailoring of the Leidenfrost transition temperature means that it is also possible to supress the transition point of a stainless steel surface and hence the film boiling regime.

4. Conclusions

In this work we have demonstrated that the Leidenfrost transition point (LTP) for stainless steel can be increased by the use of a mesh rather than smooth surface. The increase in LTP is shown to correlate to the area between the strands of the mesh as would be expected from a simple heat transfer argument. This is important for heat transfer and cooling applications where a film boiling regime is the limitation to the cooling process.

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