EPAPS

Drag Reduction by Leidenfrost Vapor Layers

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Experimental Details

Materials

The perfluorinated liquid used (FC-72, 3M™ Fluorinert™ Electronic Liquid) is a clear, colourless, fully-fluorinated liquid, mostly composed of perfluorohexane (C_6F_{14}) with a boiling point T_C = 56 °C (at 1 atm); heat of vaporization H_{vap} = 88 kJ/kg; liquid density ρ = 1680 kg/m^3 (at 25 °C) and dynamic viscosity μ = 0.64 mPa.s (at 25 °C).

The spheres used were polished grinding balls (FRITSCH GmbH) of various materials: stainless steel (ρ_s = 7.7 g/cm^3, d = 5 – 30 mm); agate (SiO_2), (ρ_s = 2.6 g/cm^3, d = 20 and 30mm); tungsten carbide (ρ_s = 14.9 g/cm^3, d = 5, 10 and 20 mm). Each sphere diameter was determined precisely with a digital calliper micrometre (±0.01 mm) and exact weight measured on a microbalance (± 0.001 g).

Moving sphere experiment

The vessel in which the falling sphere experiments were conducted was a cylindrical tank with height of 2.0 m and inner diameter of 80 mm. The cylinder was made of clear Acrylic with a wall thickness of 5 mm. A wire mesh net was placed inside a small aluminium basket at the bottom of the tank before release in order to facilitate extraction of the sphere and prevent heat damage.

Spheres were heated to the desired temperature in a temperature control furnace for at least 30 minutes. The heated spheres were held by metallic tweezer and carefully released from below the liquid free-surface at the top of the tank. Experiments for the ascending sphere were performed in the same tank with the aid of a pulley system, shown schematically in Fig 1S. A small hole (0.5 mm) was drilled through the centre of the sphere using an electric discharge drill and threaded with a thin metallic wire attached to a fine fishing line (0.3

mm). The line was passed through the pulley and fixed to a counter-weight whose mass was adjusted in order to replicate the velocity and respective Reynolds number for the equivalent falling sphere experiment.

The sphere fall or ascent was monitored by a high-speed video camera (Photron Fastcam SA-1) with a typical filming frame rate of 1000 fps. The instantaneous velocity of the sphere was determined by image analysis in Matlab. Fig. 2S shows examples of the sphere velocity vs. depth during the fall of a 20 mm steel sphere at room temperature (T_s = 25 °C) and in Leidenfrost regime temperature (T_s = 200 °C). Fig. 2Sa shows the velocity along the entire length of the cylindrical tank and Figure 2Sb shows the lower part of the tank at higher resolution yielding a more accurate measurement of the terminal velocity. Multiple trials were performed for each experimental condition to ensure repeatability with maximum error in U_T of less than 0.2 m/s. See Video 2 and Video 4 for examples of falling sphere experiments and Video 3 for an example of the ascending sphere experiment.

Sphere cooling rate

For the 20 mm steel sphere used in determination of terminal velocity temperature dependence presented in Fig. 2 the measured time for cooling from initial temperature of 280 °C to the Leidenfrost temperature of 130 °C was about 45 seconds giving a temperature cooling rate of ~ 3.3 °C.s^{-1}. With a 2 m deep tank used in the experiment, the duration of each experimental drop of the spheres is of the order of 1–2 s, which is enough for the spheres to reach terminal velocity (Fig. 2S). During the experiment time of 1–2 s, the sphere will still remain in the Leidenfrost regime as it would have cooled at most ~ 7 ºC. However, with a sufficiently deep tank, the falling sphere will eventually cool to below the Leidenfrost temperature and there will be a re-entrant effect as drag coefficient increases and the sphere slows down to the terminal velocity of a cold solid sphere

The cooling rate of the steel spheres of different sizes was measured to be approximately inversely proportional to the sphere diameter: about 2.0 °C.s^{-1} for the 30 mm, 3.3 °C.s^{-1} for the 20 mm spheres, 6.5 °C.s^{-1} for the 10 mm sphere, etc.. This is expected as the sphere heat capacity is proportional to R^3 and the heat release rate to R^2. The tungsten carbide spheres cooling rate was similar to that of steel spheres and the agate sphere cooling rates were about 20% higher. In all cases the Leidenfrost regime drag coefficients experimental data for various spheres summarized in Fig. 3 were done at initial sphere temperature of about 200 °C that ensures that the sphere remain in Leidenfrost regime during the entire experiment. The explosive release of bubbles when the sphere cools below the Leidenfrost temperature (Fig. 1b) was also used for visual confirmation that the sphere was in the Leidenfrost regime during the fall experiment.

Estimation of the vapor layer thickness

To estimate the Leidenfrost vapor layer thickness we aligned the focus of the high-speed camera on the edge of a steel sphere held stationary on a magnetic holder inside the FC-72 liquid. A back light illumination is used to observe the "silhouette" images of the sphere. Experimental results for a 20 mm steel sphere are shown in Fig. 3S. The images in Fig. 3Sa to 3Sd are taken at a fix position near the sphere equator (θ = 90º) and images in Fig. 3Se to 3Sh are taken at the bottom of the sphere (θ = 0º). The thickness of the layer is estimated from the reference position at the sphere edge for sphere without vapor layer (Fig. 3Sa and Fig. 3Se). Estimated vapor layer thicknesses are: at the sphere equator from about 200 µm at 260 °C to about 100 µm at temperature just before the rupture of the layer (at ~140 °C); at the sphere bottom from about 120 µm at 260 °C to about 70 µm before layer ruptured. Notice that the layer thickness at the equator will fluctuate with the passing of the surface waves (Video 1).

Notes on Drag Coefficient Determination

To determine the drag coefficient, the measured terminal velocity was first corrected to account for wall effects using the following expression (Newton, 1687)[1S]

$$\frac{U_T}{U_{T\infty}} = \left(1 - \left(\frac{d}{D}\right)^2\right)\left(1 - 0.5\left(\frac{d}{D}\right)^2\right)^{\frac{1}{2}} \qquad \text{eq. S1}$$

Where U_T is measured terminal velocity, $U_{T\infty}$ is the corrected terminal velocity for infinite domain, $d = 2R$ is the sphere diameter and D is the cylinder diameter. The correction factor given by eq. S1 is a good approximation for the case of spheres moving at Reynolds Number in the range 1×10^4 - 2×10^5 which is investigated here[1S]. The drag coefficients were then calculated using the following equation:

$$C_D = \frac{8}{3}\frac{(\rho_s - \rho)gR}{\rho U_{T\infty}^2} \qquad \text{eq. S2}$$

Where g is the acceleration due to gravity, ρ_s is the sphere density and ρ is the liquid density. Notice that both the drag coefficient and Reynolds number presented in Fig. 3 were calculated using the corrected terminal velocity, $U_{T\infty}$.

For the case of ascending spheres pulled upward in the cylinder with a counter-weight the force balance on a sphere moving at terminal velocity is:

$$F_D = F_g^M - F_g^m + F_b - F_{fr} \qquad \text{eq. S3}$$

Where F_D is the drag force, F_g^M gravity force on the counter-weight, F_g^m gravity force on the sphere; F_b is the buoyancy force and F_{fr} is the friction force in the pulley system.

$$F_D = \frac{1}{2}\rho_l(\pi R^2)C_D U_T^2 \quad \text{eq. S4}$$

$$F_g^M - F_g^m + F_b = (M - m + \frac{4}{3}(\pi R^3)\rho_l)g \quad \text{eq. S5}$$

Where M is counter-weight mass and m is the sphere mass. To estimate the drag coefficient of a sphere pulled upward in the liquid in Leidenfrost regime we make the following assumptions: (i) ascending spheres at room temperature have the same drag coefficient as falling spheres at room temperature of corresponding Re number, e.g. for the considered Reynolds numbers range $C_D^R \approx 0.44 - 0.46$ (ii) for each combination of sphere and counter-weight the value of F_{fr} was assumed to be constant, e. g. did not depend on the sphere terminal velocity. At these assumptions the drag coefficients on ascending sphere moving at terminal velocity in Leidenfrost regime, C_D^L can be estimated as:

$$C_D^L = C_D^R\left(\frac{U_{T\infty}{}^L}{U_{T\infty}{}^R}\right)^2 \quad \text{eq. S6}$$

Where $U_{\mathrm{T}\infty}{}^{\mathrm{R}}$ is the terminal velocity of the ascending sphere at room temperature (T_{S} =25 °C) and $U_{\mathrm{T}\infty}{}^{\mathrm{L}}$ is the terminal velocity of ascending sphere at Leidenfrost regime (T_{S} = 200 °C) measured for a given combination of sphere and counter-weight.

Reference:

1S. Di Felice R., Gibilaro L. G., Foscolo P. U., On the hindered settling velocity of spheres in the inertial flow regime, *Chemical Engineering Sciences* **50**, 3005–3007 (1995).

Supplemental Video Legends:

Video 1. Cooling a 15 mm diameter steel sphere in FC-72 filled flat walls container. The sphere is suspended on a Teflon-coated magnetic bar at the rear of the sphere (not visible on the video). The initial temperature of the sphere, T_S = 250 °C. The frame rate used was 62.5 fps with shutter speed set at 1/4000 sec for sharper contrast. Video playback speed is 30 fps, i.e. about two times slower than real time.

Video 2. Combined video showing the fall of a 20 mm steel sphere at T_S = 25 °C, T_S = 110 °C and T_S = 180 °C. For T_S = 110 °C there is an intensive bubble release and for T_S = 180 °C there is a continuous vapor film. The frame rate used was 1000 fps and the video playback speed is 30 fps. See also Fig. 2 in the manuscript.

Video 3. Combined video showing the ascent of a 20 mm steel sphere at T_S = 25 °C and T_S = 200 °C using a pulley and a counter-weight (Fig. 1S). The frame rate used was 1000 fps and the video playback speed is 30 fps.

Video 4. Combined video showing close-ups of the fall of a 20 mm steel sphere at T_S = 110 °C and T_S = 200 °C. The experiments were performed in a tank with square cross-section (80×80 mm) with a height of 1.5 m. The video clips were taken close to the bottom of the tank. The frame rate used was 2000 fps and the video playback speed is 30 fps.

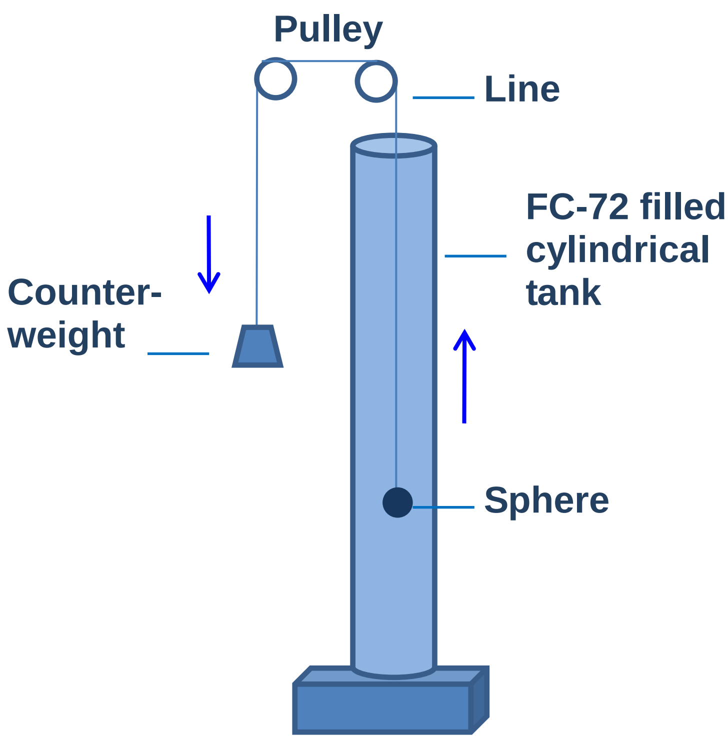
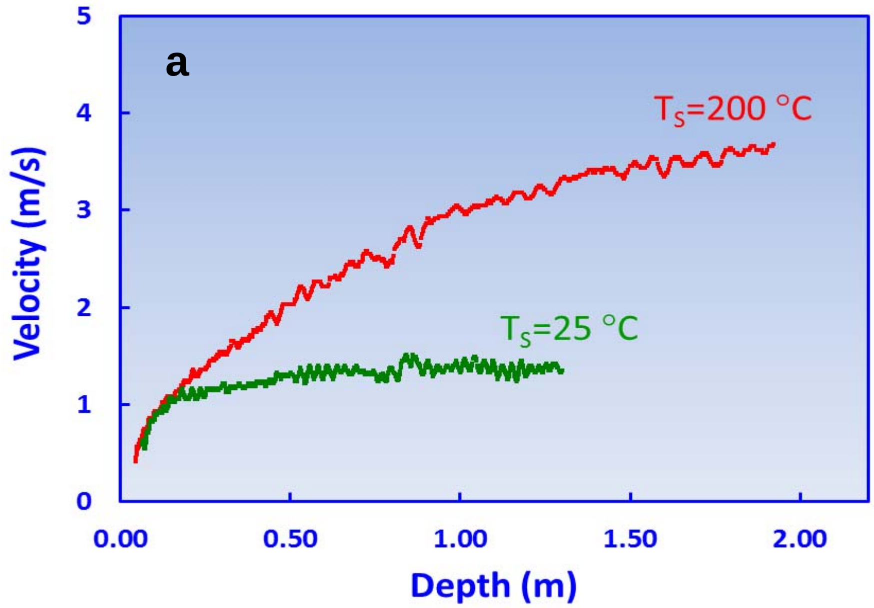


Fig. S1. Schematic of the experimental set-up used for the ascending sphere experiments. See also Video 3.



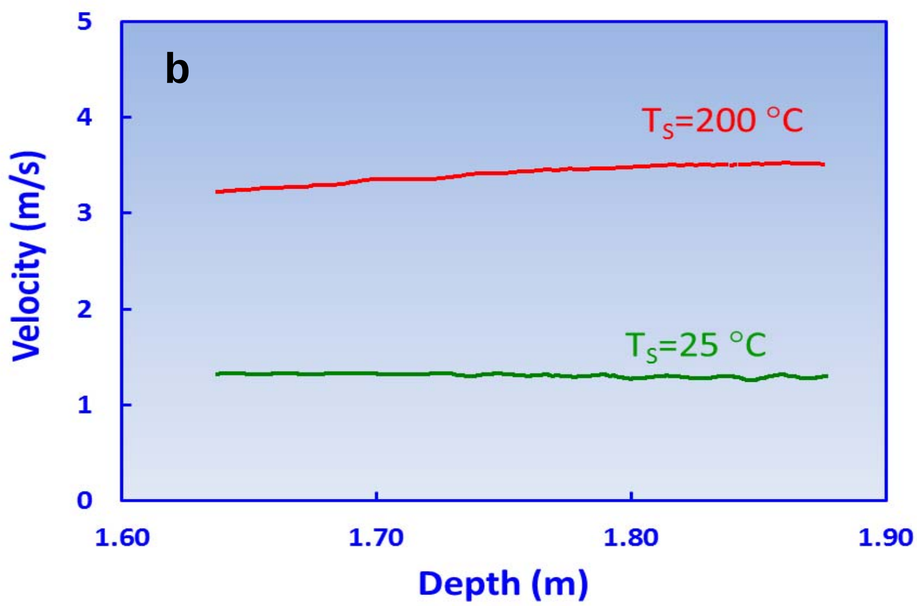


Fig. S2. Velocity vs. depth profiles for the fall of a 20 mm steel sphere at T_S = 25 °C and T_S = 200 °C. (a) Measurements performed over the entire cylinder length. (b) Higher resolution measurements from high-magnification imaging in the lower part of the cylinder.

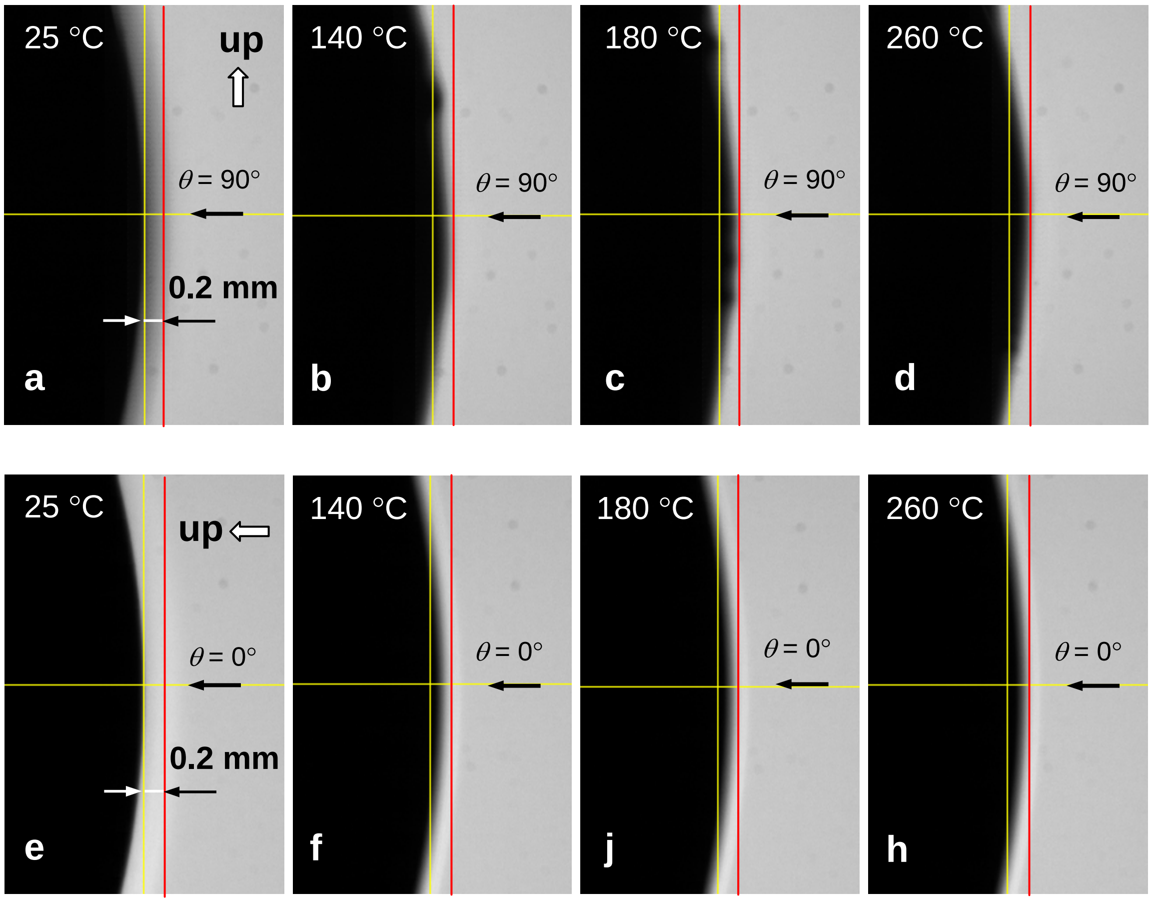


Fig. 3S. Magnified high-speed video frames taken on the edge of a 20 mm steel sphere used to estimate the thickness of the vapor layer as a function of the sphere temperature. Images (a) to (d) are taken at the sphere equator ($\theta = 90^o$) and images (e) to (h) are at the bottom of the sphere ($\theta = 0^o$) with the upward direction marked on frames (a) and (e) for the respective series. A reference sphere at room temperature (25 ºC) for each series is shown in (a) and (e). The temperature corresponding to the other images are indicated on each frame. The Leidenfrost temperature is 130 ºC. In all frames, the location of the sphere surface is indicated by the yellow vertical line and the red vertical line is positioned 0.2 mm from the yellow vertical line.