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EFFECT OF VAPOUR PRESSURE ON POWER OUTPUT OF A LEIDENFROST HEAT ENGINE

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1. INTRODUCTION

In the Leidenfrost effect, when a liquid droplet comes in contact with a surface heated to temperatures significantly above the liquid's boiling point, a vapour layer forms instantly due to which the droplet levitates on the surface [1]. The vapour layer also acts as a thermal insulator that reduces the evaporation rate of the liquid. The same effect is observed for sublimating solids, such as dry-ice [2]. Due to the reduced friction the levitating liquids/solids are highly mobile and can self-propel [2, 3, 4] on asymmetrically textured surfaces such as herringbone patterns [5] or ratchet grooves [4, 6]. The substrate asymmetry rectifies the escaping vapor in a preferential direction, which produces a viscous drag on the levitating component, propelling it in a specific direction. This low friction propulsion can also be used to rotate liquid droplets and sublimating dry-ice disks on asymmetrically textured surfaces [7] or asymmetrically arranged levitating components [8]. We have previously shown that on turbine-like patterned substrates, these rotating droplets can continuously transfer torque to additional surface tension coupled non-volatile solids [9]. This continuous thermal to mechanical energy conversion establishes the concept of a closed cycle Leidenfrost heat engine.

In this Leidenfrost engine, the power output depends on the pressure in the vapour layer that supports the weight of the levitating rotors [3, 9]. Above the Leidenfrost temperature, these rotors demonstrate an invariance in the power output with temperature, thereby hampering its efficiency at increased temperatures [9]. In this work, we demonstrate a method to control this output power by mechanically altering the pressure in the vapour layer. This is achieved by supporting the weight of the evaporating liquid and a coupled solid plate using a bearing assembly and mechanically altering the gap between the solid plate and the heated substrate. Although we introduce a bearing friction by removing levitation, we observe an increase in the terminal speed of rotation, which gives an indication of the increase in power output.

By controlling its power output and understanding the dynamics of rotation of these Leidenfrost rotors, these Leidenfrost engines opens possibilities of developing heat engines for power generation at millimeter and sub-millimeter scales. At microscales the virtually frictionless vapor bearing can be advantageous for energy harvesting [10], while at macroscales, operation in micro-gravity conditions, such as for space and planetary exploration, can be a potential application. These engines can provide transportation ease by using alternate naturally occurring substances such as ices of H_2O, CO_2 and CH_4 in extreme temperature and pressure conditions for thermal energy harvesting [11,12].

2. METHDOLOGY

The experimental setup, shown in Figure 1, comprises of an aluminum solid component connected to a z-axis motion stage through a bearing assembly, to allow for free rotation above the turbine-like substrate. The solid component comprises of a shaft and a plate which is coupled via surface tension to an evaporating liquid. The substrate is heated to temperatures above 280 °C to ensure a thin-film boiling regime. Liquid is continuously supplied to the assembly via a syringe pump. As the assembly is lowered onto the substrate, the liquid comes in contact with the hot substrate and undergoes thin-film boiling. The escaping vapour is rectified which is observed as rotation of the

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solid plate. The angular speed of the plate is tracked over time for different gaps (H) to ascertain the final constant angular speed (termed as the terminal angular speed).

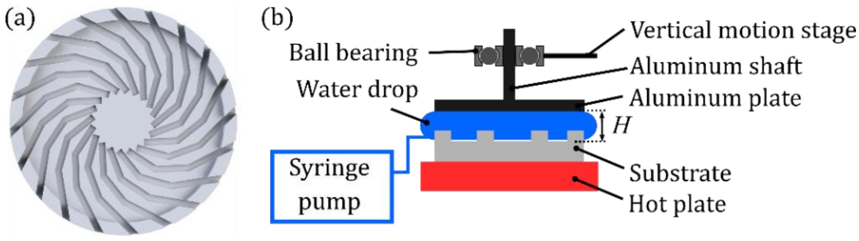

Fig. 1 (a) Depiction of the turbine-like substrate. The groove depth is 100 µm. (b) Experimental setup.

3. RESULTS

Figure 2(a) shows the variation of angular speed of the plate with time as it accelerates from rest to an eventual constant speed. The rotation of the coupled liquid-solid components is driven by the torque from the vapor flow over the substrate and is resisted by an inertial resistance due to liquid deformation over the substrate [5, 9]. The equation of motion of this coupled liquid-solid rotor can be written as [9]:

$$I\dot{\omega} = \Gamma_v - c_i\omega^2, \quad (1)$$

where, ω is the angular speed of the rotor, I is the inertia of the rotor, Γ_v is the driving torque from the vapour flow and c_i is the coefficient of inertial resistance due to liquid deformation. The solution to equation (1) is obtained as $\omega = \omega_t \tanh(t/\tau)$, where ω_t is the terminal velocity as $t \to \infty$ and τ is the relaxation time which is a measure of the rotor acceleration. By fitting the equation (1) on the experimental data, the starting torque on the rotor can be calculated by $\Gamma_v = I\omega_t/\tau$. However, as the rotation speed increases, the centrifugal force on the liquid forces droplets to eject from the gap. This droplet ejection releases some built-up pressure in the liquid, which leads to a momentary drop in the speed, as indicated in Figure 2(a). As a result, due to this random droplet ejection event, the rotor configuration changes frequently during acceleration that does not provide a reliable fit for torque estimation. Therefore, we rely only on the terminal angular speed as a measure of power output from rotation.

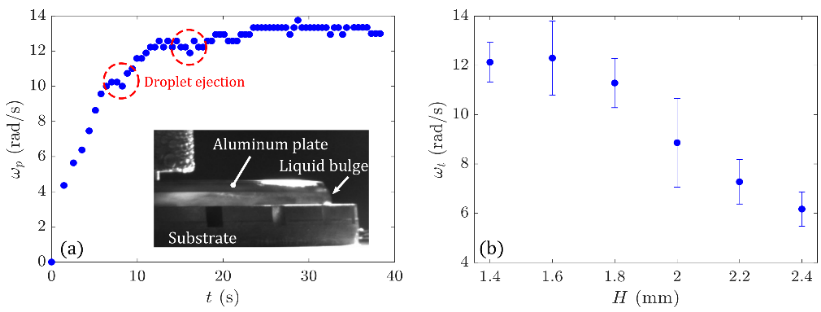

Fig. 2 (a) Plate rotation speed over time. (b) Comparison of terminal speed for different gap thickness H.

Figure 2(b) shows an increase in the terminal angular speed with decrease in the gap between the plate and the substrate above the Leidenfrost temperature. For a given volume of liquid between the plate and the substrate, a change in the gap H alters the liquid distribution over the substrate which can be observed from the extent by which the liquid bulges out of the assembly, as depicted in Figure 1(b) and seen in the inset of Figure 2(a). For instance, for a decreasing H, the curvature of the liquid bulge will increase. This liquid bulge indicates an increase in the pressure in the liquid. Considering that the radius of the substrate is an order of magnitude higher than H, the capillary pressure in the liquid can be approximated as $P_c \approx 2\gamma/H$. Therefore, as H decreases, the pressure in the liquid increases, which corresponds to an increase in the vapour layer pressure. An increase in the vapour layer pressure results in a higher torque and, by extension, terminal speed [3], which agrees with our observations in Figure 2(b). Due to the high pressure at the centre of this Leidenfrost pool, a vapour bubble develops [13], which is aided by the centrifugal force due to rotation. As a result of this bubble, the liquid distribution over the substrate assumes the shape of a ring. This bubble formation is suppressed by the hydrostatic pressure from the liquid pool. Therefore, at lower values of H, and at higher temperatures, the bubble formation is enhanced and the radius of the liquid ring increases [9]. As a result, a smaller area of the liquid levitates over the substrate and therefore reduces the generated torque. This reduction in the area covered by the liquid ring is observed as a saturation in the terminal angular speed, despite the increased pressure due at decreasing H. Nevertheless, despite the added friction from the bearings, the speeds obtained here are higher than that obtained in the case of pure levitation (~ 10 rad/s) [9].

4. CONCLUSIONS

In the present work we have demonstrated a method to control the power output (via the angular speed) of a conceptual Leidenfrost heat engine. Although we remove the low friction aspect of levitation by supporting the rotors with a friction-included bearing, we observe an increased angular speed of rotation by decreasing the gap between the substrate and the plate. Therefore, this configuration of a Leidenfrost rotor allows us to control and increase the output power beyond that obtained in the case of levitation only. These design principles can be extrapolated to alternative liquid and solids to develop engines utilizing thin-film boiling for eliminating friction. Potential applications of such engines can be in extreme environments with naturally occurring low pressures and high temperature differences, such as in space or for planetary exploration. Additionally, their virtually frictionless operation can be used for developing microscale engines for thermal energy harvesting.

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