

1 **Abstract**

2 The Leidenfrost effect – the levitation and hovering of liquid droplets on hot solid surfaces –
3 generally requires a sufficiently high substrate temperature to activate liquid vaporization. Here
4 we report the modulation of Leidenfrost-like jumping of sessile water microdroplets on
5 micropillared surfaces at a relatively low temperature. Compared to traditional Leidenfrost effect
6 occurring above 230 °C, the fin-array-like micropillars enables water microdroplets to levitate and
7 jump off the surface within milliseconds at a temperature of 130 °C by triggering the inertia-
8 controlled growth of individual vapor bubbles at the droplet base. We demonstrate that droplet
9 jumping, resulting from the momentum interactions between the expanding vapor bubble and the
10 droplet, can be modulated by tailoring of the thermal boundary layer thickness through pillar height.
11 This enables regulation of the bubble expansion between the inertia-controlled mode and the heat-
12 transfer-limited mode. The two bubble growth modes give rise to distinct droplet jumping
13 behaviors characterized by constant velocity and constant energy regimes, respectively. This
14 heating strategy allows the straightforward purging of wetting liquid droplets on rough or
15 structured surfaces in a controlled manner, with potential applications including the rapid removal
16 of fouling media, even when located in surface cavities.

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1 Research on the Leidenfrost effect dates back to Johann Gottlob Leidenfrost's observation of
2 water droplets' blistering motions on a hot surface in the 18th century.^{1, 2} Since then, intensive
3 research has addressed this intriguing phenomenon due to its critical importance in various
4 applications such as boiling heat transfer³, spray cooling⁴, electrospray printing,^{5, 6} and additive
5 manufacturing⁷. It is widely accepted that the continuous vapor cushion⁸ formed beneath the
6 Leidenfrost droplet eliminates the physical contact between the droplet and the surface⁹ and
7 consequently minimizes the interfacial hydrodynamic resistance¹⁰ associated with the contact line
8 pinning and solid-liquid friction¹¹, which is particularly useful for agile droplet manipulations^{12, 13}
9 and sustained liquid transport^{10, 14}. However, the thermally-insulating vapor cushion also incurs a
10 large thermal resistance³ and leads to the severe degradation¹⁵ of solid-liquid heat transfer, which
11 is why a substantial surface temperature, *i.e.*, the Leidenfrost point (LFP), must be reached to
12 sustain the intense liquid vaporization essential for droplet levitation. For water droplets on smooth
13 metal surfaces, LFP is usually around 250 °C¹⁰ whereas the effective heat flux is only one third of
14 that on a 110 °C temperature substrate^{16, 17}. Therefore, activation of the Leidenfrost-like droplet
15 levitation without sacrificing the heat transfer performance deserves further research. Possible
16 measures include surface engineering and wettability modifications¹⁸ that can alter liquid
17 vaporization and vapor bubble dynamics during the phase-change heat transfer.

18 As such, achieving maneuverable droplet levitation on hot engineered surfaces will be of great
19 benefit for many applications in highly demanding heat transfer devices^{19, 20}. One of the prominent
20 examples is the purging of surface fouling agents²¹, *i.e.*, the physical deposition of contaminating
21 particulates on heat exchanging surfaces, which severely impairs the performance of thermal
22 systems like boilers, condensers, and heat exchangers by impeding the effective heat exchange
23 between the working liquids and the solid surface. In particular, this problem becomes further
24 exacerbated for engineered heat transfer surfaces²² that incorporate corrugations, posts, pyramids,
25 and fins. In this scenario, neither Leidenfrost droplets nor cold droplets at room temperature, such
26 as in spray cooling and tap water rinsing, can effectively remove the sticky fouling materials from
27 surface roughness and cavities. The presence of a continuous vapor layer prevents Leidenfrost
28 droplets from penetrating surface structures and contacting the fouling particles, whilst factors
29 such as contact line pinning and interfacial friction also hinder the capability of cold droplets to
30 effectively dislodge contaminants from wetted surfaces²³. Methods to address these problems
31 include the redesign of surface textures that allows the controllable wetting²⁴ and self-purging²³ of

1 sessile droplets in a controllable manner, *i.e.*, the lotus effect, but the problem still remains a
2 challenge.

3 In this work, we report a new discovery where controllable levitation and purging of sessile
4 Wenzel-state droplets can be achieved at a temperature well below traditional LFP on an
5 engineered surface decorated with micropillar arrays. Here we show that a fin-like micropillar
6 array that penetrates into the droplet base significantly enhances the solid-liquid heat transfer and
7 facilitates the propagation of the thermal boundary layer (TBL)²⁵, which fosters a superheated
8 environment for inertia-controlled bubble growth²⁶. The immense momentum gained from the
9 droplet-bubble interaction eventually stimulates prompt droplet levitation and instantaneous
10 jumping at a markedly low temperature of 130 °C. Decreasing the micropillar height switches the
11 vapor bubble growth to a heat-transfer-limited mode²⁷ where the otherwise continuous bubble
12 growth is interrupted by vapor condensation at the bubble-droplet interface, causing significant
13 and prolonged vibration of a droplet prior to its jumping. We reveal the mechanisms underlying
14 the tunable Leidenfrost-like droplet jumping by developing appropriate physical models to
15 elucidate the roles of fine surface structures on bubble dynamics. Importantly, we demonstrate its
16 applications in the facile removal of fouling materials from the cavities of hot engineered surfaces.

17 The surface, which consists of a square lattice of round posts with uniform diameter (D
18 = 20 μm), post-to-post spacing ($L = 120 \mu\text{m}$) and height ($H = 80 \mu\text{m}$), hereafter named as
19 $[D, L, H] = [20, 120, 80] \mu\text{m}$, was fabricated on a silicon wafer by means of photolithography
20 and deep reactive ion etching.²⁸ A thin layer of fluoropolymer was then applied via spin-coating
21 to lower the surface energy of the substrate. The droplet levitation experiment was conducted by
22 recording the dynamic behaviors of a sessile water droplet (diameter $D_d \sim 2 \text{ mm}$) by a high-speed
23 camera at the rate of 10000 frames per second (Extended Data Fig. 1). At room temperature, the
24 droplet remained in a stable Wenzel state²⁹ with a static contact angle of $118^\circ \pm 1^\circ$ and a sliding
25 angle of $67^\circ \pm 1^\circ$ (Extended Data Fig. 2), due to the sparse distribution of micropillars. After the
26 sessile droplet and the substrate were gently transferred onto a hot plate maintained at 130 °C
27 (Extended Data Fig. 3), the droplet could be levitated and jump off in a Leidenfrost-like manner,
28 *i.e.*, prompt droplet levitation enabled by the liquid vaporization.

29 The “cold” Leidenfrost phenomenon on modestly heated substrates has been reported in the
30 past^{11, 30, 31, 32}. However, what distinguishes our observations from those reported previously is that
31 the low surface superheat utilized here not only triggers the non-wetting transition, but also gives

1 rise to prompt droplet jumping. Fig. 1a shows selected snapshots of the Leidenfrost-like prompt
 2 jumping of a sessile water microdroplet. To investigate the kinematic dynamics of the droplet, the
 3 onset of the droplet shape deformation, resulting from the capillary perturbations caused by surface
 4 heating, was defined as $t = 0$ ms. After that, the droplet was levitated and directly jumped off the
 5 substrate within only 1.33 ms. In contrast to the conventional thermally-driven droplet actuations,
 6 as in the case of trampolining drops in the traditional Leidenfrost effect³³, the droplet in this
 7 scenario exhibited an explosive upward motion. In Fig. 1b, its center of mass monotonically rose
 8 with time without any discernible oscillations and eventually reached the maximum jumping
 9 height of 2.3 mm at $t = 15.33$ ms, suggesting a distinct mechanism for droplet actuations.

10 We show that the Leidenfrost-like droplet prompt jumping results from the rectification of the
 11 kinetic energy carried by the growing vapor bubble into the upward momentum that is sufficient
 12 to lift the entire droplet. At surface temperature $T_w = 130$ °C, contact boiling occurred at the
 13 droplet base¹⁷, leading to the successive nucleation and growth of individual vapor bubbles²⁷. Fig.
 14 2a shows that an individual vapor bubble firstly nucleated at $t = 0$ ms. After that, the vapor
 15 bubble expanded rapidly and reached the droplet's periphery at $t = 1.32$ ms. The striking
 16 coincidence between this timescale and the droplet's dwelling time (1.33 ms) implies that the
 17 Leidenfrost-like droplet jumping is contingent on the momentum interactions between this
 18 individual vapor bubble and the sessile droplet.

19 A detailed inspection on the vapor bubble growth in Fig. 2b reveals a bubble expanding
 20 velocity as fast as $U_e \approx 4$ m/s, leading to an average Reynolds number of $Re = \frac{U_e D_d}{\nu} \approx 2 \times 10^4$
 21 and Mach number of $Ma = \frac{U_e}{c} \approx 2.6 \times 10^{-3}$, where ν is water kinematic viscosity and c is the
 22 speed of sound in water. Therefore, the effect of viscous dissipation and water compressibility
 23 could be neglected, indicating that the vapor bubble interface expansion follows an inertia-
 24 controlled mode²⁷. This allows us to treat the vapor bubble expansion using the Rayleigh-Plesset
 25 equation in a potential flow approach²⁷:

$$26 \quad \rho_1 R \ddot{R} + \rho_1 \frac{3\dot{R}^2}{2} = \left(P_v - P_\infty - \frac{2\sigma}{R} \right) \sin^2 \beta \quad (1)$$

27 where R is the bubble contact radius, ρ_1 is water density, P_v is pressure inside the bubble, P_∞ is
 28 the pressure of bulk water, β is the bubble contact angle and σ is the surface tension, as shown in
 29 Fig. 2c. Eq. (1) describes how the overpressure-induced potential energy stored in the expanding
 30 vapor bubble is converted into the kinetic energy of the droplet (Supplementary Discussion 2). The

1 vaporization-induced bubble overpressure could be estimated by the Clausius-Clapeyron
 2 equation²⁷ as $P_v - P_\infty = \left(\frac{\Delta T}{T_{\text{sat}}}\right)h_{\text{lv}}\rho_v$, where ΔT is the vapor bubble superheat temperature change,
 3 T_{sat} is the water saturation temperature, h_{lv} is specific evaporation enthalpy, and ρ_v is the vapor
 4 density. In general, ΔT would vary with time and the position in the bubble, but a constant ΔT
 5 could be assumed in the case of a strong thermal diffusion that makes the temperature gradient
 6 inside the bubble negligible³⁴. This approximation holds true as long as the characteristic diffusion
 7 length $L_H \sim \sqrt{2\alpha_v t}$ is larger than the bubble size R , where α_v is the thermal diffusivity of water
 8 vapor. Using $\Delta T = 30$ K gives rise to a rough estimation of $P_v - P_\infty \approx 1.08 \times 10^5$ Pa. As shown
 9 in Fig. 2b, the detected vapor bubble growth started from $R = 90$ μm , yielding the Laplace
 10 pressure $\frac{2\sigma}{R} \leq 1.31 \times 10^3$ Pa. Therefore, the Laplace pressure term in Eq. (1) is neglected. In the
 11 first stage of the bubble expansion with a constant ΔT , Eq. (1) can be solved analytically as:

$$12 \quad R(t) = \left[\frac{2}{3} \left(\frac{\Delta T}{T_{\text{sat}}(P_a)} \right) \frac{h_{\text{lv}}\rho_v}{\rho_l} \right]^{\frac{1}{2}} \sin\beta \cdot t \quad (2)$$

13 Such a linear increase of $R(t)$ with time implies that the bubble expansion would eventually
 14 surpass the thermal diffusion³⁴, which has the time dependence $R \sim t^{0.5}$, after which the cooling
 15 effect of vaporization³⁴ causes ΔT to rapidly deteriorate at the liquid-vapor interface. The
 16 overpressure would quickly relax to zero³⁵, resulting in $P_v - P_\infty - \frac{2\sigma}{R} \approx 0$. This prediction aligns
 17 well with the sharp turning of the bubble radius curve at $t_1 \approx 0.1$ ms in Fig. 2b. At this moment,
 18 the bubble expansion was solely sustained by the droplet inertia and the total kinetic energy of the
 19 bubble-droplet system was conserved: $\frac{d}{dt}(\rho_l R^3 \dot{R}^2) = 0$. The contact bubble radius R for $t > t_1$ can
 20 be solved as:

$$21 \quad R = (R_1^{3/2} \dot{R}_1 t)^{0.4} \quad (3)$$

22 where R_1 is the contact radius at t_1 . Fig. 2b shows a remarkable agreement between the
 23 experimental results of bubble expansion and the two-stage theoretical model proposed by us,
 24 further confirming the dominant role of the overpressure and inertia effect in controlling the bubble
 25 growth for Leidenfrost-like droplet jumping.

26 The inertia-controlled bubble growth contributes to the droplet levitation by its momentum
 27 exchange with the water droplet. The propulsive force is obtained by taking the derivative of the
 28 droplet's upward momentum M_z (Supplementary Discussion 3).

$$F_z = \frac{dM_z}{dt} \approx \frac{\pi\rho_l R^2 \dot{R}^2 (4 - 3\cos\beta)\cos\beta}{\sin^4\beta} \quad (4)$$

Combining Eq. (3) and Eq. (4) gives an estimated value for $F_z \approx 2.44 \times 10^{-3}\text{N}$. As illustrated in Fig. 2d, the droplet gravity is $G = 4.16 \times 10^{-5}\text{N}$, which is orders of magnitude smaller than F_z . Notably, the growing vapor bubble gradually separates the physical contact between the droplet base and the substrate, causing a continually decreasing surface adhesion. Therefore, with the rectified kinetic energy overwhelming the resistance, the water droplet became levitated and instantaneously jumped off the substrate without apparent oscillations, in a Leidenfrost-like manner but at a markedly low temperature of 130 °C.

We find the Leidenfrost-like droplet jumping breaks down on substrates with shorter pillars as the droplet-vapor dynamics become different. Fig. 3a presents the selected snapshots of a droplet's actuation on a substrate with short micropillars ($H = 20 \mu\text{m}$). In contrast to the direct Leidenfrost-like jumping, the droplet experienced substantial vertical stretching and vibrations until its ultimate jump off with an extended dwelling time of 941 ms, which is >700 times greater than that for Leidenfrost-like jumping. In Fig. 3b, the droplet actuations could be generally divided into two stages. Before $t = 600$ ms, the droplet fluctuated randomly with a small magnitude and no apparent periodicity. After $t = 600$ ms, the oscillations became more pronounced with an evident frequency of 41.6 Hz, which is consistent with the characteristic frequency of a water spring in bouncing drops³⁶. Therefore, we term this phenomenon as vibrational droplet jumping, as the droplet's dwelling time is increased by hundreds of times due to the prolonged vibrations.

To unveil the mechanism of vibrational droplet jumping, we investigated the dynamics of individual growing bubble as represented by the snapshots in Fig. 4a. Initially, the vapor bubble followed an inertia-controlled expansion (Fig. 4b) because the bubble expansion is always initiated by the vaporization-induced overpressure. However, the bubble growth in vibrational droplet jumping was interrupted by an apparent bubble shrinking process (from 0.9 ms to 4 ms), causing the bubble radius to decrease for several milliseconds and then rise again as shown in Fig. 4b (Extended Data Fig. 4). This intermittent shrinking is attributed to the limited propagation of the TBL, within which the liquid becomes superheated due to surface heating but remains subcooled elsewhere. For the thermal interaction between the sessile droplet and the heating substrate, the thermal timescale³⁷ can be estimated as $\tau_{\text{th}} = \frac{K_w \rho_l c_p}{h_c^2} \approx 25$ ms with K_w being the thermal

1 conductivity of liquid water, c_p being the thermal capacity of liquid water and $h_c \approx 10000$
2 $\text{W}/(\text{m}^2 \cdot \text{K})$ being the estimated convective heat transfer coefficient between the droplet and the
3 substrate²⁷. The Fourier number characterizing the extent of heat conduction is estimated to be
4 $Fo = \frac{\alpha_w \tau_{\text{th}}}{D_d^2} = 1.05 \times 10^{-3}$, verifying the presence of a thin TBL with a steep temperature gradient.
5 Here α_w is the thermal diffusivity of liquid water. Then the TBL propagation velocity v_{TBL} can be
6 further evaluated by solving the heat transfer equation at the droplet base (Supplementary
7 Discussion 4).

$$8 \quad v_{\text{TBL}} = \text{erf}^{-1}\left(\frac{T_{\text{sat}} - T_w}{T_0 - T_w}\right) \sqrt{\frac{\alpha_w}{t}} \quad (5)$$

9 where $T_0 = 20 \text{ }^\circ\text{C}$ is the initial temperature of water. Specifically, the characteristic TBL
10 propagation velocity can be evaluated as $v_{c, \text{TBL}} \approx 6.4 \times 10^{-4} \text{ m/s}$ by substituting $t = \tau_{\text{th}}$. This
11 value is three orders of magnitude smaller than the inertia-controlled bubble expansion $U_{i,e} \approx 4$
12 m/s . Therefore, the inertial bubble expansion would inevitably surpass the TBL propagation whilst
13 the TBL thickness remains almost constant. As depicted in Fig. 4c, the vapor inside the bubble
14 would condensate once its outer edge breaches the TBL. The bubble growth can continue only if
15 the heat transfer from the substrate eventually surpasses the energy loss via condensation,
16 indicating a heat-transfer-limited mode. Therefore, we applied the energy balance to describe the
17 bubble expansion herein:

$$18 \quad h_{\text{lv}} \rho_v \frac{d}{dt} \left(\frac{\pi}{3} \frac{(2 + \cos\beta)(1 - \cos\beta)^2}{\sin^3\beta} R^3 \right) = 2\pi R^2 q_b \quad (6)$$

19 where q_b represents the heat flux from the silicon substrate to the bubble base. Specifically, the
20 convective heat flux can be estimated as $q_b = h_c(T_w - T_{\text{sat}})$. As a result, the temporal evolution
21 of vapor bubble radius in this stage follows:

$$22 \quad R(t) \sim \frac{q_b}{h_{\text{lv}} \rho_v} \frac{2 \sin^3\beta}{(2 + \cos\beta)(1 - \cos\beta)^2} \cdot t \quad (7)$$

23 Such a linear growth of bubble with time is validated by our experimental results as shown in Fig.
24 4b.

25 The propulsive force provided by the heat-transfer-limited bubble growth can be evaluated by
26 combining Eqs. (4) and (7), yielding $F_z \approx 2.16 \times 10^{-6} \text{ N}$. Given the droplet gravity $G = 4.16 \times$
27 10^{-5} N , the water droplet could not be completely levitated by an individual expanding bubble.
28 The droplet hence entered the trampolining mode with strong capillary oscillations caused by

1 droplet-bubble interactions, until it could build up sufficient kinetic energy for subsequent
 2 jumping^{33, 38, 39}.

3 A detailed analysis on the droplet jumping velocity v_j versus the droplet volume V_0 reveals
 4 two distinct jumping modes as delineated in Fig. 4d. For Leidenfrost-like droplet jumping, the
 5 kinetic energy E_k of the jumping droplet originates from the overpressure potential energy of an
 6 individual bubble, which is mainly determined by the superheat²⁷. The initial potential energy
 7 stored in each individual vapor bubble formed inside droplets with varying volumes can be taken
 8 at the same level, considering the droplets are deposited on the substrate with identical surface
 9 temperature. As a result, the kinetic energy $E_k \sim \frac{1}{2} \rho_l V_0 v_j^2$ is approximately constant for different
 10 droplet volume V_0 , yielding a scaling of $v_j \sim V_0^{-0.5}$ as manifested by Leidenfrost-like droplet
 11 jumping (Fig. 4d). For vibrational jumping on the substrate $[D, L, H] = [20, 120, 20] \mu\text{m}$, the
 12 droplet needs to overcome the gravity G and surface adhesion from the substrate F_A . The surface
 13 adhesion F_A is proportional to the pillar perimeter⁴⁰ $\sigma\pi D$ and the number of pillars under the
 14 droplet base $\left(\frac{D_d}{L}\right)^2$, giving $F_A \sim \frac{\sigma\pi D}{L^2} D_d^2 \approx 1.27 \times 10^{-3} \text{ N}$. The droplet gravity $G = 4.16 \times 10^{-5} \text{ N}$
 15 is thus neglected in the force analysis. The propulsive force is scaled by considering the temporal
 16 variation of momentum as $F_z \sim \rho_l D_d^3 \frac{v_j}{D_d/v_j}$. A threshold velocity acquired by $F_z = F_A$ marks the
 17 onset of droplet levitation, yielding $v_j \sim \sqrt{\frac{\sigma D}{L^2 \rho_l}}$ for vibrational jumping. This prediction indicates that
 18 all water microdroplets jump with a constant velocity, aligning well with the observed jumping
 19 velocities as shown in Fig. 4d.

20 To comprehensively understand the influence of micropillars on the droplet-substrate heat
 21 transfer and two distinct jumping modes, we conducted experiments of droplet jumping on
 22 substrates with varying temperature T_w and pillar height H . The phase map in Fig. 5a depicts three
 23 different regimes of droplet behaviors. Increasing T_w above 130 °C gave rise to the vibrational
 24 droplet jumping (regime I) and Leidenfrost-like droplet jumping (regime II). We emphasize that
 25 the jumping mode is predominantly determined by the micropillar height H and increasing T_w
 26 does not necessarily initiate the vibration-to-Leidenfrost-like transition. Specifically, the
 27 vibrational droplet jumping occurred for $H < 60 \mu\text{m}$ even with $T_w = 170 \text{ °C}$ (Extended Data Fig.
 28 5), and the Leidenfrost-like droplet becomes probable only when $H \geq 60 \mu\text{m}$. This is a strong

1 indication of the fact that increasing T_w does not markedly impact the TBL propagation whilst the
2 structure of the TBL could be significantly altered by the microstructures. Such effect can be
3 examined by revisiting Eq. (5) to estimate the TBL propagation velocity v_{TBL} , as shown in Fig.
4 5b. Increasing T_w from 130 °C to 170 °C only increases v_{TBL} by 78.6% from 6.4×10^{-4} m/s to
5 1.1×10^{-3} m/s, which are still orders of magnitude smaller than the inertia-controlled bubble
6 expansion ($U_{i,e} \approx 4$ m/s). Therefore, during the short-term inertial bubble expansion that
7 determines the ultimate droplet jumping mode, the TBL remains almost unchanged even when T_w
8 is significantly increased. We conducted heat transfer simulations on COMSOL 5.6 to investigate
9 the effect of micropillars on the distribution of TBL (Supplementary Discussion 5). Specifically,
10 Fig. 5c shows that the temperature distribution in the vicinity of the substrate. The isothermal
11 contour of $T = 100$ °C, which marks the boundary of the TBL, conforms to the profile of
12 micropillars, suggesting that the microstructures act as micro-fins to extend the superheated liquid
13 domain. We define the TBL thickness as $h_{\text{TBL}} = \frac{V_{\text{sup}}}{L_p}$, where V_{sup} corresponds to the total volume
14 of superheated liquid and L_p is the projected length of the computational domain (Supplementary
15 Discussion 5). We compare h_{TBL} at different T_w and H in Fig. 5d. Increasing T_w from 130 °C to
16 170 °C only marginally increases h_{TBL} from 90 μm to 115 μm , aligning well the theoretical
17 prediction of Eq. (5) that $\Delta h_{\text{TBL}} = \int_0^{\tau_{\text{th}}} [v_{\text{TBL}}(T_w = 170 \text{ °C}) - v_{\text{TBL}}(T_w = 130 \text{ °C})] dt \approx 20 \mu\text{m}$.
18 Alternatively, for $T_w = 130$ °C, h_{TBL} is substantially increased from 40 μm to 90 μm when the
19 pillar height is increased from 20 μm to 80 μm , confirming that the effect of microstructures in
20 extending the TBL. Moreover, in regime III of Fig. 5a where T_w is below 120 °C, no vapor bubble
21 can be observed and the droplet would steadily remain in the Wenzel state till complete
22 evaporation, due to the insufficient thermal energy input for bubble formation and growth.

23 We demonstrate that engineering surface microstructures to manipulate the growth of bubble
24 expansion and droplet jumping behaviours can be employed as an effective strategy for rapid
25 droplet shedding on hot substrates. Figs. 6a and 6b show time-lapsed images of ejection of sessile
26 water droplets on tilted substrates with different pillar heights. For the tilted substrate $[D, L, H] =$
27 $[20, 120, 20]$ μm , the vibrating droplet initiated the out-of-plane jumping and then the water
28 droplet landed softly on the substrate remaining in the low-friction Cassie state until it slid off the
29 substrate. For the tilted substrate $[D, L, H] = [20, 120, 80]$ μm , the explosive droplet jumping
30 caused the droplet to jump off the substrate with a maximum height of 6 mm, which is three times

1 as large as the droplet diameter. Then the droplet experienced repetitive rebounding and falling for
2 several cycles before it finally rolled off the substrate.

3 The rapid shedding of initially sticky droplets on heated substrates is of particular relevance to
4 the fouling removal on the highly-demanding heat exchanger surfaces. Under spray cleaning or
5 rinsing conditions, neither Leidenfrost nor cold droplets effectively eliminate deposited
6 particulates from surface roughness. A continuous vapor layer restricts Leidenfrost droplets from
7 accessing surface structures, while factors like contact line pinning and interfacial friction impede
8 the ability of cold droplets to dislodge contaminants. Fig. 6c illustrates an alternative process of
9 removing fouling in the interstitial cavities of surfaces by leveraging the explosive droplet jumping
10 discovered by this work. The contaminant used in the experiments was hydrophilic prism polishing
11 powder ($\sim 3 \mu\text{m}$ in diameter). To mimic the gradual deposition of particles on the surface of heat
12 exchangers, the powder particles are suspended in a water droplet with later evaporation process
13 to deposit them on the surface, which is analogous to coffee ring effect⁴¹ (Supplementary
14 Discussion 6). For surface defouling, the droplet was at first in Wenzel state, which allows it to
15 penetrate into the interstitial cavities to catch the contaminants. As the surface temperature was
16 heated up to a moderate level ($T_w = 130 \text{ }^\circ\text{C}$), the generation of vapor bubbles effectively dislodged
17 the residual contaminant particles and drove them to suspend in the droplet. Along with the droplet
18 jumping, the fouling even in surface roughness and cavities can be effectively purged in a deep
19 cleaning manner.

20 We envisage that the above-discussed strategy for facile actuations of sessile liquid droplets in
21 an ultrafast, yet controlled manner has a wide range of applications in highly demanding heat
22 transfer and fluid manipulation scenarios. Particularly, this study paves a new path for the deep
23 cleaning of fouling settled in surface cavities, a critical factor that tends to lead to the severe
24 performance degradation of engineered surfaces. From a broader perspective, the exploration of
25 minimizing the thermal cost associated with the vapor-mediated droplet actuations represents an
26 important advance in our understanding of the complex transport of momentum, mass and heat in
27 the phase change heat transfer process, enabling the rational design of surfaces with exceptional
28 heat transfer performance, extended durability, and excellent anti-fouling properties.

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7 research. W.H. designed and carried out the experiments, W.H., L.Z. and J.C. analyzed the data
8 and wrote the original manuscript. W.H., X.H., C.P.C., D.P.B., Y.L., Z.Z., J.L. and J.C. prepared
9 the samples. All authors wrote and edited the manuscript.

10 **Competing interests** The authors declare no competing interests.

11

12 **Figure Captions**

13 **Figure 1. Leidenfrost-like droplet jumping dynamics on hot micropillared surface.** **a** Selected
14 snapshots of Leidenfrost-like droplet jumping on a micropillared substrate ($[D, L, H] =$
15 $[20, 120, 80] \mu\text{m}$) with surface temperature $T_w = 130 \text{ }^\circ\text{C}$. The inset in **(a)** is the scanning electron
16 micrography (SEM) of the micropillared substrate. **b** Height variation of the center of mass of the
17 droplet shown in **(a)**. The time $t = 0 \text{ ms}$ denotes the onset of the interfacial deformation.
18 Supplementary Movie S1 provides additional details.

19 **Figure 2. Rapid vapor bubble expansion for Leidenfrost-like droplet jumping.** **a** Top-view
20 snapshots of vapor bubble growth on substrate $[D, L, H] = [20, 120, 80] \mu\text{m}$ at $130 \text{ }^\circ\text{C}$. The scale
21 bar is 1 mm. Supplementary Movie S2 provides additional details. **b** Temporal evolution of the
22 vapor bubble radius from **(a)**. The error bars represent the potential resolution errors. **c** Diagram
23 of vapor bubble expansion via momentum interaction with the surrounding liquid. **d** Equivalent
24 upward force generated by the rapid bubble expansion.

25 **Figure 3. Droplet vibration jumping dynamics on hot micropillared surface.** **a** Selected
26 snapshots of droplet's vibrational jumping on the micropillared substrate $[D, L, H] =$
27 $[20, 120, 20] \mu\text{m}$ at $130 \text{ }^\circ\text{C}$. The inset in **(a)** is the SEM image of the micropillared substrate. **b**
28 Height variation of the center of mass of the droplet shown in **(a)**. Supplementary Movie S3
29 provides additional details.

30 **Figure 4. Vapor bubble shrinking during the vibrational droplet jumping.** **a** Top-view
31 snapshots of vapor bubble growth on substrate $[D, L, H] = [20, 120, 20] \mu\text{m}$ at $130 \text{ }^\circ\text{C}$. **b**
32 Temporal evolution of vapor bubble radius on substrates with different micropillar heights
33 ($H = 20, 60, 80 \mu\text{m}$). The error bars represent the potential resolution errors. Supplementary

1 Movies S4 and S5 provide additional details. **c** Schematic illustrations of superheated interfacial
2 water layer impacting the bubble growth. The growing vapor bubble condensates after meeting the
3 subcooled water outside the TBL. **d** Jumping velocity of droplets with different volumes during
4 vibrational jumping (on substrate $[D, L, H] = [20, 120, 20] \mu\text{m}$) and Leidenfrost-like jumping
5 (on substrate $[D, L, H] = [20, 120, 80] \mu\text{m}$).

6 **Figure 5. Effect of micropillar height H and substrate temperature T_w on droplet jumping**
7 **behaviors. a** Phase map of droplet jumping behaviors on substrates with different micropillar
8 heights and different surface temperatures. **b** Theoretical prediction of the TBL propagation
9 velocity at different substrate temperatures. **c** Simulated results of temperature distribution
10 showing the TBL on substrates with micropillar height ranging from $20 \mu\text{m}$ to $80 \mu\text{m}$. The
11 isothermal contour of $100 \text{ }^\circ\text{C}$ is denoted with white dashed line. **d** Simulated TBL thickness on
12 substrates with different micropillar heights (from $20 \mu\text{m}$ to $80 \mu\text{m}$) and different substrate
13 temperatures (from $130 \text{ }^\circ\text{C}$ to $170 \text{ }^\circ\text{C}$).

14 **Figure 6. Rapid droplet purging on microstructured substrates and surface deep fouling**
15 **removal. a** Droplet sliding on substrate $[D, L, H] = [20, 120, 20] \mu\text{m}$ at $130 \text{ }^\circ\text{C}$. **b** Droplet sliding
16 on substrate $[D, L, H] = [20, 120, 80] \mu\text{m}$ at $130 \text{ }^\circ\text{C}$. **c** Schematic (top) and experimental
17 snapshots (bottom) of dislodging and removal of deep fouling from surface roughness by sliding
18 droplet on tilted substrate $[D, L, H] = [20, 120, 20] \mu\text{m}$ at $130 \text{ }^\circ\text{C}$. All the substrates were tilted
19 at 16° . Supplementary Movies S6 and S7 provide additional details.

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8 9 **Methods**

10 **Substrate preparation**

11 Polished P-type silicon wafers of 100 mm diameter and $550 \pm 25 \mu\text{m}$ thickness were used as the
12 substrates in this work. Standard photolithography process was performed with a SUSS MicroTech
13 contact aligner. Then the substrates were etched with Oxford RIE to fabricate the well-defined
14 micropillar arrays. The micro-pillared substrates were conformally coated with fluoropolymer
15 (PFC 1601V, Cytonix Corporation) using a spin coater at 3000 rpm for 30 s and then baked at 100
16 °C for 1 hour. Substrate micropillar diameter, height and periodicity (pitch-to-pitch distance) are
17 denoted with D , H and L , respectively. More detailed information about the substrates is given in
18 Extended Data Fig. 2. The surface roughness of the substrates, assessed using atomic force
19 microscopy (AFM, Asylum Jupiter XR), is approximately 7 nm, as illustrated in Supplementary
20 Fig. 2.

21 **Data availability**

22 Data analyzed during this study are included in this Article. Source Data are provided with this
23 paper.

24 **Code availability**

25 Codes used to generate the data presented in this study are available from the corresponding
26 authors upon reasonable request.

27