Sublimation Engines — some proof-of-concept results

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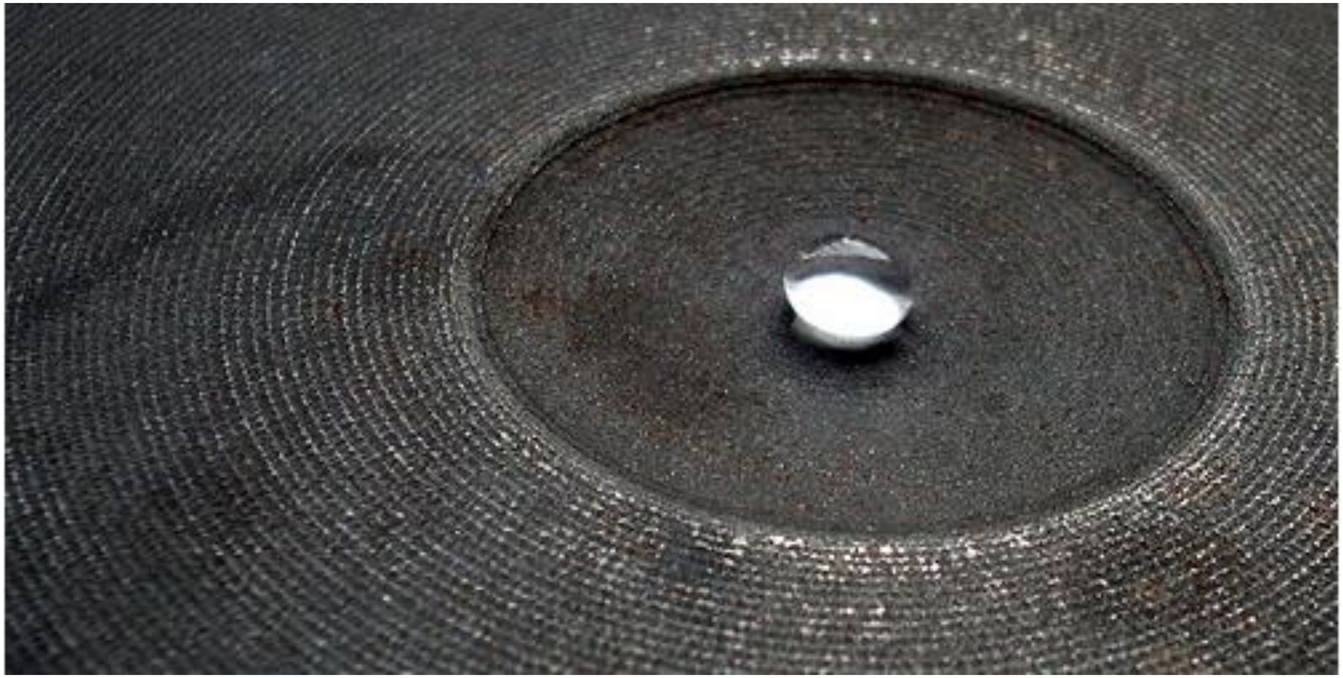
Leidenfrost Effect



Source: flickr.com

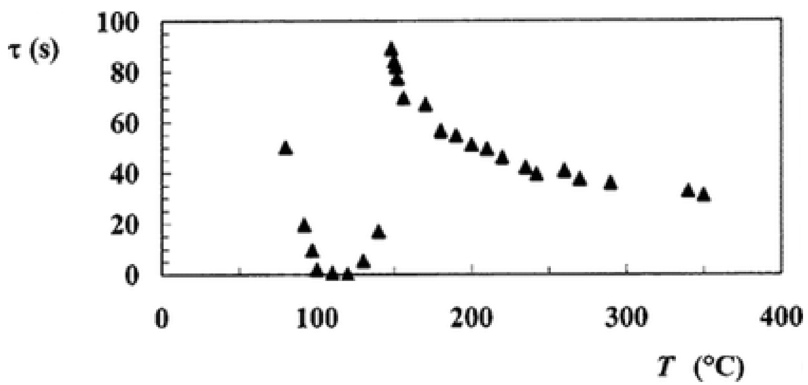
Leidenfrost (1756)

On hot enough surfaces a drop will skid off with very little friction

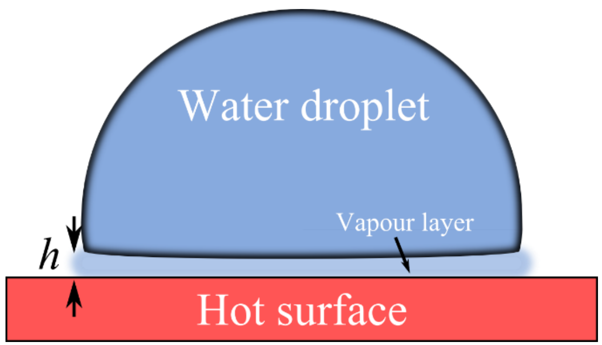
Leidenfrost Drops

Underpinning physics

1. At the ‘Leidenfrost point’ the evaporation time peaks
2. This corresponds to the transition from volume boiling to thin film boiling.
3. Above the Leidenfrost point the drop sits on a layer of its own vapour.



Biance, Clanet & Quéré, Phys. Fluids 15 1632 (2003)



The bottom surface acts as a superhydrophobic material

Leidenfrost Blocks

Dry-ice sublimates at -78 C at STP

The CO_2 gas expelled leads to the same effect, leading to low-friction levitating blocks

Self-propulsion

Linear Ratchets

1. A linear asymmetric ratchet will induce the self-propulsion of the Leidenfrost drop or block.
2. The translational motion occurs in the downhill direction of the ratchet

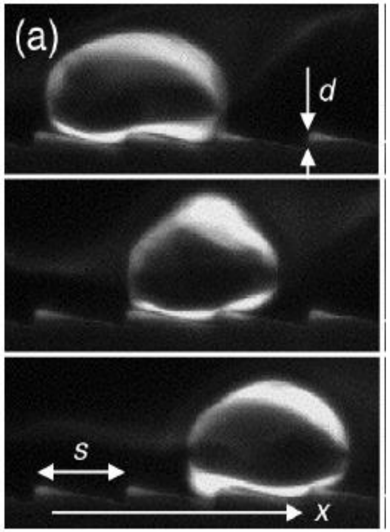


Image: Linke et al (2006)

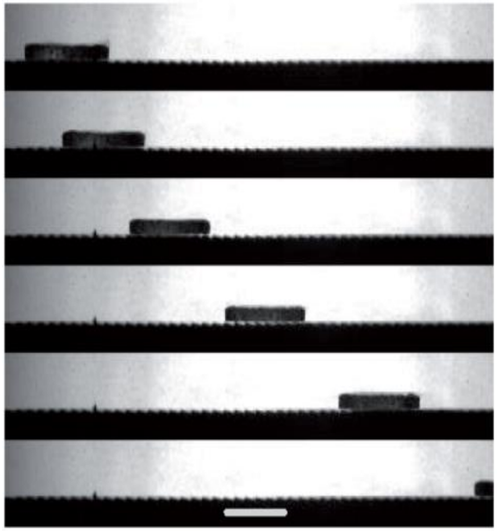
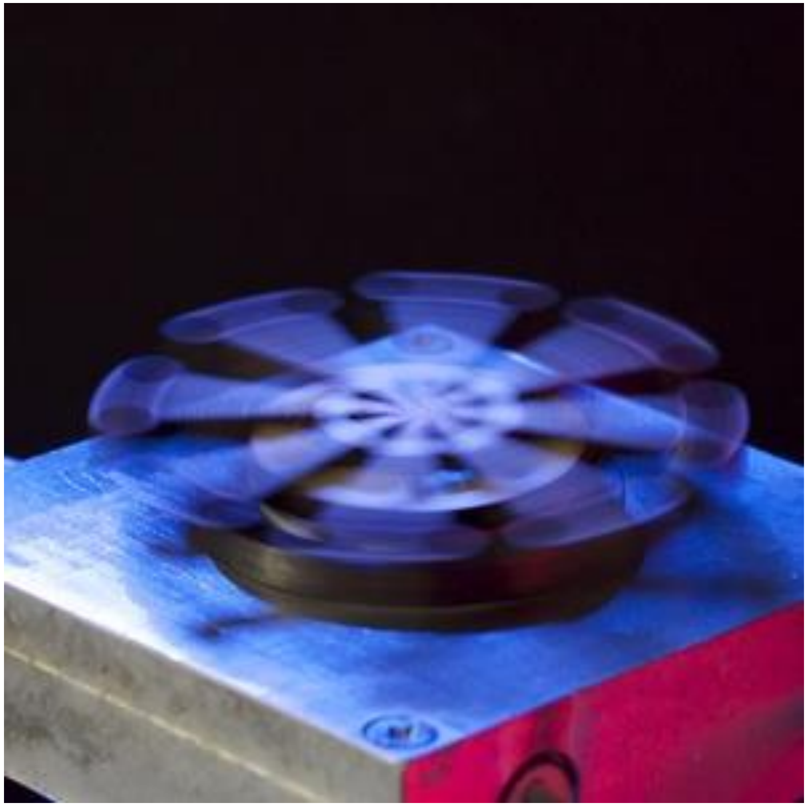


Image: Lagubeau et al (2011)

New concept – A Leidenfrost Engine

An engine which converts temperature differences into mechanical work via the Leidenfrost Effect.

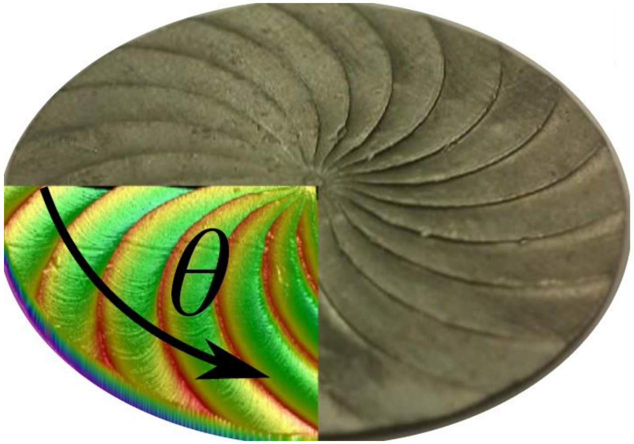


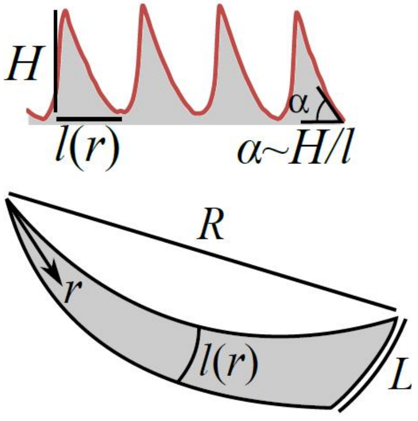
Turbine-like surfaces

Aluminium substrates using Computer Numerical Control (CNC) machining

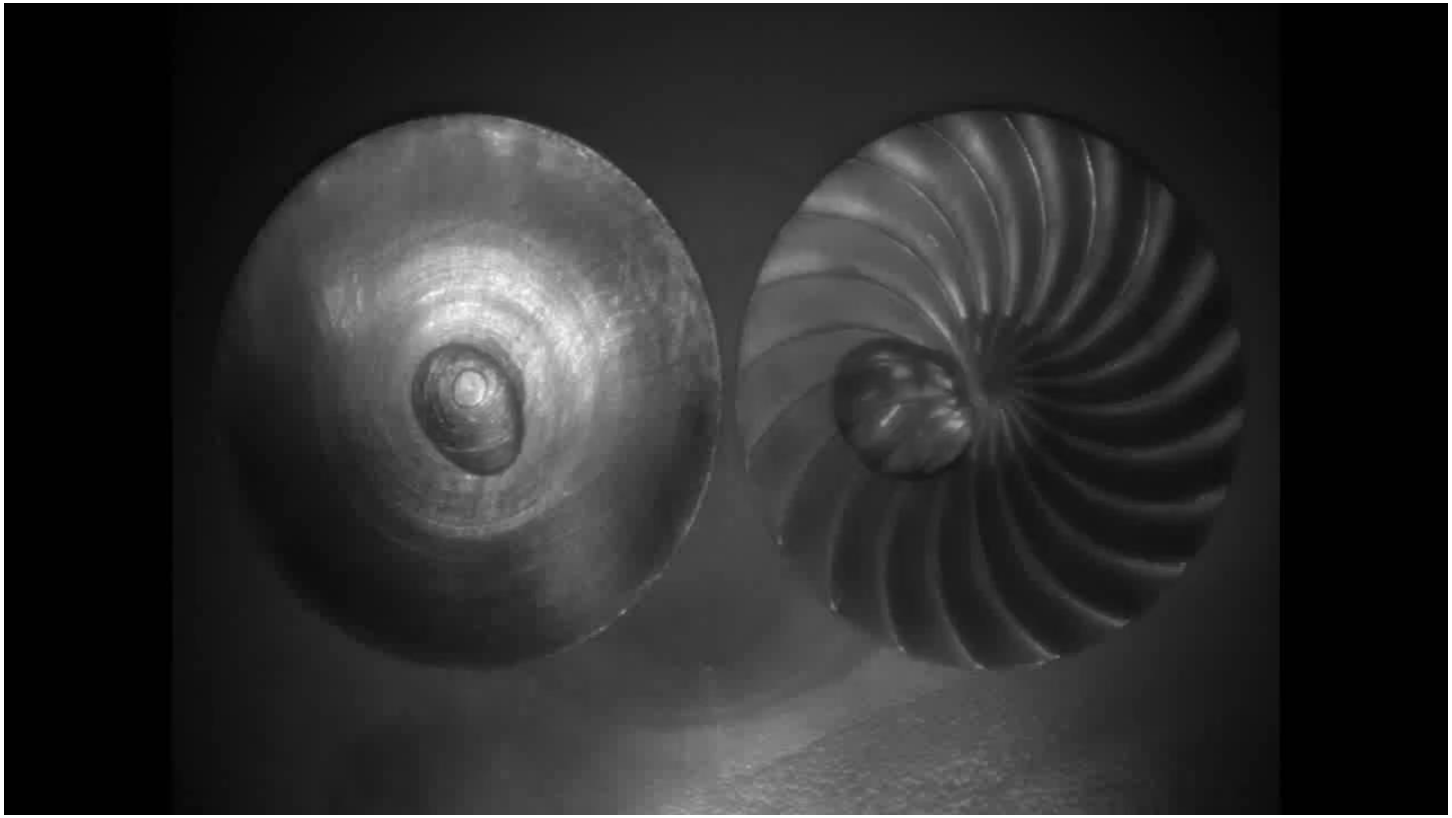
Our surfaces are based on axial gas turbine designs

R=0.75-2 cm, N=10, 20, 30

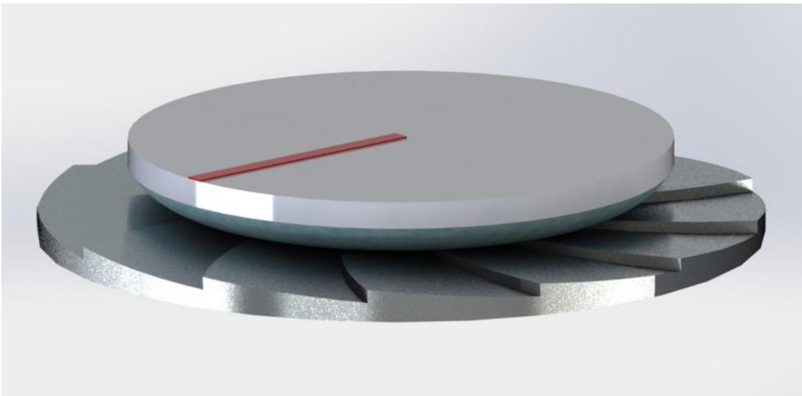


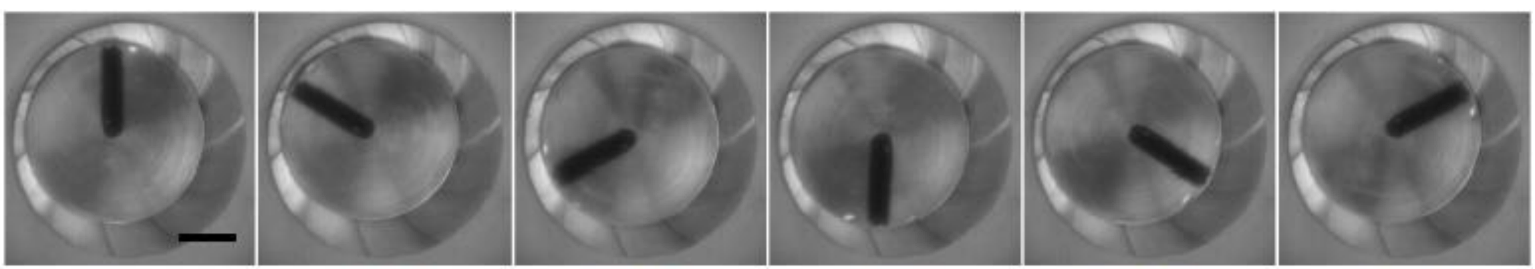


From orbiting/spinning drops to rigid-body rotational motion



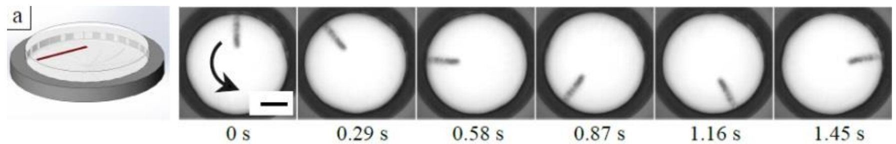
Rotation via Droplet Coupled Disks

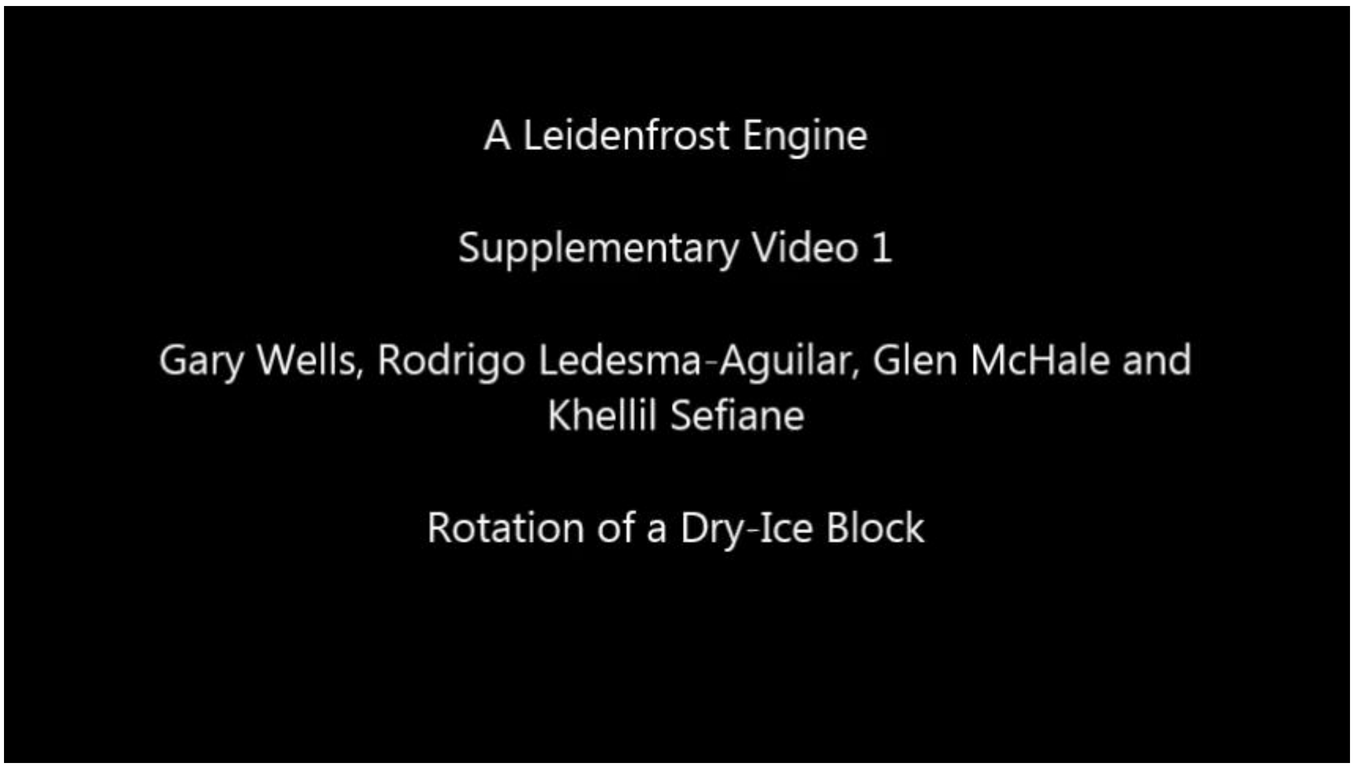




0 s 0.16 s 0.32 s 0.48 s 0.64 s 0.80 s

Rotational Motion via Sublimation



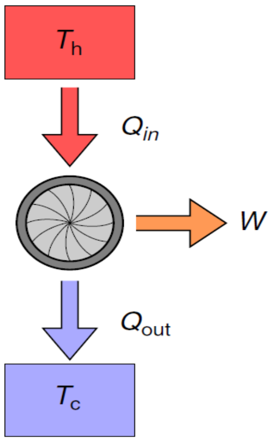


Sublimation Heat Engine Concept

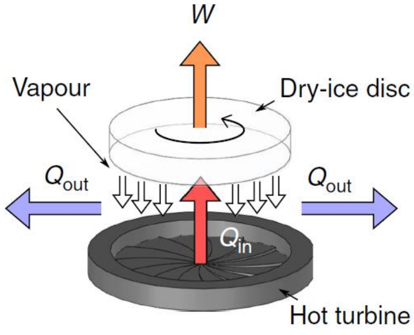
Sublimation Thermal Cycle

1. Sublimation (solid-vapor) equivalent to the Rankine cycle used in steam powered engines
2. The working substance is a solid (e.g. CO_2 but could be other ices such as H_2O or CH_4)
3. Harvest thermal energy Q_{in} via difference in temperature between reservoirs at T_h and T_c
4. Released vapor is rectified to produce mechanical work, W
5. Cooling releases Q_{out} to surroundings
6. Maximum theoretical efficiency limited by Carnot engine efficiency $\varepsilon = 1 - T_c/T_h \approx 1 - T_c/T_{ave} \approx 0.67$

Principle



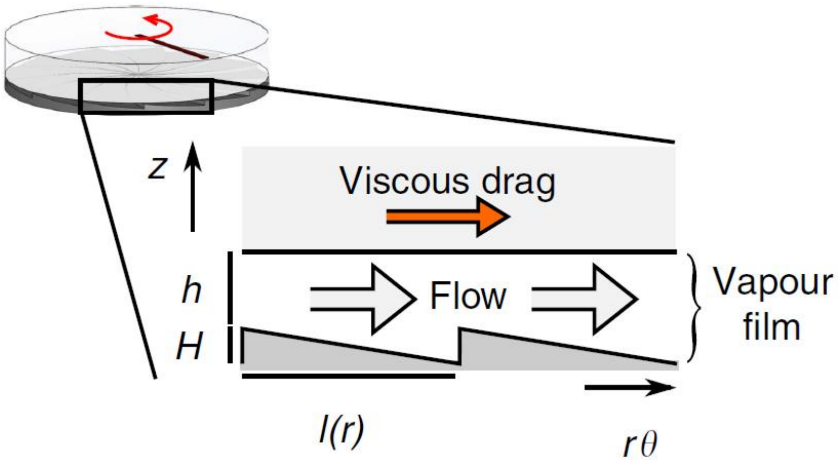
Realization



Efficiency: $\varepsilon = W/Q_{in}$

Physical Mechanism

- Estimate rate of evaporation from surface of levitating dry ice
- Energy flux across vapour layer by conduction
- Vapour pressure supports the levitation of the drop or block
- Rectified vapour flow induces a net viscous drag
- This drag results in a net torque driving the rotational motion



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Theoretical Model

<u>Governing Equations in the gas phase</u> Follow approach by Quéré and co-workers (2003-2013):

Mass and momentum conservation

$$\nabla \cdot \mathbf{v} = 0$$

$$\rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \eta \nabla^2 \mathbf{v} + \rho \mathbf{g},$$

<u>Low Reynolds number limit</u>

$$\mathrm{Re} \equiv \frac{\rho h^2 U}{R \eta}$$

$$\mathrm{Re} \sim \frac{\lambda \Delta T}{\eta \Delta H} \approx 0.01$$

Mass conservation

$$\pi R h U \sim \pi R^2 v_n,$$

Evaporation speed

$$v_n \approx \frac{\lambda}{\rho \Delta H} \frac{\Delta T}{h}$$

Theoretical Model

Once the pressure field is found we are able to compute net forces and torques.

Net lift force

$$\mathbf{F} = N \int_0^R r dr \int_0^{2\pi/N} p(r,\theta) d\theta \hat{\mathbf{z}}.$$

$$\mathbf{F} \approx \frac{3\pi\eta v_{n0} R^4}{2h_0^3} \hat{\mathbf{z}}.$$

The balance of this force with gravity sets the thickness of the vapour layer

$$h_0 = \left(\frac{3}{2}\right)^{1/4} \left(\frac{\eta\lambda\Delta T}{\rho\Delta H \rho_{\mathrm{f}} g}\right)^{1/4} \frac{R^{1/2}}{h_{\mathrm{f}}^{1/4}}.$$

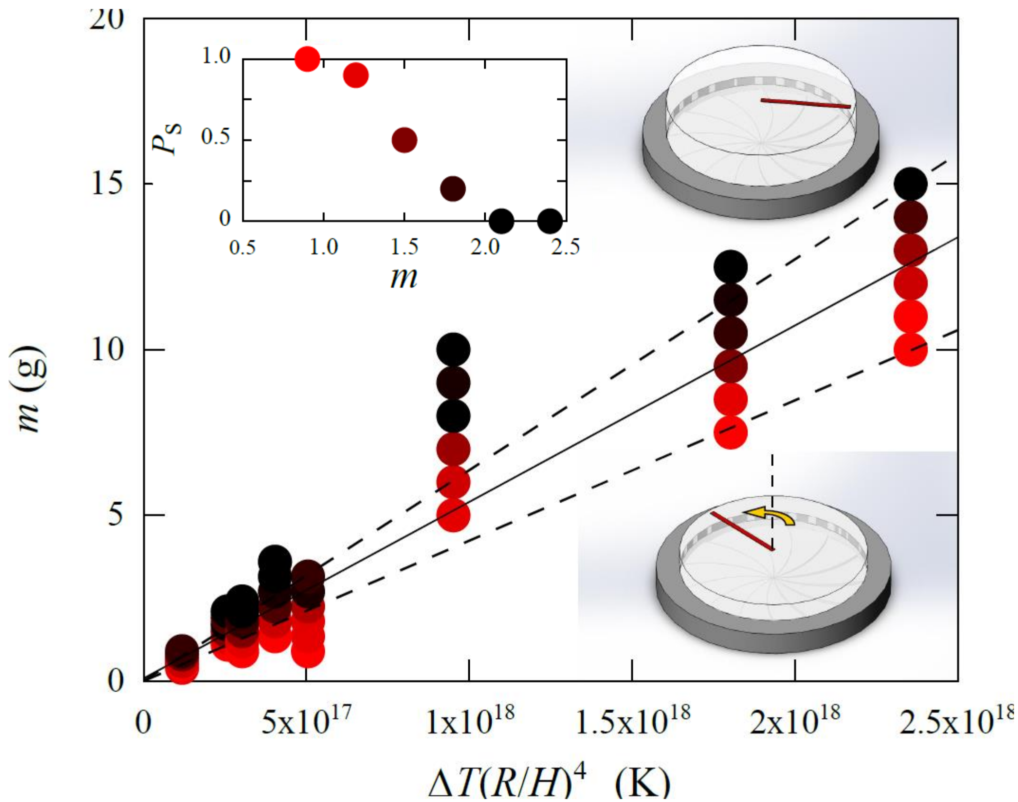
When the thickness of the vapour layer becomes comparable to the thickness of the ratchet teeth we expect hampering of the rotational motion

Critical mass

$$mg = \frac{3\pi}{2} \left(\frac{\eta\lambda}{\rho\Delta H}\right) \frac{\Delta T R^4}{H^4}$$

Experiments: *to spin or not to spin?*

1. Experiments with changes in (ΔT, R, H) to work out probability of dry ice disk spinning (R=7.5-20 mm, T_h=300-500 C, H=165-229 μm)
2. ca. 60 experiments per mass to determine probability P_S with m_c defined by P_S=0.5



Theoretical Model

<u>Local viscous stress</u>

$$\tau_{\theta z} = \eta \frac{\partial v_\theta}{\partial z} = \frac{2z - h}{2r} \frac{\partial p}{\partial \theta}$$

<u>Average viscous stress</u>

$$\hat{\tau}_{\theta z} = \frac{N}{\pi R^2} \int_0^R r dr \int_0^{2\pi/N} \tau_{\theta z} d\theta$$

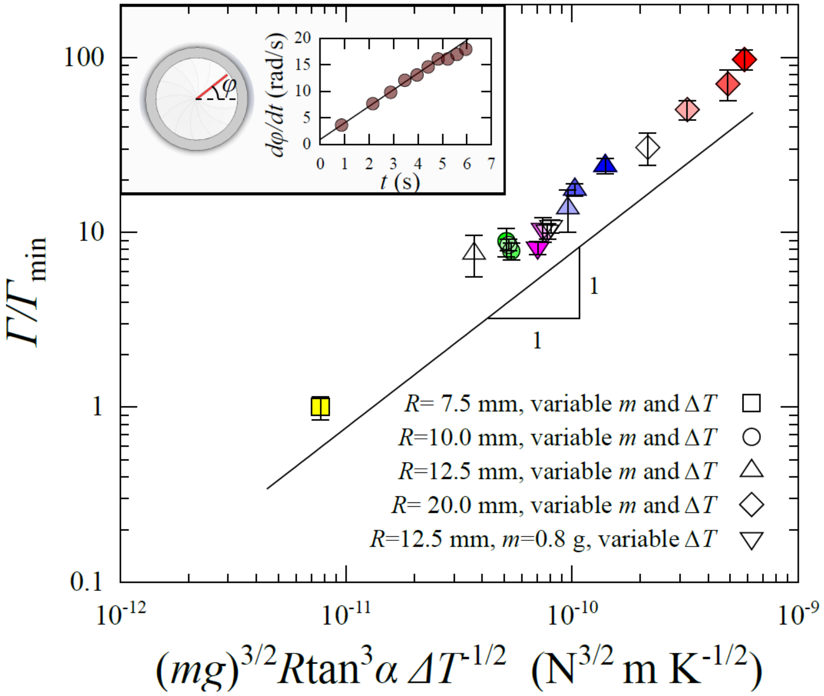
<u>Net torque acting on the top surface</u>

$$\mathbf{T} = -N \int_0^R r^2 dr \int_0^{2\pi/N} \tau_{\theta z} d\theta \hat{\mathbf{z}}$$

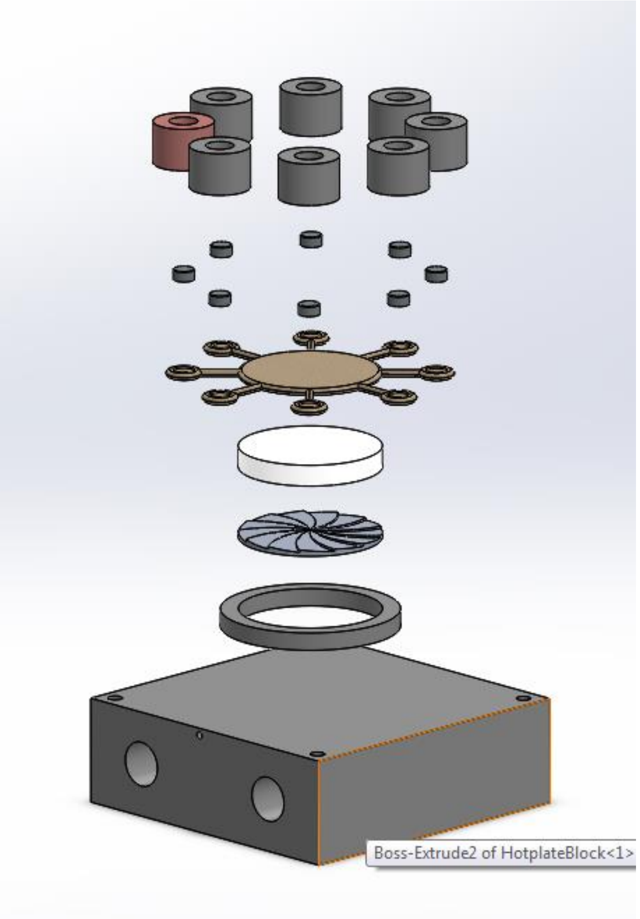
$$\mathbf{T} = c \left(\frac{\rho \Delta H}{\eta \lambda} \right)^{1/2} \frac{(mg)^{3/2} R \tan^3 \alpha}{\Delta T^{1/2} N^4} \hat{\mathbf{z}}$$

Experiments: *torque scaling*

1. Measured angular velocity of dry ice disks ⇒ angular acceleration and hence torque ($\Gamma = I\alpha$) (R=0.75-2 cm, T_h=350-500 C, α=2.25-4.15°, m=0.19-5.13 g)
2. Minimum torque Γ_{min}=0.0109 μN m.



Conversion to electrical power



Stator coils

Neodymium Magnets

Commutator Ring

Dry Ice Block

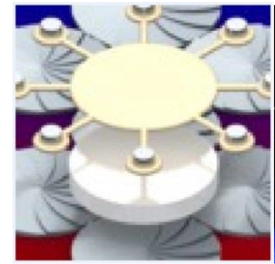
Turbine

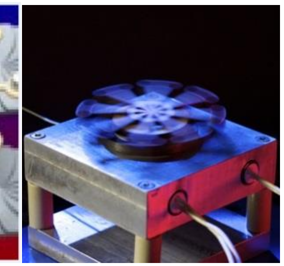
Confinement Ring

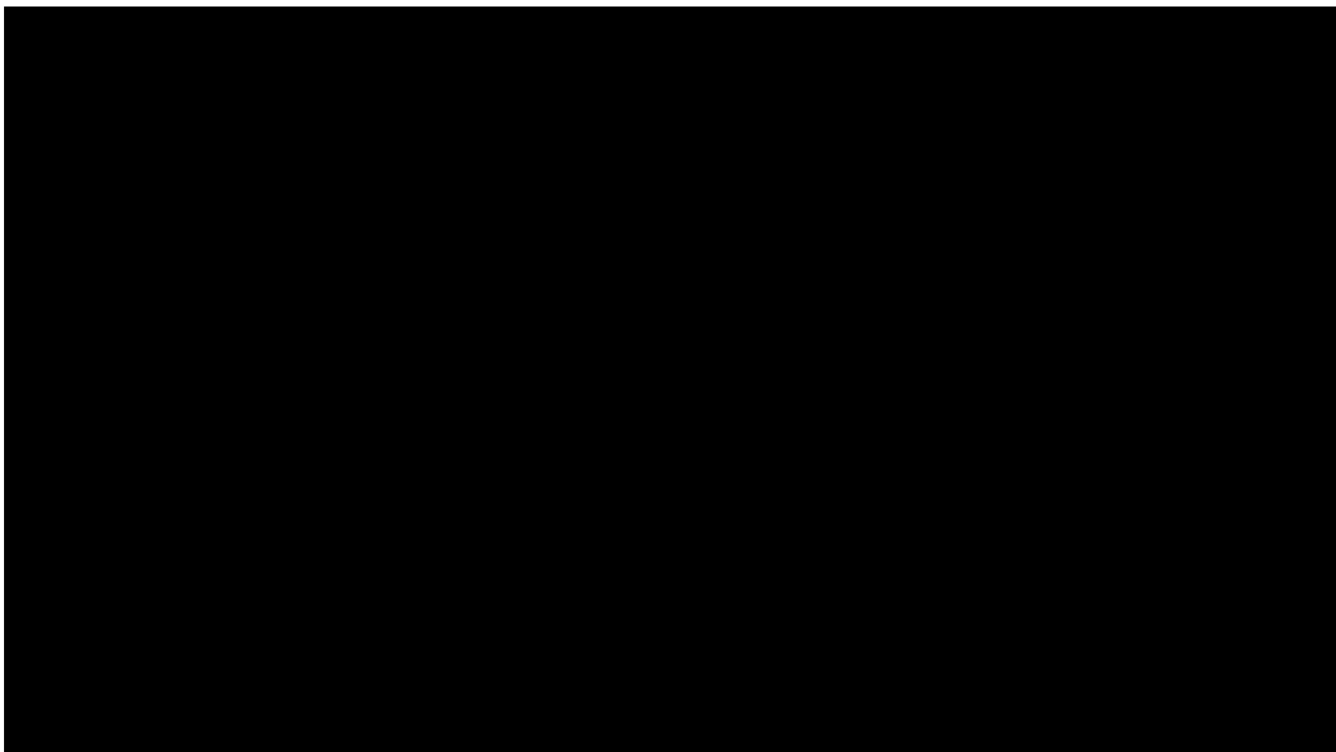
Hot Plate

Conversion to electrical power

1. 8-lobed commutator with magnets attached to a dry-ice rotor
2. 8-lobe multi-segment induction coil system lowered into proximity to the rotating assembly
3. Generated voltage visualized on an oscilloscope
4. Low phase transition-to-rotational energy efficiency – most energy expended on levitation, but future designs can avoid this







Applications of an LF Engine

<u>Microfluidics</u>

1. MEMS micro-heat engines for scavenging waste energy (e.g. Epstein et al, IEEE Transducers 1997, Fréchette et al, PowerMEMS 2003 Conferences)

Image: Fréchette et al, (2003)

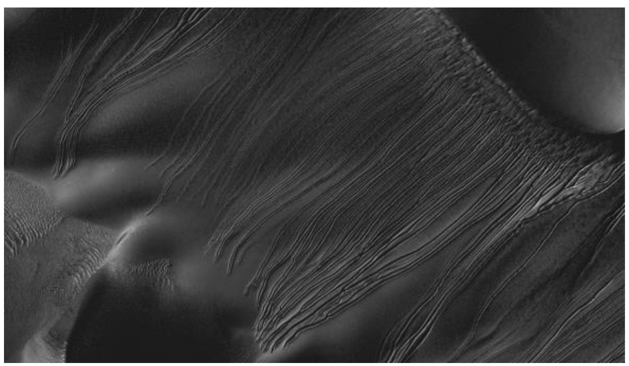
<u>Space engineering</u>

1. Large temperature differences exist
2. Deep space has abundance of locally available dry ices, e.g. H_2O, CO_2, CH_4
3. Idea of sublimation for use in micro-thrusters is an established space concept

Applications of an LF Engine

Linear Gullies on Mars

1. Hypothesis: Sliding dry ice blocks due to seasonal temperature variations
2. Tested idea on slopes of dunes in the desert
3. Sublimation Leidenfrost effect



Diniega *et al*, *Icarus* (2013) **225**, 526-537. Jet Propulsion lab video archive – "Dry Ice Moves on Mars - June 11, 2013" (Truncated version from http://mars.nasa.gov/mro/multimedia/videoarchive/)

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Breakthrough in energy harvesting could power life on Mars

Mar 05, 2015


A team of enthusiastic scientists are dressing in space suits and recreating life on Mars - in a rocky red desert on Earth. Researchers from the Mars Society live at a simulated Martian base in Utah, built with the help of American space agency NASA.

Mashable.com

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Summary

- Summary
  - Turbine-like substrates for rotation (orbiting and spinning motions)
  - Exemplification of rotation using solid CO_2 (and metal disks coupled by droplets)
  - Concept and demonstration of a “Leidenfrost Engine” driven by solid-vapor and liquid-vapour phase changes
  - Concept and demonstration of a “Sublimation Heat Engine”

Challenges

- Fundamental
  - LF temperature dependence on surface properties
  - Interaction between LF levitators, rotors, propellers
- Applied
  - Efficiency of the LF engine – optimisation through surface geometry and materials
  - Main route: microfluidics – low gravitational effects, increases surface to volume ratios

Acknowledgments

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You can check our paper here:

Wells, et al. 'A sublimation heat engine', Nature Communications, **6** 6390 (2015)

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