The Extremes of Fluid Dynamics

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FYFD in brief...

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A Leidenfrost droplet impregnated with hydrophilic beads hovers on a thin film of its own vapor. The Leidenfrost effect occurs when a liquid touches a solid surface much, much hotter than its boiling point. Instead of boiling entirely away, part of the liquid vaporizes and the remaining liquid survives for extended periods while the vapor layer insulates it from the hot surface. Hydrophilic beads inserted into Leidenfrost water droplets initially sink and are completely enveloped by the liquid. But, as the drop evaporates, the beads self-organize, forming a monolayer that coats the surface of the drop. The outer surface of the beads dries out, trapping the beads and causing the evaporation rate to slow because less liquid is exposed. (Photo credit: L. Maquet et al; research paper - pdf)

http://fuckyeahfluidynamics.tumblr.com

228,900+ followers  2,600+ followers
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Small versus large
Small versus large

*E. Coli* – swimming micro-organisms
Small versus large

Tufts microfluidic device courtesy of J. Guasto

Microfluidic devices

Micro-organisms

Physical size
Small versus large

Blood flow

Microfluidic devices

Micro-organisms

Physical size

J. Freund et al.
Small versus large

Blood flow

Microfluidic devices

Micro-organisms

Soap films

Physical size
Small versus large

Soap films
Blood flow
Atmospheric flows

Microfluidic devices
Micro-organisms

Physical size
Small versus large

Soap films
Blood flow
Microfluidic devices
Micro-organisms

Oceanic flows
Atmospheric flows

Physical size
Small versus large

Solar dynamics

Soap films

Blood flow

Microfluidic devices

Micro-organisms

Oceanic flows

Atmospheric flows

Physical size
Small versus large

Physical size

Soap films
Blood flow
Microfluidic devices
Micro-organisms

Supernova remnants

Solar dynamics
Oceanic flows
Atmospheric flows

NASA/ESA
Small versus large

- Soap films
- Blood flow
- Microfluidic devices
- Micro-organisms

- Supernovas
- Solar dynamics
- Oceanic flows
- Atmospheric flows

Physical size
Small versus large

Soap films
Blood flow
Microfluidic devices
Micro-organisms

Supernovas
Solar dynamics
Oceanic flows
Atmospheric flows

Physical size
Other extremes

Pitch drop experiment

Velocity
Other extremes

Pitch drop experiment

Hypersonics

Velocity
Other extremes

Pitch drop experiment

Velocity

Superfluids

Temperature

Hypersonics
Other extremes

Pitch drop experiment

Velocity

Superfluids

Temperatures

Hypersonics

Plasmas
We define fluid dynamics by extremes.
What is a fluid?
What is a fluid?

Atom
What is a fluid?

Atom

Fluid Atoms
What is a fluid?

Atom

Fluid Atoms

Knudsen Number

$Kn = \frac{\text{mean free path}}{\text{flow lengthscale}}$
What is a fluid?

\[ Kn = \frac{\text{mean free path}}{\text{flow lengthscale}} \]

Atom \hspace{1cm} Fluid Atoms \hspace{1cm} Knudsen Number

Free Molecular Flow
What is a fluid?

Atom

Fluid Atoms

Knudsen Number

$Kn = \frac{\text{mean free path}}{\text{flow lengthscale}}$

Atom

Fluid Atoms

Knudsen Number

Continuum Mechanics

Free Molecular Flow
Navier-Stokes

\[ \frac{\partial \bar{u}}{\partial t} + (\bar{u} \cdot \nabla) \bar{u} = -\frac{1}{\rho} \nabla p + \bar{g} + \nu \nabla^2 \bar{u} \]
Navier-Stokes

\[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla p + \mathbf{g} + \nu \nabla^2 \mathbf{u} \]

- Unsteady
- Convective
- Pressure
- Body Force
- Viscous
Navier-Stokes

\[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla p + \mathbf{g} + \nu \nabla^2 \mathbf{u} \]

- Unsteady
- Convective
- Pressure
- Body Force
- Viscous

Scaling arguments

\[ Re = \frac{\text{inertial effects}}{\text{viscous effects}} \]
Navier-Stokes

\[ \frac{\partial \vec{u}}{\partial t} + \left( \vec{u} \cdot \nabla \right) \vec{u} = -\frac{1}{\rho} \nabla p + \vec{g} + \nu \nabla^2 \vec{u} \]

Unsteady Convective Pressure Body Force Viscous

Scaling arguments

\[ \text{Re} = \frac{\text{inertial effects}}{\text{viscous effects}} \]

Something more tractable
Extremely viscous

\[ \text{Re} = \frac{U_x}{\nu} \ll 1 \]
Extremely viscous

Slow

\[
\text{Re} = \frac{U_x}{v} \ll 1
\]
Extremely viscous

Slow

\[
\text{Re} = \frac{U_x}{\nu} \ll 1
\]

Mantle Convection

W. Bangerth and T. Heister
Extremely viscous

\[ \text{Tiny} \]

\[ \text{Re} = \frac{U_x}{\nu} \ll 1 \]
Extremely viscous

Re = \frac{U_x}{\nu} << 1

Tiny

Beating Cilia

Extreme closeup (150x) of coral cilia interact with a particle suspended in the fluid.
Extremely viscous

\[ \text{Re} = \frac{U_x}{\nu} \ll 1 \]

Hard to deform
Extremely viscous

\[ \text{Re} = \frac{U_x}{v} \ll 1 \]

Hard to deform
Inertially-dominated

$$\text{Re} = \frac{U_x}{\nu} \gg 1$$
Inertially-dominated

Fast

\[
\text{Re} = \frac{U_x}{\nu} \gg 1
\]
Inertially-dominated

Big

\[ \text{Re} = \frac{U_x}{\nu} \gg 1 \]

Peregrine Falcon

Phytoplankton Blooms

M. Baird
Inertially-dominated

\[
\text{Re} = \frac{U_x}{\nu} \gg 1
\]

Phytoplankton Blooms

Peregrine Falcon

M. Baird

NASA
Inertially-dominated

\[ \text{Re} = \frac{U_x}{\nu} \gg 1 \]

Phytoplankton Blooms

Peregrine Falcon

Boundary Layers

\[ u_0 \quad u(y) \]
Boundary layers

30 m

[Image: Wikimedia]
Boundary layers

30 m

0.01 m

[Image: Boundary layer of an airplane] (Wikimedia)

[Image: Linear and nonlinear instabilities of the laminar boundary layer] (From H. Werlé (ONERA))
Boundary layers

Laminar Boundary Layer

Turbulent Boundary Layer

30 m

0.01 m

From H. Werlé (ONERA)
Boundary layers

Protruding Gap Filler
Boundary layers

Protruding Gap Filler

Hypersonic Re-Entry and Boundary Layer Transition

Fig. 8. STS-119  Mach 8.4
Turbulent flow from wing protuberance
Turbulent flow from unknown origin

Fig. 9. STS-125  Mach 14.3
Elevon gap heating
Body flap heating
Laminar flow

Fig. 10. STS-128  Mach 14.7
Heating footprint from wing protuberance
Body flap heating
Elevon gap heating
Laminar flow
Boundary layers

Protruding Gap Filler

Removing the Gap Filler

Hypersonic Re-Entry and Boundary Layer Transition

Fig. 8. STS-119 Mach 8.4

Fig. 9. STS-125 Mach 14.3

Fig. 10. STS-128 Mach 14.7

Horvath et al. AIAA 2010-241
Tile Gap Filler, Shuttle, STS-114

This object is on display in the Moving Beyond Earth exhibition at the National Air and Space Museum, Washington, DC.

Related Collections:

Human Spaceflight
Boundary layers

Mako shark

jidanchaomian
Boundary layers

Mako shark

Denticles
Boundary layers

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A. Lang et al.
Living in boundary layers

\[ U(z) \]

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S. Rohrlach

Feather Mites

S. Mironov & R. Palma

Mayfly Nymphs

S. Vogel

S. Vogel, Life in Moving Fluids
Living in boundary layers

$U(z)$

Humans

Barnacles

Feather Mites

Mayfly Nymphs

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U(z)

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Droplet Splashing

L. Xu et al.

High Pressure
Where small becomes important

Superhydrophobic Surfaces

G. Azimi et al.

K. Hounsell et al.

Droplet Splashing

L. Xu et al.

High Pressure

Low Pressure

100 kPa

17.2 kPa

0 ms

0.276 ms

0.552 ms

2.484 ms
Where small becomes important

Shock Waves

NASA Langley
Where small becomes important

Shock Waves

NASA Langley
Where small becomes important

Shock Waves

HH47

1994

...and not very small

NASA/ESA/P. Hartigan/G. Bacon
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Von Karman Vortex Street

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Saturn's Weird Hexagon Vortex Stuns in NASA Photo

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