Gerris/Basilisk in an industrial context: (drop) impact in aeronautics

Basilisk/Gerris Users' Meeting 2019

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Introduction

Research interests

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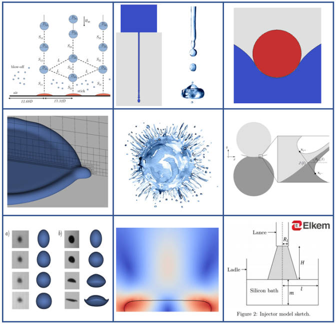
My **research interests** lie at the interface between modelling, analysis and simulation of

- **highly nonlinear, multi-scale, multi-physics** systems

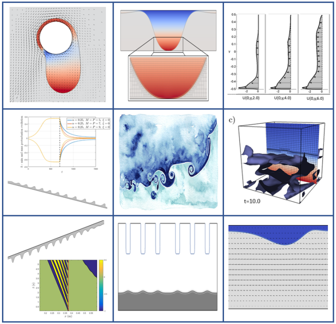
in continuum mechanics, with a strong emphasis on combining

- novel methodologies in **asymptotic analysis** and
- developments in **scientific computing**.

WP1 Drop impact - from early to late stage dynamics



WP2 Multi-layer flows in confined geometries



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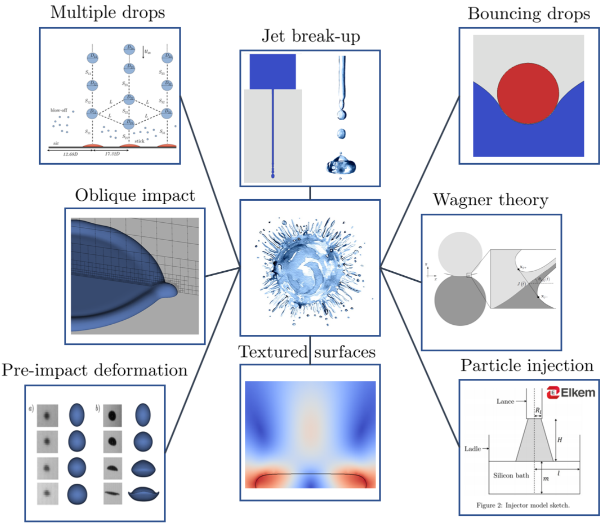
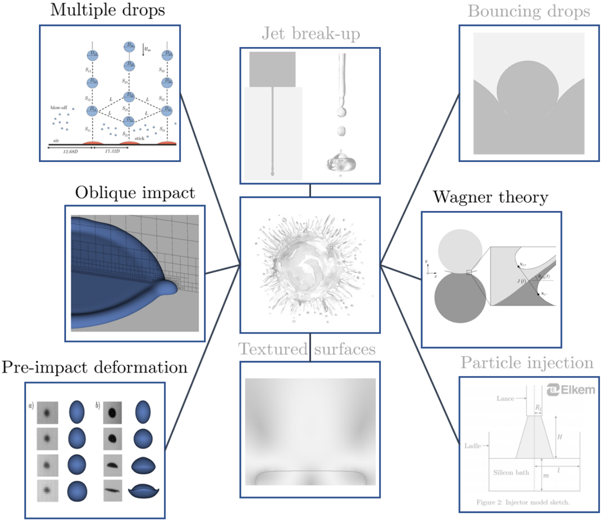
Introduction
Research interests: WP1 Drop impact



6 academic collaborations, 3 industrial links, 2+5 publications, 1 patent application

Introduction
Research interests: WP1 Drop impact



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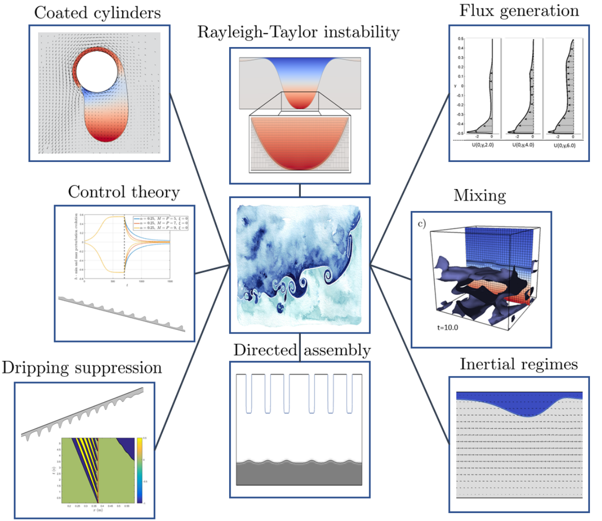
Introduction
Research interests: WP2 Multi-layer flows



7 academic collaborations, 5+4 publications, several supervised projects

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High speed drop impact - from early to late stage dynamics

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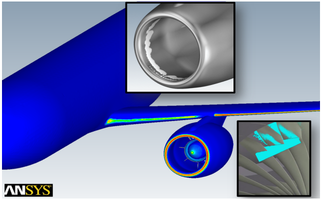
Motivation
Background

Studying the dynamics of **droplets in high speed flow conditions** has ramifications particularly in the aeronautics industry, where the following flight conditions:

- heavy **rainfall**
- **high liquid water content (LWC)** regions - clouds

are commonplace.

Ice formation severely affects aerodynamic performance. Of particular interest are the adverse effects on the **nacelle** system.



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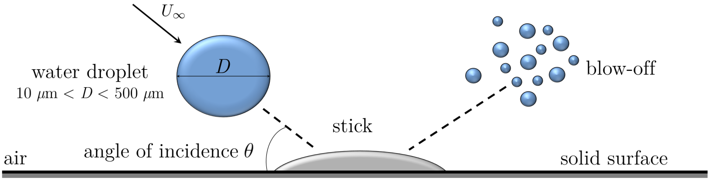
Introduction
Fundamental Research Question

Proposed new rulemaking by both EASA and the FAA is requiring water catch analysis to consider freezing rain and drizzle, which are characterized by water droplets of larger diameter than what are general considered for certification.

Task description:

- Blowoff factors for water catch are currently not well understood;
- required in the analysis of Nacelle ice protection system performance;
- would result in reduced bleed air offtake demand on the engine compressor, hence reduced fuel burn.



Primary objective: Using modelling, analysis and computational fluid dynamics (CFD) tools in order to study the rich dynamics of drop impact onto solid surfaces (including drop formation and pinch-off) within parameter ranges suitable from the physical standpoint.

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Introduction
Standard Methodology

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Let us understand the current notion of **water catch** on a surface is **defined**.

R. W. Gent, N. P. Dart and J. T. Cansdale

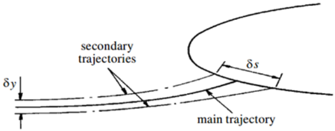

Figure 7. Method used to calculate local catch efficiency, $\beta = \delta y/\delta s$

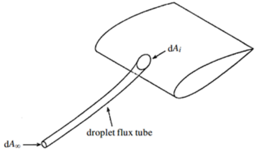

Figure 9. Definition of the local catch efficiency on a three-dimensional geometry, $\beta = dA_\infty/dA_i$.

While such an **approximation** is necessary in the context of the **very large lengthscales** involved:

- **droplets** are assumed to be **spherical and non-deformable**;
- all droplet and liquid film related **effects on the surrounding flow are neglected**;
- there is **no interaction between drops** (e.g. coalescence);
- **no splashing** (ejection of droplets) is considered.

Particle trajectory approaches contain little to **no information on the complex fluid dynamics** driving the impingement process.

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Background

Early history

The first recorded investigative efforts on drop impact **date back to 1876**, when Worthington conducted beautiful **experimental studies** of drop impact in his Proc. Royal Society work during **the advent of the photography era** (image below: Josserand & Thoroddsen, Annu. Rev. Fluid Mech., 2016).

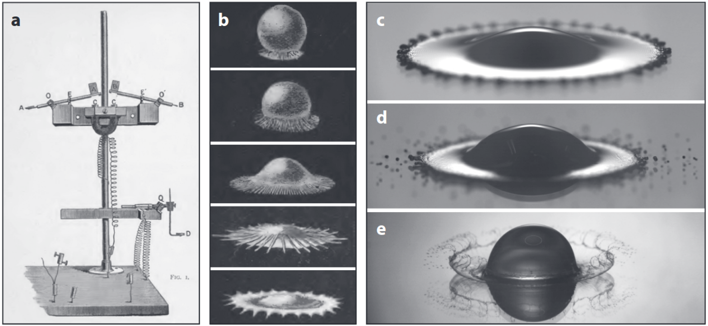


Figure 1

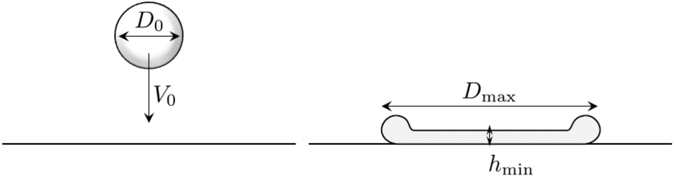
(*a*) Worthington's drop-release setup and (*b*) his sketches of an impacting mercury drop. (*c*) Reproduction of Worthington's impact conditions for mercury on glass using modern video technology. (*d*) Prompt splash for mercury drop impacting superhydrophobized glass. (*e*) Corona splash for ethanol drop on glass. Panels *d* and *e* courtesy of Erqiang Li.

Background

Classical quantities of interest

Easily **measurable quantities of relevance to applications**:

- spreading and retraction dynamics, **maximum spreading diameter**;
- **minimum film thickness** and general increase in **interfacial area**;
- the presence of **entrapped gas bubbles** underneath the spreading liquid.



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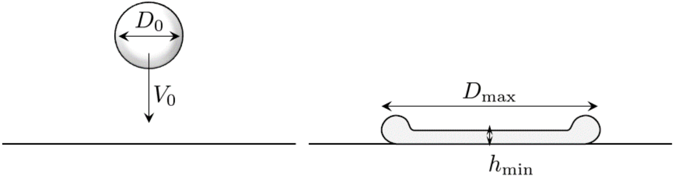
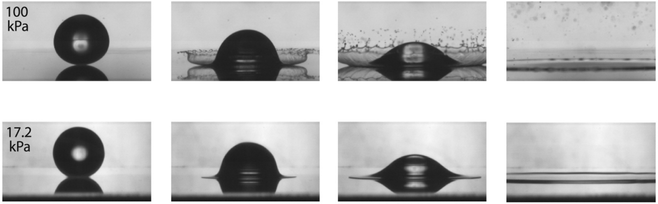


The seminal work of Eggers et al. (PoF, 2010) as well as recent research by Wildeman et al. (JFM, 2016) provide suitable handles on the **conversion of kinetic energy into surface energy**.
This leads to **simple estimates**, e.g. for the maximum spreading radius $R_{\max}/R^* \approx (We/6)^{1/2}$ and $h_{\min} \approx R^*/Re^{2/5}$.

Background
The past decade

At the turn of the century, most research in this area was concentrated towards finding the so-called splashing threshold as a function of the liquid parameters. Until 2005, when Sidney Nagel's group in Chicago found something surprising:



0 ms 0.276 ms 0.552 ms 2.484 ms

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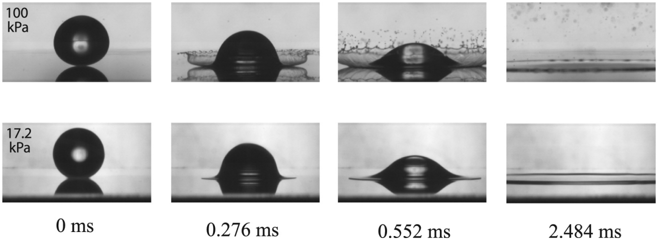

"A drop which splashes in Chicago would not necessarily splash on the top of Mt. Everest and would definitely not splash on the Moon."

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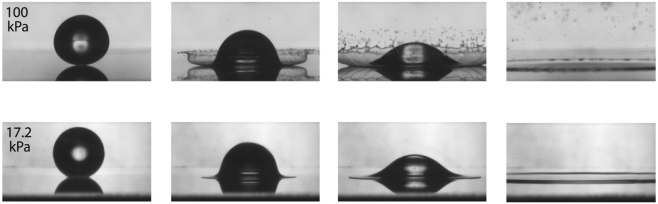

0 ms | 0.276 ms | 0.552 ms | 2.484 ms

"A drop which splashes in Chicago would not necessarily splash on the top of Mt. Everest and would definitely not splash on the Moon."

Since then, further progress has been encouraged by

- advancement in **experimental techniques and equipment**;
- improved and **specialised algorithms**, coupled with a significant **rise in computing power**.

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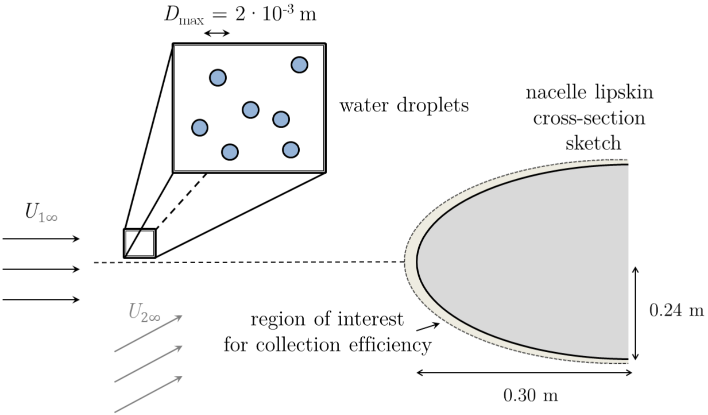
Model

Geometry of Interest - Scaling Argument

In the context of **reducing computational effort** and using a more realistic geometry, we suggest reducing the domain to include only the nacelle lipskin for our simulations. Can we do even better?



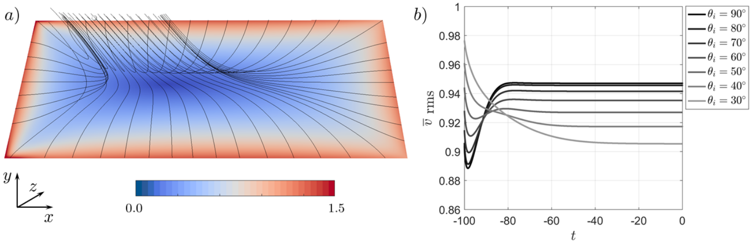
Impact geometry.

Model

Oblique stagnation-point flow - RC & Papageorgiou, IJMF 107, 192-2017 (2018)

The **local background air flow** closely resembles the well-known **oblique stagnation-point flow**, one of the rare cases in which obtaining analytical solutions to the Navier-Stokes equations is possible.

Convergence of the background flow as a function of time is illustrated below, for a variety of impingement angles.



Main advantages:

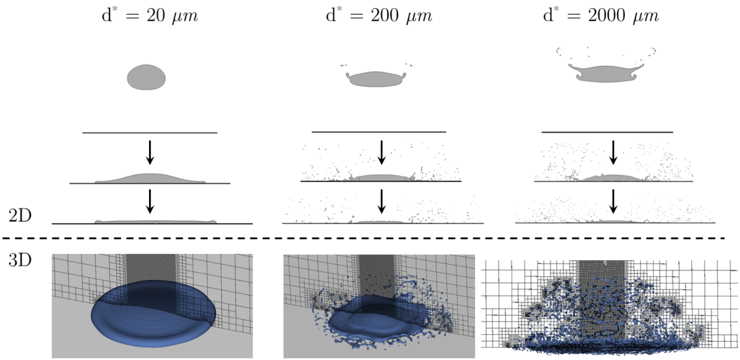
- the drops encounter the same type of **developing boundary layer structure** as in the large scale flow;
- the **approximately uniform flow** far away from the solid surface **prevents violent break-up** of the drop before impingement.

Single drop impact

Droplet behaviour - summary - RC & Papageorgiou, IJMF 107, 192-2017 (2018)

Detailed analysis of splashing dynamics has been performed in **both two and three dimensions**, revealing **similar qualitative and quantitative features**.

- **small** drops: pancaking behaviour, **no splashing**;
- **medium** drops: deformation before impact, **moderate splashing**;
- **large** drops: stronger deformation, **violent splashing**;



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Pre-impact dynamics

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Pre-impact dynamics
Experiments (NASA & INTA)

During 2012 – 2015, Vargas, Sor and Magarino (**NASA - INTA Madrid collaboration**) have conducted a set of experiments on **droplet breakup near the leading edge of an airfoil**.

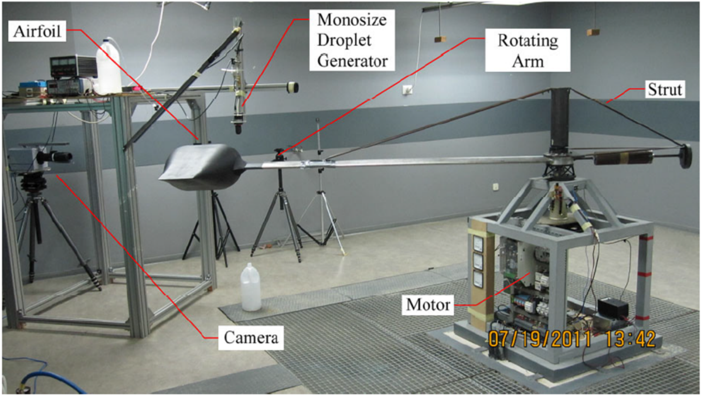

Figure 2.—Experiment set-up in the INTA test cell.

Pre-impact dynamics

Experiments (NASA & INTA)

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Key observations:

- small drops tend to retain their shape;
- medium sized drops flatten into squashed ellipsoidal shapes;
- large drops eventually break under violent rupture.

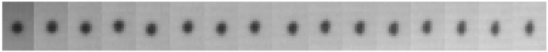


Fig. A1 Case 1249 droplet deformation evolution: airfoil velocity = 90 m/s, chord size = 690 mm, and droplet radius = 181 μm.

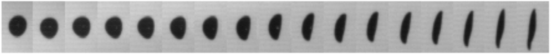
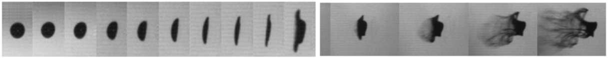


Fig. A5 Case 1041 droplet deformation evolution: airfoil velocity = 90 m/s, chord size = 690 mm, and droplet radius = 565 μm.

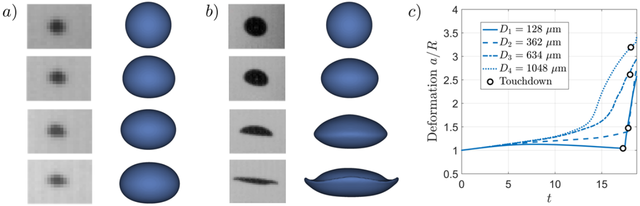


Drop deformation and breakup as $D = 362$ µm (above), $D = 1130$ µm (middle) and $D = 2064$ µm (below)

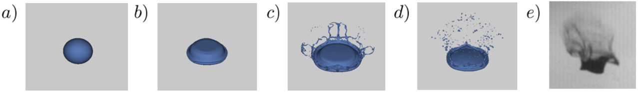
Pre-impact dynamics

Comparison - RC & Papageorgiou, IJMF 107, 192-207 (2018)

Excellent qualitative agreement is found between the experiments and computations in the same parameter range, with good quantitative agreement also found in the proposed deformation rate metric.



With the aid of the simulations dynamics for **much smaller drops** is analysed, while also gathering break-up data in the timesteps **just before impact**.



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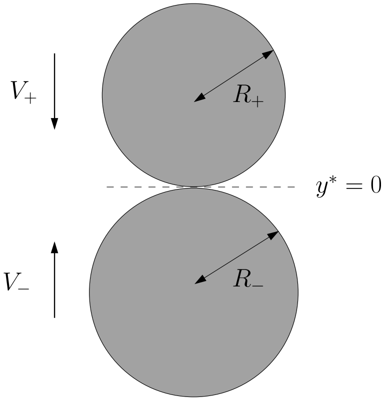
High speed liquid-liquid impact

Geometry - RC & M.R. Moore, JFM 856, 764-796 (2018)



Assumptions:

- immiscible fluids;
- incompressible fluids;
- inviscid flow;
- surface tension ignored;
- any other external forces negligible (**inertia-dominated**);
- two-dimensional.

The aim is to **characterise the jet** resulting from the **violent impact**, especially in view of **asymmetric cases** ($R = R_-/R_+ \neq 1$ or $V = V_-/V_+ \neq 1$), as well as **distinguished limits**, e.g. $R_- \to \infty$ (impact onto a liquid pool).

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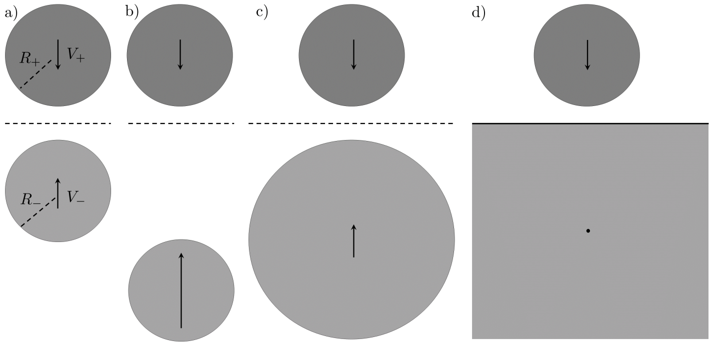
High speed liquid-liquid impact

Geometry - RC & M.R. Moore, JFM 856, 764-796 (2018)

Some of these **interesting cases** are presented below:



a) $R = \frac{R_-}{R_+} = 1$, $V = \frac{V_-}{V_+} = 1$

b) $R = \frac{R_-}{R_+} = 1$, $V = \frac{V_-}{V_+} = 4$

c) $R = \frac{R_-}{R_+} = 2$, $V = \frac{V_-}{V_+} = 1$

d) $R = \frac{R_-}{R_+} = \infty$, $V = \frac{V_-}{V_+} = 0$

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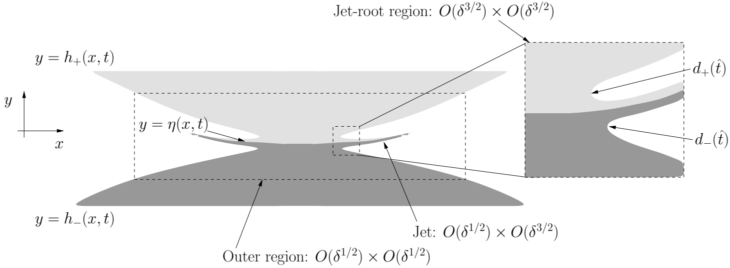
Impact

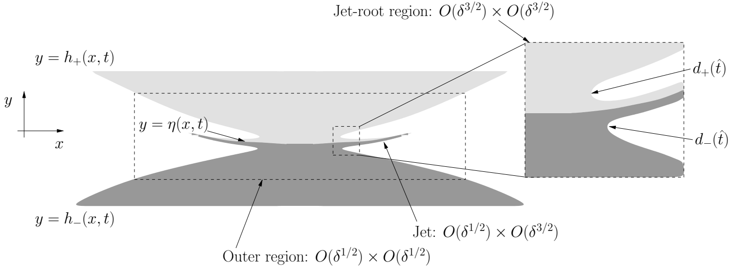
Asymptotic structure - RC & M.R. Moore, JFM 856, 764-796 (2018)



Early-time asymptotic structure according to Wagner theory.

Impact

Asymptotic structure - RC & M.R. Moore, JFM 856, 764-796 (2018)



Early-time asymptotic structure according to Wagner theory.

- **Outer**: boundary conditions linearise onto $y = 0$, solved using Riemann-Hilbert techniques.
- **Inner ('jet-root')**: quasi-steady Helmholtz flow, solved using Schwarz-Christoffel mappings.
- **Jet**: thin, high-speed jet governed by zero-gravity shallow-water equations, solved using characteristics.

Asymptotic structure

Outer region - RC & M.R. Moore, JFM 856, 764-796 (2018)

Under the above assumptions and since the flow is initially irrotational, there is a velocity potential $\phi_{\pm}$, such that $_{\pm} = \nabla\phi_{\pm}$. Thus, by the continuity condition,

$$\nabla^2\phi_{\pm} = 0 \text{ in the fluid,}$$

with the liquid pressure given by Bernoulli's equation.

$$\nabla^2\hat{\phi}_{+0} = 0$$

$$\hat{\phi}_{+0} = 0, \quad \frac{\partial\hat{\phi}_{+0}}{\partial\hat{y}} = \frac{\partial\hat{h}_{+0}}{\partial\hat{t}} \qquad \hat{\phi}_{+0} = \hat{\phi}_{-0}, \quad \frac{\partial\hat{\phi}_{\pm0}}{\partial\hat{y}} = \frac{\partial\hat{\eta}_0}{\partial\hat{t}} \qquad \hat{\phi}_{+0} = 0, \quad \frac{\partial\hat{\phi}_{+0}}{\partial\hat{y}} = \frac{\partial\hat{h}_{+0}}{\partial\hat{t}}$$

$$-\hat{d}_0(\hat{t}) \qquad \hat{d}_0(\hat{t})$$

$$\hat{\phi}_{-0} = 0, \quad \frac{\partial\hat{\phi}_{-0}}{\partial\hat{y}} = \frac{\partial\hat{h}_{-0}}{\partial\hat{t}} \qquad \hat{\phi}_{-0} = 0, \quad \frac{\partial\hat{\phi}_{-0}}{\partial\hat{y}} = \frac{\partial\hat{h}_{-0}}{\partial\hat{t}}$$

$$\nabla^2\hat{\phi}_{-0} = 0$$

In the outer region, use scaling

$$(x, y) = \delta^{1/2}(\hat{x}, \hat{y}), \; \phi_{\pm} = \delta^{1/2}\hat{\phi}_{\pm}, \; p_{\pm} = \delta^{-1/2}\hat{p}_{\pm}, \; h_{\pm} = \delta\hat{h}_{\pm}, \; \ldots$$

and expand the variables in asymptotic series in powers of δ:

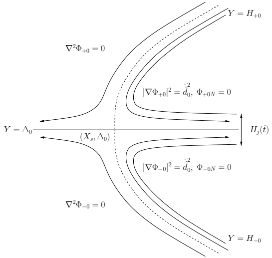
$$\hat{\phi}_{\pm} = \hat{\phi}_{\pm 0} + \delta^{1/2}\hat{\phi}_{\pm 1} + O(\delta)$$

The leading-order problem is a Riemann-Hilbert boundary value problem of index -1, since the velocity potentials have square-root behaviour close to the turnover points.

Asymptotic structure

Inner region - RC & M.R. Moore, JFM 856, 764-796 (2018)

- Locally to $x = \pm\delta^{1/2}\hat{d}(\hat{t})$, we have the following structure:
- The appropriate scales for this region are derived in Howison et al. (1991) for the related problem of water entry:



$$x = \delta^{1/2}\hat{d}_+(\hat{t}) + \delta^{3/2}X,\ y = \delta\hat{h}_{+0}(\hat{d}_0(\hat{t}), \hat{t}) + \delta^{3/2}Y.$$

Matching with the leading-order outer solution gives the leading-order jet thickness to be

$$H_j(\hat{t}) = \frac{\pi}{16}\frac{(1+V)^2\hat{d}_0(\hat{t})}{\dot{\hat{d}}_0(\hat{t})^2} = \frac{\pi(1+V)^{3/2}}{8}\sqrt{\frac{1+R}{R}}\hat{t}^{3/2},$$

with the **far-field jet velocity**, $U_j(\hat{t})$, given by

$$U_j = 2\dot{\hat{d}}_0 = 2\sqrt{\frac{(1+V)R}{1+R}}\hat{t}^{-1/2}.$$

Asymptotic structure

Jet region - RC & M.R. Moore, JFM 856, 764-796 (2018)

- It is sensible to **move to a frame (ξ, η) based on the jet-root curve**.
- Use ξ to represent arc length along the curve and η is a normal direction to the curve.
- Based on the known size of the jet-root, scale

$$\xi = \delta^{1/2}\bar{\xi}, \ \eta = \delta^{3/2}\bar{\eta}.$$

and ultimately satisfy the **zero-gravity shallow water equations** in $\bar{\xi} > \hat{d}_0(\hat{t})$:

$$\bar{u}_{0\hat{t}} + \bar{u}_0\bar{u}_{0\bar{\xi}} = 0, \ \bar{\chi}_{0\hat{t}} + (\bar{u}_0\bar{\chi}_0)_{\bar{\xi}} = 0,$$

subject to the jet-root conditions

$$\bar{u}_0(\hat{d}_0(\hat{t}), \hat{t}) = U_j(\hat{t}), \ \bar{\chi}_0(\hat{d}_0(\hat{t}), \hat{t}) = H_j(\hat{t}).$$

Using the **method of characteristics**, the above can be solved to find

$$\bar{u}_0 = \frac{\bar{\xi}}{\hat{t}}, \ \bar{\chi}_0 = \frac{4\pi(1+V)^4R^2}{(1+R)^2}\frac{\hat{t}^4}{\bar{\xi}^5}.$$

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Results

Summary - RC & M.R. Moore, JFM 856, 764-796 (2018)

Given time and patience, **useful quantitative information** about the impact process and properties of the resulting jet is retrieved:

Location of jet root:

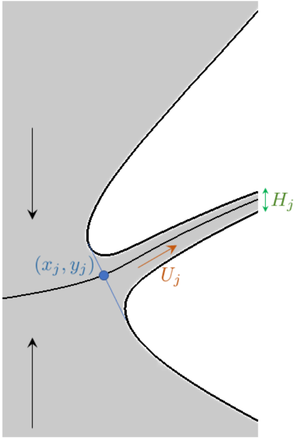
$$\hat{x}_j = 2\sqrt{\frac{(1+V)R}{1+R}\hat{t}},$$
$$\hat{y}_j = \left(\frac{(3RV+R-V-3)}{2(1+R)}\hat{t}\right).$$

Jet thickness:

$$H_j(\hat{t}) = \frac{\pi(1+V)^{3/2}}{8}\sqrt{\frac{1+R}{R}}\hat{t}^{3/2},$$

Jet velocity:

$$U_j = 2\dot{\hat{d}}_0 = 2\sqrt{\frac{(1+V)R}{1+R}}\hat{t}^{-1/2},$$

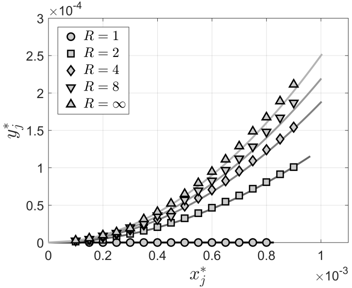


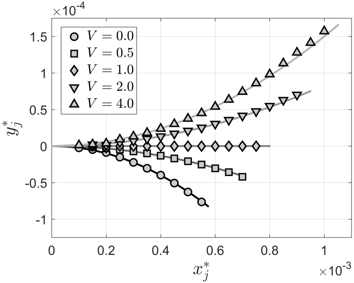
Results

Jet root location - RC & M.R. Moore, JFM 856, 764-796 (2018)

At early times we find excellent agreement between the two approaches. This begins to deteriorate (in an anticipated manner):

- at the tip of the jet;
- when not correcting for the presence of entrapped air bubbles;
- once we force the underlying assumptions (e.g. lower impact velocities);
- at sufficiently large times;





Results

Velocity along the jet - RC & M.R. Moore, JFM 856, 764-796 (2018)

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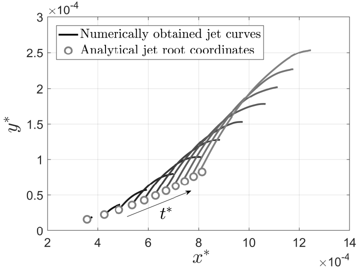
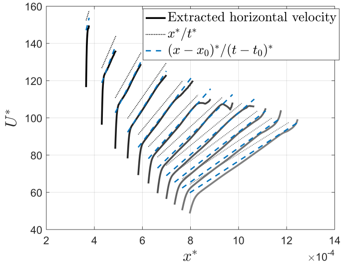
- once we force the underlying assumptions (e.g. lower impact velocities);
- at sufficiently large times;





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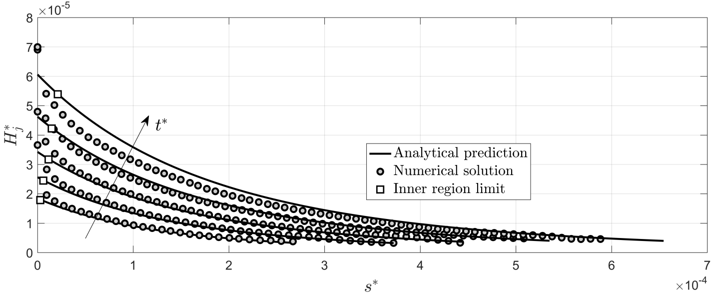
Results

Jet thickness - RC & M.R. Moore, JFM 856, 764-796 (2018)

At early times we find excellent agreement between the two approaches. This begins to deteriorate (in an anticipated manner):

- at the tip of the jet;
- when not correcting for the presence of entrapped air bubbles;
- once we force the underlying assumptions (e.g. lower impact velocities);
- at sufficiently large times;



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Post-impact dynamics

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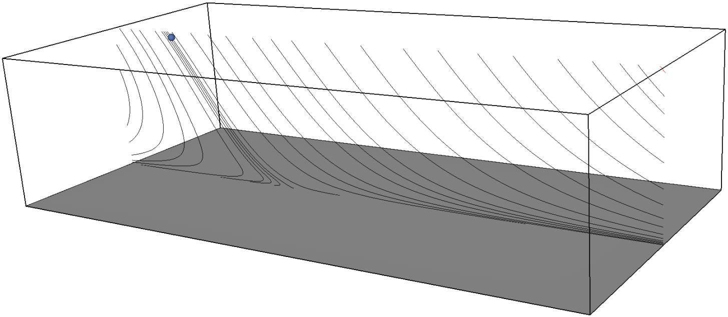
Post-impact dynamics

Asymmetric spreading - RC & DTP, IJMF 107, 192-2017 (2018)

The system is **extremely rich** in interesting phenomena, such as for example the case of spreading dynamics under **oblique impact** conditions, which is **largely unexplored** beyond very short timescales.

Drop $D = 20\ \mu$m, impingement angle of 50°, $U_\infty = 75$ m/s.



- How does the **pre-impact deformation** affect the **spreading**?

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Post-impact dynamics

Asymmetric spreading - RC & DTP, IJMF 107, 192-2017 (2018)

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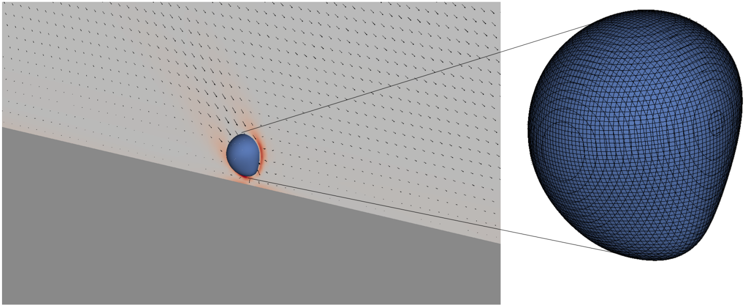
Drop $D = 20\ \mu$m, impingement angle of 50°, $U_\infty = 75$ m/s.
Final (saved) timestep before impact.



- How does the **pre-impact deformation** affect the **spreading**?

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How to make a splash

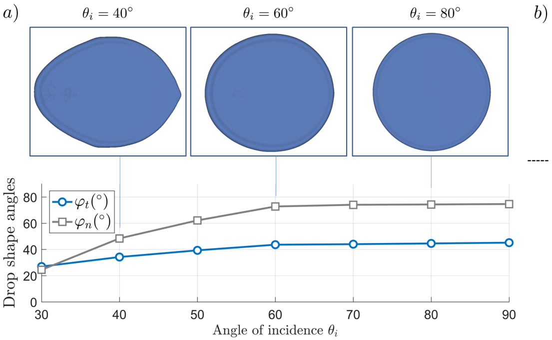
Radu Cîmpeanu

Mathematical Institute
University of Oxford
United Kingdom

Post-impact dynamics

Asymmetric spreading - RC & Papageorgiou, IJMF 107, 192-2017 (2018)

As a result of the oblique impingement and the presence of the air flow affecting the spreading dynamics, we find **exciting new structures** in the flow.

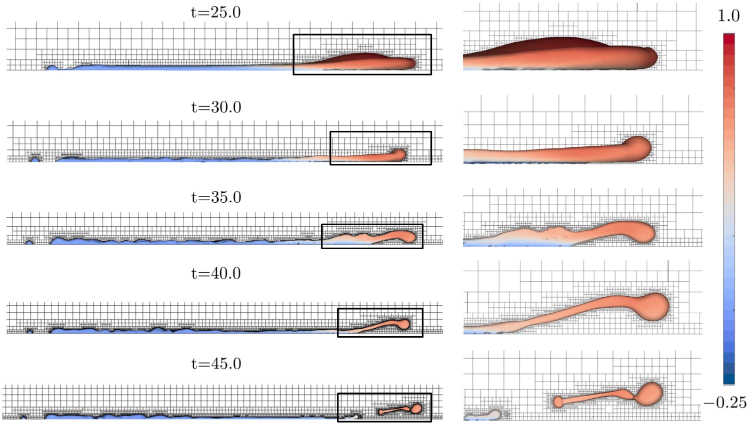


* For the non-oblique impact case we find **good agreement with the existing body of literature** in terms of **spreading diameter** (Wildeman et al, JFM, 2016) and minimal **film thickness** (Eggers et al, PoF, 2010).

Post-impact dynamics

Asymmetric spreading - RC & DTP, IJMF 107, 192-2017 (2018)

In summary, as a result of the oblique impingement and the presence of the air flow affecting the spreading dynamics, we find **exciting new structures** in the flow.



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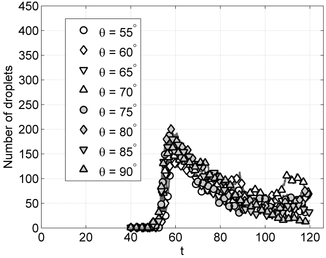
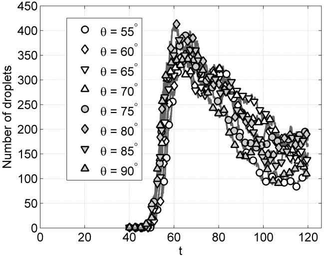
Post-impact dynamics

Droplet number dynamics

The main difference between impact of small diameter droplets and their larger counterparts is most visible when inspecting **the blow-off structure.**



(a) $D = 200\ \mu m$.



(b) $D = 2000\ \mu m$.

The number of droplets rises significantly with the increase in Reynolds and Weber numbers. However **the total mass of fluid** ejected in the two cases is approximately equal.

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Post-impact dynamics

Droplet distribution - RC & Papageorgiou, IJMF 107, 192-2017 (2018)

The volumes of the satellite droplets in the system follow a **log-normal distribution** during most of the simulation, with an **average area equal to roughly 1/10000 relative to the initial droplet**. This behaviour is **consistent with experimental observations** (Mundo, *IJMF*, 95 and Yarin, *JFM*, 1995) for lower velocity impacts onto solid surfaces.

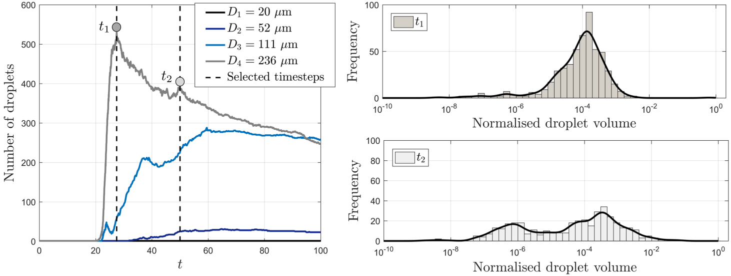
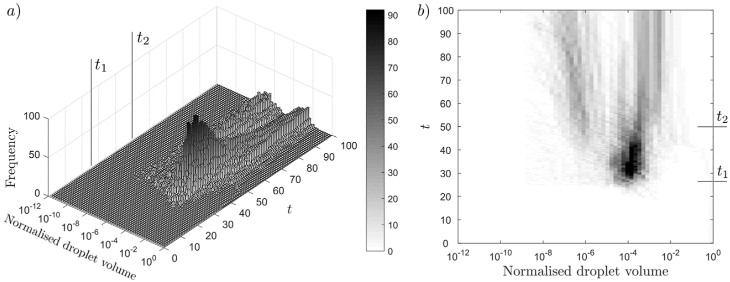


Figure: Droplet distribution for an $\theta = 60^\circ$ angle of incidence impact in the case of a range of droplet sizes.

Post-impact dynamics

Twin peaks - RC & Papageorgiou, IJMF 107, 192-2017 (2018)



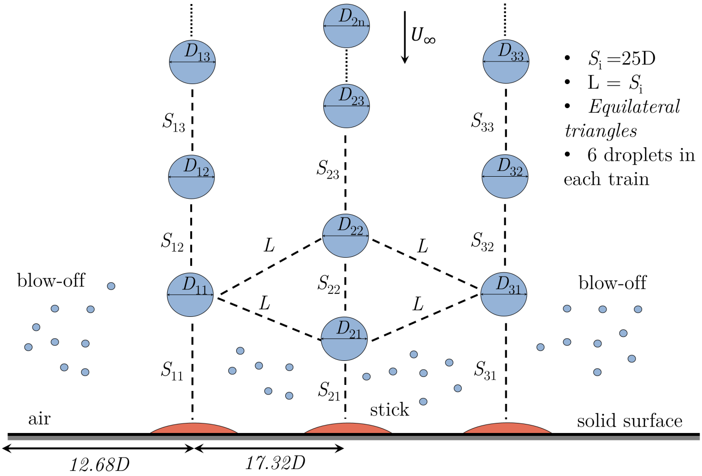
The **evolution of the drop size distribution** hints at a separation in drop behaviour depending on size:

- the **larger fluid volumes are found as spherical caps** in contact with the solid surface.
- are more likely to grow in time as coalescence events take place.
- the **smaller drops are airborne** and subjected to the strong background flow.
- tend to break up as long as capillary forces allow it.

Multiple droplet impact

Multiple impact sites

The introduction of **multiple impact sites adds to the complexity of the droplet-droplet interactions** and brings the constructed machinery even closer to real-life conditions.



- S_i =25D
- L = S_i
- *Equilateral triangles*
- 6 droplets in each train

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Using the impingement analysis
Multi-scale summary

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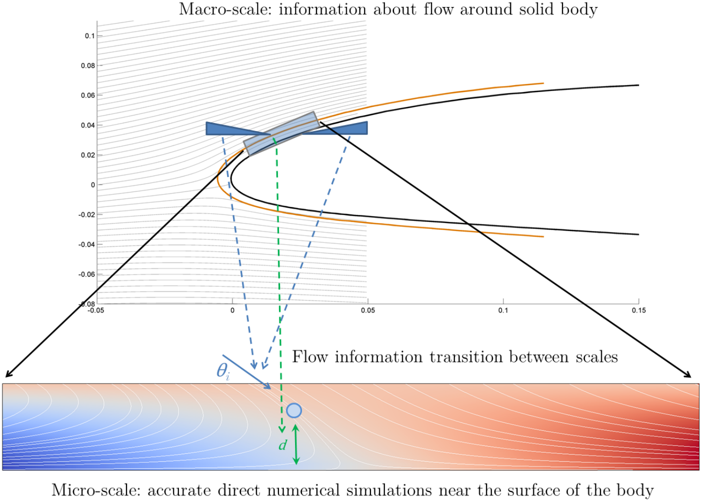
How is the particular **flow and geometry information transmitted** to the **local impingement analysis**? As **tailored initial conditions**.



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Conclusions
Challenges

From the perspective of the **theoretical formulation**:

- suitable **coupling** between the different phases;
- role of **compressibility** at these large velocities;
- **temperature effects** on longer time-scales;
- interesting **fundamental problems** in 3D.

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Conclusions
Challenges

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From the perspective of the **theoretical formulation**:

- suitable **coupling** between the different phases;
- role of **compressibility** at these large velocities;
- **temperature effects** on longer time-scales;
- interesting **fundamental problems** in 3D.

From the **computational standpoint**:

- **multi-scale** nature of the flow in both space and time;
- **numerical schemes** that ensure accuracy under extreme conditions when tracking topological transitions;
- **moving contact line** in this regime;
- **"big data"(sets)** - storage and algorithms;
- **multi-physics** capabilities in light of the **complex dynamics** described above.

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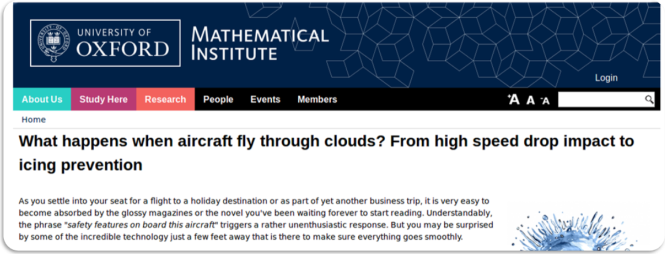
A few general articles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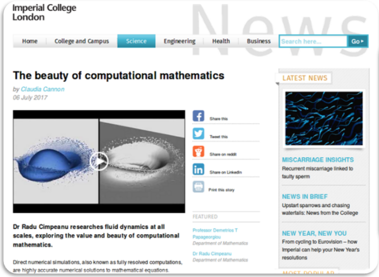
What happens when aircraft fly through clouds? From high speed drop impact to icing prevention

As you settle into your seat for a flight to a holiday destination or as part of yet another business trip, it is very easy to become absorbed by the glossy magazines or the novel you've been waiting forever to start reading. Understandably, the phrase "*safety features on board this aircraft*" triggers a rather unenthusiastic response. But you may be surprised by some of the incredible technology just a few feet away that is there to make sure everything goes smoothly.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The beauty of computational mathematics

by Claudia Cannon
06 July 2017

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Dr Radu Cimpeanu researches fluid dynamics at all scales, exploring the value and beauty of computational mathematics.

Direct numerical simulations, also known as fully resolved computations, are highly accurate numerical solutions to mathematical equations.

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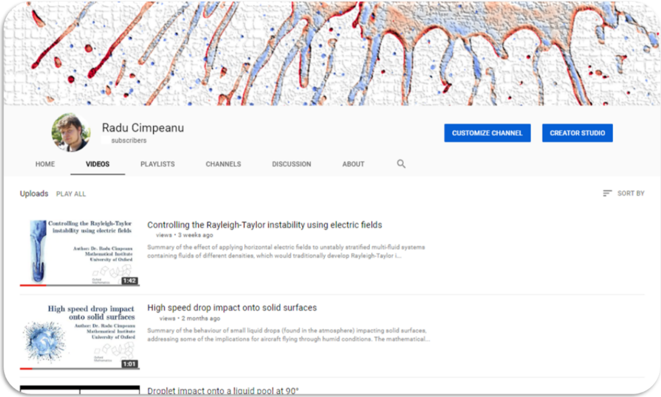

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WATERCOLOR ENTHUSIAST ANIMAL LOVER AND ILLUSTRATOR AT HEART

YouTube

@rcimpeanu

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Conclusions

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- the Oxford Centre for Industrial and Applied Mathematics,
- the industrial collaborators (Bombardier Aerospace, INTA),

without which this work would not have been possible.

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Thank you for your attention

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