**Institution: University of East Anglia**

**Unit of Assessment: 10 – Mathematical Sciences**

**Title of case study:**

**Improving Aircraft Safety in the Presence of Ice Build-up**

## 1. Summary of the impact

Aircraft icing is a significant factor in many aircraft accidents and incidents. Ice accretion on the wings has adverse aerodynamic effects, such as loss of lift and control, and ice can also block inlets into key flight sensors. Work by Richard Purvis and his Research Associate, Peter Hicks at UEA, in collaboration with *AeroTex UK* and *QinetiQ*, led to better understanding of how the impacts and splashing of water droplets influence the ice that forms on aircraft wings. This led to improved computer prediction codes, which are used by industry to improve design and help satisfy certification requirements.

## 2. Underpinning research

Mathematical research by **Dr Richard Purvis** and colleagues uses a combination of numerical and analytical techniques to gain a fundamental understanding of what happens when a water droplet hits a moving object, notably the wing of an aircraft. The objective was to better understand the splashing process, and thereby inform the empirical models of splashing that were traditionally used in icing prediction software.

Several important processes must be understood before an accurate model of splashing can be incorporated into more wide-ranging icing models. Two issues of particular importance are (i) predicting how much liquid gets splashed off the wing surface by a droplet impact, and (ii) establishing if, and where, that splashed liquid mass re-impinges further back on the wing. The research was partly supported by EPSRC and Nuffield Foundation grants to Purvis (2007-2009).

The main underpinning research includes using a novel Volume-of-Fluid numerical technique to investigate which parameters influence the splash, focussing mainly on the ratio of droplet size to layer depth [1]. It offered a prediction of how much water is splashed from the surface during an impact event for a variety of droplet sizes, impact speeds and impact angles. It was found that much of the splashed water is displaced from the relatively warm water lying on the wing rather than the colder water originating in the droplet. This finding has implications for the speed of ice growth, especially because previous tentative splash models had assumed that all the splashed water would be cold; a deficiency that has now been corrected. Additionally, the study [1] describes experimental results carried out in the Cranfield icing wind tunnel and draws comparisons with Purvis' numerical solutions. Excellent agreement was found between the experiments and numerical predictions in the early stages after impact, until the influence of the local airflow becomes dominant. This, and other experimental findings, identified the importance of air behaviour during the droplet impact process.

A more theoretical basis was used in [2], to consider an analytical asymptotic small-time study, capturing the initial behaviour as a large droplet enters a thin water layer. This is of interest as a validation to the numerical approaches and for estimating the initial impact pressure that may erode any surface coating of the wing that might be used to prevent ice build-up.

The research described in [3, 4 and 5] identified and examined the importance of air cushioning in droplet impacts. These studies focused on the entrapment of air bubbles as impact is approached onto both dry and wetted wings. Considering the local behaviour near touchdown of a droplet onto a substrate or water film, a coupled viscous-inviscid model was developed by exploiting the large density and viscosity differences between air and water. The research identified the important parameter ranges for air cushioning and these compare favourably to experimental measurements.

**Research Personnel**

Lead academic: Dr Richard Purvis – UEA 2005 to date.

Postdoctoral Research Associate: Dr Peter Hicks who worked on droplet impact and splashing at the UEA from 2007-2009, funded by an EPSRC award to Purvis. He subsequently moved to University College London and then worked on a secondment in industry at *AeroTex*, helping to develop new icing codes. He now holds a lectureship in Engineering at the University of Aberdeen.

## 3. References to the research

### Research Papers

(UEA authors in bold)

[1] M. Quero, D.W. Hammond, **R. Purvis** and F.T. Smith (2006) Analysis of super-cooled water droplet impact on a thin water layer and ice growth. *Paper AIAA-2006-466 of 44th AIAA Aerospace Sciences Meeting and Exhibit 9-12 January 2006, Reno Nv, USA.* ISBN: 1563478072;978-156347807-9

[2] S.D. Howison, J.R. Ockendon, J.M. Oliver, **R. Purvis** and F.T. Smith (2005) Droplet impact on a thin fluid layer, *Journal of Fluid Mechanics*, **542**, 1-23 doi:10.1017/S0022112005006282.

[3] **P.D. Hicks** and **R. Purvis** (2010) Air cushioning and bubble entrapment in three-dimensional droplet impacts, *Journal of Fluid Mechanics*, **649**, 135-163 doi:10.1017/S0022112009994009.

[4] **P.D. Hicks** and **R. Purvis** (2011). Air cushioning in droplet impacts with liquid layers and other droplets. *Physics of Fluids*, **23**, 062104 doi:10.1063/1.3602505.

[5] **P.D. Hicks**, E.V. Ermanyuk, N.V. Gavrilov and **R. Purvis** (2012) Air trapping at impact of a rigid sphere onto a liquid, *Journal of Fluid Mechanics,* **695**, 310-320 doi:10.1017/jfm.2012.20.

### External Funding

(Purvis was Principal Investigator on both grants)

Research Grant: **EPSRC** “Three-dimensional droplet impacts and aircraft icing.” £156,762 (2007-2009)

Research Grant: **Nuffield Foundation** “Air effects on high-speed droplet impacts and aircraft icing.” £5000 (2006-2007)

## 4. Details of the impact

During flight through clouds, suspended super-cooled water droplets impact onto the wings and all forward facing parts of an aircraft, and then turn to ice. Unchecked, this icing can lead to loss of lift and ultimately control, with very serious safety implications. The total loss of an ATR72 of American Eagle flight 4184 in 1995 at Roselawn which killed all 68 people on board, was primarily due to aircraft icing. This was despite the aircraft being certified as safe to fly in the weather conditions of the time, and the anti-icing systems being fully functional. It was ultimately understood that, while the existing certification and icing models were effective in conditions with clouds of small droplets (~20 microns), they were not valid for larger droplets (up to 1500 microns). Although rare, this is not an isolated incident. A similar fate befell Aero Caribbean flight 883 in 2010 where icing caused by large droplets was again the primary cause of the accident, with the loss of 68 lives.

The added complications of larger droplets, such as droplet distortion and, especially, of splashing meant the predictions of existing trusted models were wrong. They significantly over-predicted the rate of ice growth and did not predict ice formation as far back on the wing as seen in practice. Initial attempts to include simple empirical models failed to significantly improve the situation. Since 2003, much research effort worldwide has been focussed towards understanding the fundamental problems in large droplet impacts and how they relate to icing.

The impact of the research described here has been primarily achieved through collaboration with *AeroTex UK*. This is an SME established out of the aircraft icing and rotorcraft group at *QinetiQ*, a large defence company that originated from the Defence Evaluation and Research Agency (DERA). *AeroTex* offer consultancy to the aircraft industry in the field of aircraft icing, including ice prediction, icing protection and design. They develop icing prediction codes, and help to design and certify ice protection systems. Whilst details of their customer base are confidential, they have confirmed that it includes several major aircraft manufacturers and equipment suppliers (see corroborating source [A]).

Our fundamental research on large droplet impacts and splashing has enhanced understanding and offered crucial insight into a critical, and previously little understood, aspect of aircraft icing. It has fed into and informed *AeroTex* expertise, helping them to establish themselves as leading consultants in their field. The knowledge garnered from our research has enabled *AeroTex* to improve the products they can offer their clients by more accurately incorporating the influence of splashing into their prediction codes.

The value of the UEA research to *AeroTex* is confirmed in a supporting letter from the founder of *AeroTex UK* and Aircraft Icing Consultant:

> "The research undertaken at UEA has contributed to an improved knowledge of large droplet and splashing dynamics and has enhanced *AeroTex* expertise. It helped us to produce improved numerical models. As a result we can offer ice prediction and icing protection design software which is better than our competitors. Specifically we provide prediction codes, AID (Aircraft Icing Design) and DRT (Droplet Residence Time), which include aspects of super-cooled large droplet behaviour that the UEA research, along with other theoretical and experimental investigations, has helped inform."

Additionally, Hicks spent a year working at *AeroTex UK*, helping to develop further numerical models. Hicks' research and expertise in aircraft icing was developed during his postdoctoral position at UEA, making him ideally placed to help *AeroTex UK* with their product portfolio. This resulted directly in the development of new design tools, particularly for thermal and mechanical anti-icing systems (see corroborating source [B]).

By providing fundamental insights into the basic physics of droplet impacts and splashing, UEA research has aided industry to further their understanding of aircraft icing and to develop better design tools, ultimately leading to improved air safety.

**5. Sources to corroborate the impact**

[A] Letter of support from the Founder and Aircraft Icing Consultant, *AeroTex UK* (held on file at UEA)

[B] C. Hatch, R. Moser, R. Gent and P.D. Hicks (2011) The Building Blocks for a Hybrid ElectroThermal-ElectroMechanical Simulation Tool *SAE Technical Paper*, 2011-38-0035 doi:10.4271/2011-38-0035