17th Australasian Fluid Mechanics Conference
Auckland, New Zealand
5-9 December 2010

Development of a Small Icing Wind Tunnel for Simulating the Initial Stages of Solid Phase Ice Accretion

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Abstract

A number of recent turbofan failures during aircraft transit through apparently benign regions of storm clouds at high altitude have been attributed to a previously unrecognised form of icing. In this new form of icing, water in the solid phase enters the engine and builds up on the early stages of the compressor. A small wind tunnel has been developed to investigate the physics of solid phase ice accretion at thermal conditions relevant to turbofan operation during transit through high altitude clouds. The design and operation of the wind tunnel facility is described and thermodynamic and aerodynamic performance of the facility is characterized through temperature, pressure, and flow rate measurements. Operational characteristics and limitations of the wind tunnel facility are discussed. Preliminary ice accretion results indicate that configuration changes are necessary to ensure that all of the water impacting on the model surface is ice.

Introduction

Ice accretion occurs when freezing water droplets or snow particles accumulate on engineered structures. In aircraft applications, ice accretion generally occurs for flight through clouds at a temperature equal to or below the water freezing temperature.

Three modes of ice accretion are often considered: rime, glaze, and mixed rime/glaze icing. These different modes are aligned with different temperature ranges. Rime ice accretion occurs for temperatures between about -40 and -10 ºC. It appears that the rate of rime ice accretion can be identified using mass conservation on the assumption that the supercooled liquid droplets solidify when hitting the freezing surface [2]. At temperatures between -15 and 0 ºC, glaze icing occurs. At transitional conditions between rime and glaze accretion, “mixed ice” accretion occurs.

A newer type of ice accretion has recently been identified as relevant for commuter and commercial aircraft engines [3]. The ambient atmospheric temperature for transport aircraft cruising at an altitude higher than 10,000 m is approximately -50 ºC. Flight conditions with an ambient temperature of less than -40 ºC were previously considered benign from an icing perspective because at these conditions, any cloud water content is already in the solid phase. Solid ice particles do not tend to adhere to external aircraft surfaces which are already at sub-freezing temperatures. However, the temperature of the first stage of the engine compressor surfaces is typically slightly above 0 ºC for such conditions so when the aircraft enters a cloud, a water layer can form in the compressor. The water layer forms a trap for further ice particles in the air stream. If the rate of ice mass addition exceeds the rate of melting, then there will be a net increase in ice mass accretion [4]. The icing may continue to build up until engine blockage occurs and this leads to a serious loss of engine functionality.

Certain aeroengine compressors appear more susceptible to solid phase ice accretion, but the physics of accretion initiation for different configurations is not well understood. Most of the current ice accretion simulation methods are based on control volume formulations which may not be able to accurately simulate initiation if the governing initiation mechanics depends on discrete particle interactions. A discrete particle simulation method for solid phase ice accretion has been outlined in a previous publication [5], but to refine this simulation tool, further experimental data on the accretion initiation processes is necessary.

In this paper, the design and operation of a small icing wind tunnel is introduced. The thermodynamic and aerodynamic performance of the facility is characterized through temperature, pressure, and flow rate measurements. Operational characteristics and limitations of the wind tunnel facility are discussed and preliminary results from an ice accretion experiment are presented.

Wind Tunnel Scaling Considerations

Since the solid phase ice accretion problem in turbofan engines appears to depend on the solid-liquid phase transition in water, it is important to duplicate the relevant local compressor temperatures for the air (~ -15 ºC) and the surfaces (~ + 5 ºC). Such conditions might be conveniently achieved by operating an open circuit wind tunnel in a cold room environment which is at about -15 ºC. A small amount of heating can be applied to the model to achieve the required surface temperatures.

To duplicate the relevant viscous and heat transfer processes in the wind tunnel environment, preservation of the Reynolds number (Re) would be necessary. The viscosity varies with the temperature but if the temperatures in the ground-based experiments are matched to the true compressor temperatures, the product of the pressure (p), velocity (u) and length scale (L) will dictate the Re number.

An open circuit wind tunnel operated in the cold room environment will have a static pressure which is about a factor of two larger than the first stage compressor exit static pressure. Hence, for direct simulation of the compressor environment using a wind tunnel model within the constraints described above, $(uL)_{model} \approx 0.5\ (uL)_{compressor}$.

Experimental Apparatus

The present cold room wind tunnel arrangement produces relatively low flow speeds, on the order of 10 m/s. Furthermore, the test section is also small, on the order of 0.1 m diameter. Therefore, direct simulation of the relevant turbofan engine icing conditions will not be achieved. With this facility however, it should still be possible to generate some solid phase icing data for the purpose of icing model development and refinement.

An experimental rig for producing ice particles and injecting them into a wind tunnel flow was developed as illustrated in figure 1. The apparatus operates in a cold room which has a set point temperature of between -20 ºC and 0 ºC. Air temperatures within this range are encountered in the early stages of aeroengine compressors exposed to the potential high altitude solid phase ice accretion conditions.

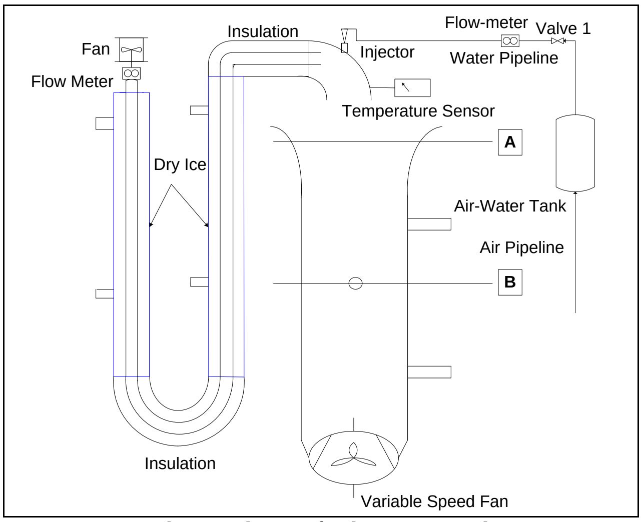

Figure 1. Schematic diagram for the experimental apparatus

Cold room air is driven through a heat exchanger designed to reduce the air stream temperature to around -50 ºC. The initial heat exchanger arrangement used in these experiments consisted of two 12.5 mm diameter vertical copper tubes each with a length of approximately 1.1 m. These copper tubes were each housed within a larger PVC pipe (40 mm) containing dry ice. In an arrangement used for subsequent experiments, the heat exchanger consisted of a 12.5 mm diameter copper tube with a length of approximately 2 m which was enclosed by an ice box containing dry ice. The temperature of the air leaving the heat exchanger was measured in the 40 mm diameter PVC 90º elbow as illustrated in figure 1.

A water injection nozzle (UniJet model TX with an orifice of 0.36 mm) delivers water droplets through an elbow at the exit of the heat exchanger. The injection nozzle was not directly inserted into the cold air stream at -50 ºC but was aligned with a hole in the outer radius of the elbow so that most of the droplet spray penetrated into the cold air stream. Water is delivered to the injection nozzle from a water tank containing purified water which can be pressurized to between 2 to 5 bar.

The water is injected into the cold air flow from the heat exchanger and the temperature of the droplets decreases through heat exchange with the surrounding air. The ice particles produced in this manner will be near spherical in shape. Mason et al. [3] indicate that producing ice particles to simulate cloud ice conditions in ground-based test facilities is a challenging task because in the high altitude atmospheric environment, numerous different shapes can occur. In fact, cloud ice particles are likely to exist in a greater range of shapes and sizes relative to super cooled droplets. The particle shape will affect the particle trajectories and the collection efficiency of aerodynamic objects. However, for current purposes – the initial testing and refining of discrete particle simulation methods – the use of near spherical particles is deemed satisfactory.

After producing the ice particles, the cold, ice-laden air stream is blended with air from the cold room environment. Mixing between the cold ice-laden air flow and the warmer air from the cold room environment occurs as the streams approach the inlet to small wind tunnel. The wind tunnel is a Perspex tube with an internal diameter of 70 mm and a variable speed fan at the downstream end of the tunnel. A variety of test objects can be positioned within the Perspex tube as required to examine the influence of geometric effect on the initiation of accretion. However, for the experiments reported herein, a 9.6 mm diameter copper tube fitted with an internal heater was used as the test object.

Experiments

Water Droplet Size Distribution

The injection nozzle was operated at a range of different working pressures and samples of the droplets prior to freezing were collected on microscope slides. A representative photograph of water droplets is presented in figure 2. Droplet sizing was achieved using a reference image of a know scale and image analysis software applied to the microscope photographs of the droplets.

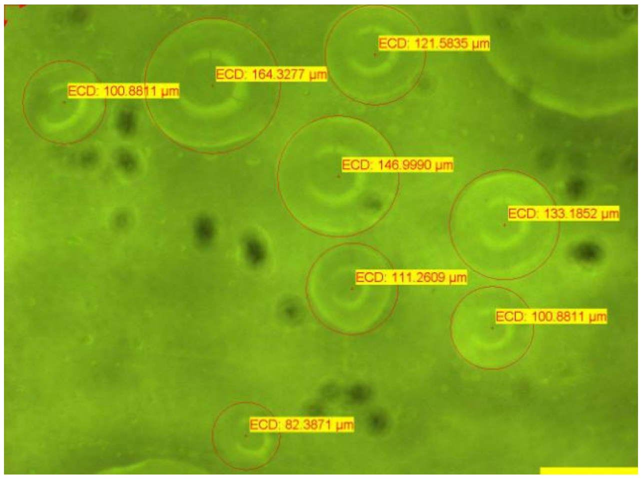

Figure 2. Photograph of water droplets on microscope slide with identification of droplet diameters.

Results from the image analysis of the droplets at different nozzle working pressures between 2.1 and 3.6 bar are presented in figure 3. For the 2.1 and 2.3 bar tests, the droplet sizes varied from 0.2 to 0.8 mm in mean volume diameter. With an increase in the working pressure, a decrease of the droplet size is observed. In the case of 3.6 bar, the observed droplet size distribution was limited to between 0.1 and 0.4 mm.

The present range of droplets sizes are substantially larger than the particle size anticipated in high altitude clouds where ice particle sizes between 1 and 50 µm are expected. An alternative injection nozzle with the capacity to generate smaller ice particle sizes is currently being investigated. Particle size is expected to be an important parameter in ice accretion simulation because viscous and heat transfer processes are likely to be influential and particle sizes are on the order of typical stagnation region boundary layer thicknesses. Having the capacity to generate a wide range of particle sizes – exceeding the range of sizes encountered in high altitude icing – provides an opportunity to thoroughly examine the validity of theoretical modelling. Thus, the present range of sizes may provide a useful contribution to the investigation of the physics of the initiation of solid phase ice accretion.

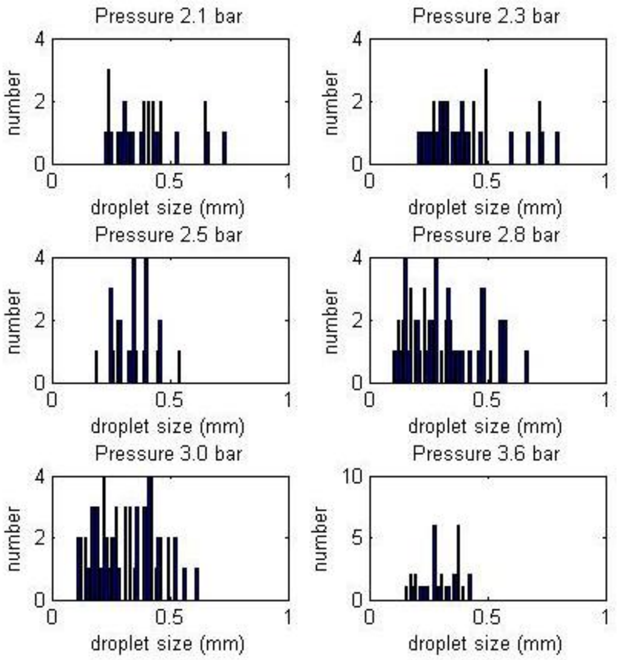

Figure 3. Droplets size distribution histograms for different nozzle operating pressures.

Heat Exchanger

A comparison of the experimental data and a heat exchanger analysis is presented in figure 4 for flow speeds through the copper tube between about 1.5 and 3.5 m/s. For these experiments, the dual dry ice tube arrangement illustrated in figure 1 was used and the inlet air temperature was -8 ºC, and the copper tubes were surrounded by dry ice with an assumed temperature of -78.5 ºC. The heat exchanger analysis presented in this figure is based on,

$$q = UA\,\overline{\Delta T} \tag{1}$$

where q is the rate of heat transfer (W), U is the overall heat transfer coefficient (W/m^2.K), and A is the surface area of the heat exchanger. In this analysis, $\overline{\Delta T}$ is the log mean temperature difference between the air flowing through the copper tube and the dry ice surfaces. The overall heat transfer coefficient product with the heat transfer area in this application was assumed to be given by

$$UA = \frac{1}{\left(\frac{1}{h_{\text{air}}A_i}\right) + \frac{\ln\left(r_o/r_i\right)}{2\pi k L} + \left(\frac{R}{A}\right)_{\text{ice}}} \tag{2}$$

The heat transfer coefficient between the inside of the copper tube and the air flow through the tube was determined using [6]

$$\text{Nu} = \frac{hd}{k} = 3.66 + \frac{0.0668\,\text{RePr}\frac{\text{d}}{\text{L}}}{1+0.04\left[\frac{\text{d}}{\text{L}}\text{RePr}\right]^{2/3}} \tag{3}$$

where Re is the Reynolds number, Pr is the Prandtl number, d is the inside diameter of the copper tube, the copper total length.

For the calculation of the overall heat transfer coefficient from equation (2), all of the quantities are therefore known or can be specified, apart from the effective heat transfer resistance between the dry ice and the outside surface of the copper tube. To determine this quantity, the outlet air temperatures for flow velocities around 2.5±0.1 m/s were selected as a reference point. The average outlet air temperature over the 6 data points in this region was -50 ºC giving a $\overline{\Delta T}$ = 46.4 ºC. The overall heat transfer rate for this operating point was then calculated using

$$q = \dot{m}c_p(T_{in} - T_{out}) \tag{4}$$

yielding a value of q = 8.97 W. This allowed equation (1) to be solved for UA (giving a value of 0.193 W/K), which then allowed deduction of the heat transfer resistance between the dry ice and the outer surface of the copper tube via equation (2). The value of resistance deduced in this manner was 3.60 K/W.

The results in figure 4 demonstrate that the experimental apparatus can produce a cold air stream with a temperature of around -50 ºC which is suitable for freezing the water droplets. There is however some variability in the outlet temperature achieved. This variability may have arisen from changes in the contact area between the dry ice and the outside of the copper tube. An improved arrangement which maintains the contact between the dry ice and the copper tube has now been established (as described in the section, "Experimental Apparatus") and this improved arrangement was used in the following work.

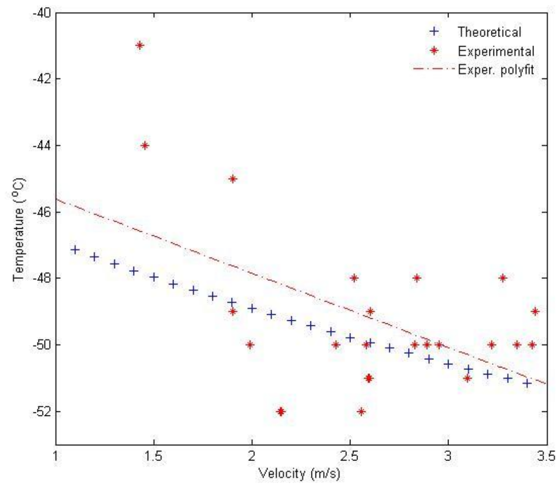

Figure 4. Temperature measurements and comparison with heat exchanger model.

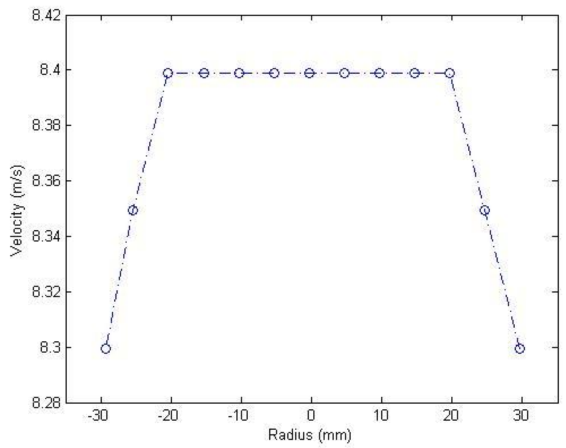

Figure 5. Velocity profile across the duct at a peak flow speed of about 8.4 m/s.

Wind Tunnel Flow Profiles

For the flow within the Perspex tube, figures 7 and 8 show the velocity profiles (obtained using a pitot-static tube) for peak flow speeds of about 8.4 m/s and 10.35 m/s respectively. A comparison of figure 5 and figure 6 indicates that the 8.4 m/s test condition produces a more uniform flow core. The difference between the two results at 8.4 and 10.35 m/s is likely to arise due to boundary layer transition on the walls of the duct – Reynolds numbers of around 1×10^6 are generated in the figure 5 case.

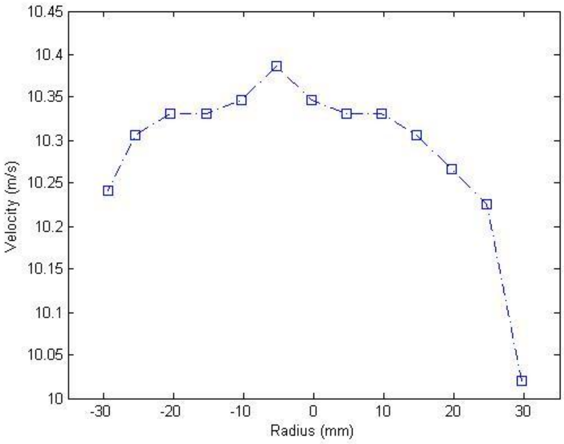

Figure 6. Velocity profile across the duct at a peak flow speed of about 10.35 m/s.

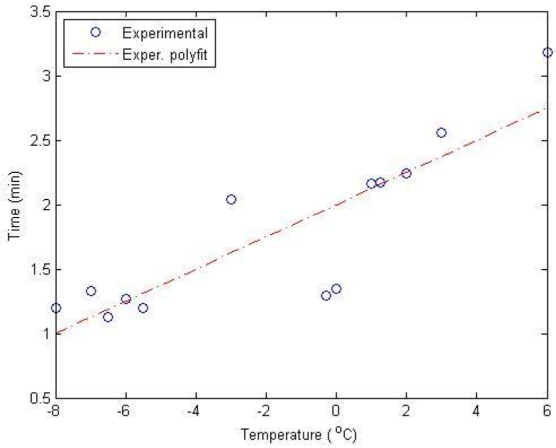

Figure 7. Variation of the time for the start of ice accretion with cylinder temperature.

Ice Accretion on Cylindrical Tube

Experiments were performed on a heated cylindrical tube inserted into the wind tunnel flow at 8.4 m/s. The accretion of ice on this tube was studied using a high speed video camera. Figure 7 presents the time required for initiation of ice accretion as a function of the cylinder temperature. The time to the start of accretion was determined by visual observation. The cylinder temperature was determined using a K-type thermocouple mounted on the cylinder.

Experiments have been performed for range of cylinder temperatures between -8 ºC and 6 ºC. Although there is substantial scatter in the results, the general trend is for shorter times to the observed start of accretion with lower cylinder temperatures. Previous observations of solid phase ice accretion have found that initiation of accretion generally does not occur for subzero surface temperatures. In contrast, accretion definitely initiated at subzero surface temperatures in the present work as indicated in figure 7. Estimates of droplet residence times in the cold air jet suggest that some droplets may not have sufficient time to freeze. Therefore the cloud drawn into the wind tunnel would contain a mixture of liquid and solid phase particles which is not representative of the solid phase ice accretion conditions being targeted.

Conclusion and Future Work

The arrangement and operation of a small wind tunnel to investigate the solid ice accretion was presented. Preliminary icing experiments using a heated cylindrical rod in the wind tunnel have been performed in an effort to establish the conditions under which icing will initiate. Results from these experiments suggest that the water cloud drawn into the wind tunnel is a mixture of solid and liquid particles which does not accurately reflect the target conditions which require the presence of only the solid phase in the cloud. The present work demonstrates that the basic hardware necessary for these experiments has been established, although improvements in the configuration are required.

References

[1] Gent, RW, Dart, NP & Cansdale, JT 2000, Aircraft icing, *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, vol. 358, no. 1776, pp. 2873-911.

[2] Thomas, SK, Cassoni, RP & MacArthur, CD 1996, Aircraft anti-icing and de-icing techniques and modeling, *Journal of Aircraft*, vol. 33, no. 5, pp. 841-54.

[3] Mason, JG, Strapp, JW & Chow, P 2006, The ice particle threat to engines in flight, *44th AIAA Aerospace Sciences meeting and Exhibit*, AIAA Paper 2006-206.

[4] Lee S & Eric, L 2008, Simulation of Icing on a Cascade of Stator Blades, *Journal of Propulsion and Power*, vol. 24, no. 6, p. 8.

[5] Buttsworth, DR, Saleh, KH & Yusaf, T 2009, Discrete particle simulation for the initial stages of ice accretion in aircraft engines: initial model development, *IEEE, Malacca, Malaysia*.

[6] Holman, JP 2002, *Heat transfer*. New York: McGraw-Hill.