 FDMP, vol.6, no.3, pp.319-335, 2010

Icing Tests in a Small Blow-Down Wind Tunnel

G. P. Russo[1], A. Esposito[1], B. Esposito[2], R. Renis[1]
F. De Rosa[1] and F. Parente[1]

Abstract: A low-cost facility, able to simulate icing conditions occurring in flight, has been built via modification of a small blow-down supersonic wind tunnel. As the storage tank (30bar) is emptied through the wind tunnel, expansion of the contained air makes temperature to decrease down to -20°C and a control valve holds such temperature for about 200s. In order to increase the liquid water content (LWC) of the flow allowing ice formation on model surfaces within the test chamber, water is sprayed in the stream within the stagnation chamber by means of a controlled spray gun. This unsteady technique allows to work only at a peculiar Mach number at which the heating from the tank walls compensates the cooling due to expansion. Both an Icing Rotating Cylinder and an Icing Blade Technique have been used to measure the LWC in the stream. The Median Volumetric Diameter (MVD) of the supercooled water drops has been measured by both a Phase Doppler Particle Analyzer (PDPA) and an Oil Slide Technique. The measured values of the LWC ranged from 0,7 to 1,5 g/m^3 and those of the MVD ranged from 20 to 50 μm in accordance with typical values encountered in flight within dangerous clouds.

Keywords: Icing wind-tunnel

1 Introduction

Meteorological adverse conditions, in particular those favoring the formation of ice on wing leading edges, empennages and fan blades, are among the principal causes of accidents occurring to aircrafts. Tests of anti-icing and de-icing systems are therefore made in large and expensive icing wind tunnels where the icing conditions on aircrafts are simulated on full-scale components.

Since operating large wind tunnels is too expensive for setup operations like calibration of probes, spray nozzles and measuring techniques, a low-cost small facility

[1] DIAS, Università di Napoli, Federico II, Italy
[2] CIRA, Capua, Italy

is more conveniently advisable for those activities. In order to offer such possibility to large wind tunnel operators an already existing supersonic pedagogical wind tunnel has been modified and equipped on purpose.

2 The experimental setup

2.1 The supersonic blow down wind tunnel

The supersonic blow-down wind tunnel, see Figs.1 and 2 [Cimino et al., 2005 and 2007], is fed by a 4.5 m^3 steel tank (6), with a maximum pressure of 30 bar, connected through a manual valve (7) to a divergent duct (8) followed by a stagnation chamber (9) and a two-dimensional convergent nozzle (10). A Mach number variable from 1 to 2.7 can be obtained in the rectangular (80mm x 40mm) test chamber (12) by means of a movable spike. Air is exhausted to atmosphere through a simply divergent diffuser (13).

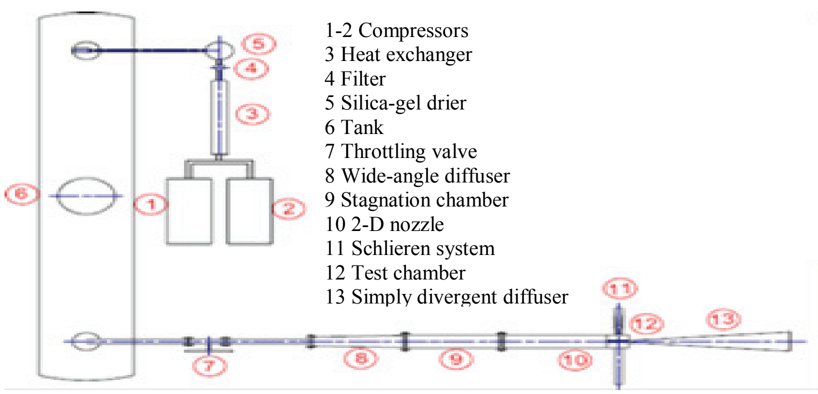

Figure 1: Layout of the blow-down supersonic wind tunnel.

In supersonic wind tunnels in order to prevent the occurrence of condensation-shock-waves due to the strong cooling of air in the expansion from the high pressure in the stagnation chamber to the low pressure prevailing in the test chamber, the working fluid must be accurately dried.

Within the wind tunnel considered here this is done before the air is stored in the tank. For this purpose the air compressed by two reciprocating compressors (1 and 2 in Fig.1), is cooled in a heat exchanger (3) where large water drops are formed and separated passing through vanes. All smaller drops are trapped in a porcelain filter (4) and water vapor is absorbed by a column of granular silica-gel (5) resulting in a residual relative humidity in the stored air around 5%.

Due to the expansion the temperature of air in the tank decreases and the relative humidity increases up to saturation. Because of the condensation of the residual water vapour a cloud is formed at the exit of the nozzle. Such cloud is made of super-cooled drops of water that solidify after the impact with the surface of a cold body, see Fig. 3.

Figure 2: The supersonic blow-down wind tunnel.

Figure 3: Condensation of residual humidity at the exit of the 2-D nozzle.

2.2 Modifications of the wind tunnel

In order to obtain a performing Icing Flow Facility from the supersonic wind tunnel, some changes were needed in order to remove several limits of the facility like:

- non constant stagnation pressure due to the manual operation of the throttling valve;
- lack of thermal insulation to reduce the heat transfer between metallic tunnel components and the surrounding environment;
- step in the convergent geometry whose entry section (40 mm x 400 mm) was a real discontinuity with respect to the cylindrical (Φ=400 mm) stagnation chamber. In these conditions most of the water drops injected upstream of the convergent would hit the wall and condensate on it and only a minimum part of them would flow through the narrow test chamber.

In order to improve the flow stability in the test chamber an automatically controlled pneumatic valve has been inserted downstream of the manual valve. An actuator operate the pneumatic valve through a PID controller which can be programmed to gradually close the valve itself once either the pressure or the temperature reaches a preset value in order to keep this value constant until the tank is emptied. Obviously the needed Δp will be lost before the tank is completely emptied making this last part useless for icing purposes.

In order to reduce the heat exchange between the cold stream and the environment the stagnation chamber, the diffuser, the flanges, the automatic and the manual valves, see Fig. 2, were coated with a layer of insulating material (polyethylene).

A double-cone convergent duct, see Fig. 4, of length 800 mm and exit diameter 65 mm, was used instead of the two dimensional nozzle.

3 Theoretical study of the expansion in the tank

Through the equation of conservation of mass and the equation of state of the perfect gases it is possible to draw the following relationship among temperature and pressure during expansion:

$$dp_T - \frac{p_T}{T_T}dT_T = -K\sqrt{T_T}dt \tag{1}$$

where K depends on tank evacuation conditions by:

$$K = \frac{A_e}{V_T}\sqrt{\gamma R}p_e M_e\sqrt{1+\frac{\gamma-1}{2}M_e^2} \quad \left[\frac{N}{m^2 s K^{1/2}}\right]$$

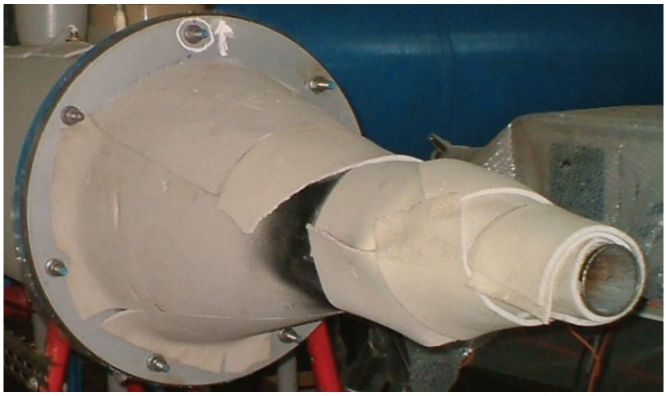

Figure 4: The axially-symmetric nozzle (area ratio n = 37.87)

Where V_T is the tank volume, A_e is the exit Area, p is the pressure, M_e is exit Mach number, T is the temperature, t is the time, R is the universal gas constant, the subscripts "T" denotes "inside the tank" and the subscripts "e" denotes "exit conditions".

The equation (1) cannot be solved unless the relationship existing between p_T and T_T is given. The real case is somehow intermediate between two limiting cases

- **isothermal expansion**: so slow that the thermal exchanges between the air contained in the tank and the steel wall of the tank succeed in compensating the cooling due to the expansion
- **adiabatic expansion**: so fast that the thermal exchanges between air and tank are negligible.

The real case can be drawn from the equation of conservation of total energy, E:

$$\frac{dE}{dt} = -\dot{m}H + \dot{Q} \qquad (2)$$

where $\dot{m}$ is the mass flow rate of air from the tank; H is the total enthalpy (H = h + $v^2/2$ where *h* is the specific enthalpy and v the velocity); $\dot{Q} = h_c S_w (T_T - T_w)$ is the thermal power exchanged between tank and contained air, S_w is the surface of the tank, h_c the global heat transfer coefficient and the subscripts "W" denotes "tank wall".

The kinetic energy within the tank is negligible so that only the internal energy must be taken into account, therefore the variation of total energy can be written as:

$$\frac{dE}{dt} = \frac{d}{dt}\left(\frac{m_a R T_T}{\gamma - 1}\right) = \frac{V_T}{\gamma - 1}\frac{dp_T}{dt} \tag{3}$$

where m_a is the mass of air in the tank.

Eq. (2) can be written as:

$$\frac{dp_T}{dt} = -K\gamma\sqrt{T_T} - \frac{\gamma - 1}{V_T}\dot{Q} \tag{4}$$

On the other hand, from Eq. (3) we can write:

$$\frac{dT_T}{dt} = (\gamma - 1)\frac{T_T}{p_T}\left(\frac{\dot{Q}}{V_T} - K\sqrt{T_T}\right) \tag{5}$$

By integrating step by step the two differential equations (4) and (5) it is possible to calculate the behavior of pressure and temperature in the tank once the thermal power transferred by the tank walls to the contained air is known.

4 Experimental assessment of heat transfer coefficient

Due to the huge mass of the tank (m_T is about 3000 kg) with respect to the mass of the contained air (m_a is about 120 kg; the ratio between heat capacity of air and that of the tank goes from 1/13 to zero during expansion) the temperature of the tank wall is practically constant in expansion and the tank acts therefore as an heat sink for the contained air.

A test has been performed in which the tank is evacuated at M_e = 0,6 until the temperature reaches -20°C and then flow is stopped. Temperature of air in the tank and temperature of the wall are monitored both during expansion and during the following heating for about 500 s, see Fig. 5. The global heat transfer coefficient between tank walls and contained air can be calculated by the equation:

$$h_c = \frac{m_a c_v}{S_w}\frac{dT_T/dt}{T_T - T_w}\left[\frac{W}{m^2 K}\right]$$

where c_v is the specific heat capacity of air at constant volume.

As expected the temperature of the tank wall is practically constant during the evolution.

The global heat transfer coefficient can be determined by the slope of the curve T(t) in the heating phase, from which results that:

$$\frac{dT_T/dt}{T_w - T_T} \cong .01\ s^{-1}$$

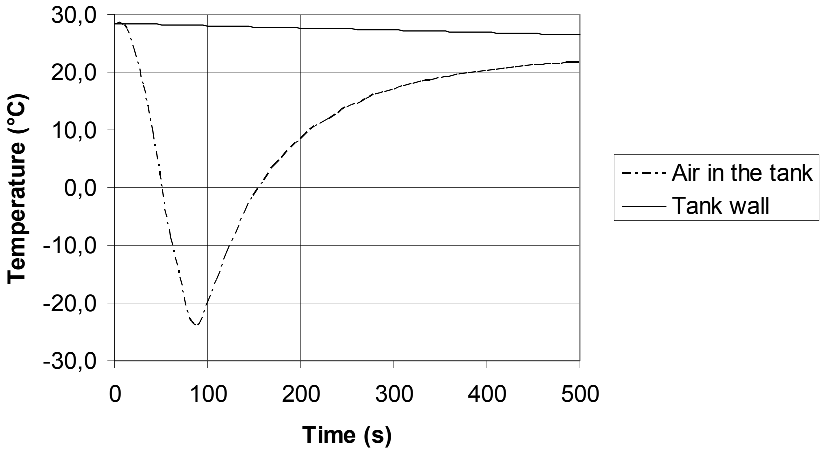

Figure 5: Expansion followed by spontaneous heating to ambient temperature.

The value of the heat transfer coefficient is therefore given by:

$$h_c = 0,005625 p_T / T_T$$

And the thermal power by:

$$\dot{Q} = 0,1125\,(T_w - T_T)\,p_T \big/ T_T \tag{6}$$

5 Finding the proper Mach number for expansion to low temperature

Applying Eqs. (4), (5) and (6) to complete tank evacuation at various Mach numbers (from M = 0.2 to M = 1.0), the graph in Fig. 6 is obtained. The values of T_T attainable at the end of the test vary from -75˚C for the expansion at M_e =0.2 to around -93˚C at M_e =1.0 and, correspondingly, the time of expansion reduces from 460s to 80s.

As shown in Fig. 7, a given temperature can be achieved more rapidly increasing the evacuation Mach number M_e, so that more air remains in the tank and a longer isothermal flow can therefore be obtained. Unfortunately an expansion at M_e above 0.6 causes an intolerable noise level in the laboratory which is forbidden by Health & Safety domestic rules. On the other hand the effect of the Mach number becomes less important at moderately low temperatures (around -20˚C) as those needed for the icing condition simulation, therefore an exit Mach number equal to 0,6 has been chosen. In this way a temperature of -20˚C can be reached when more than half of the initial mass of air is still in the tank.

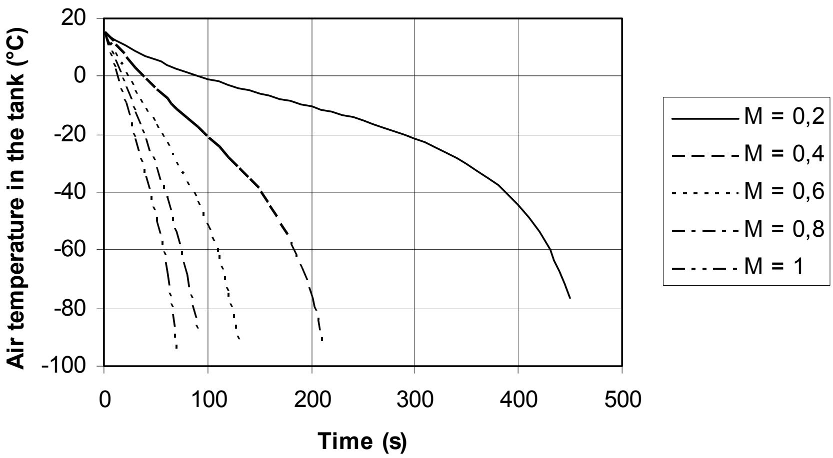

Figure 6: Temperature in the tank at various rates of expansion.

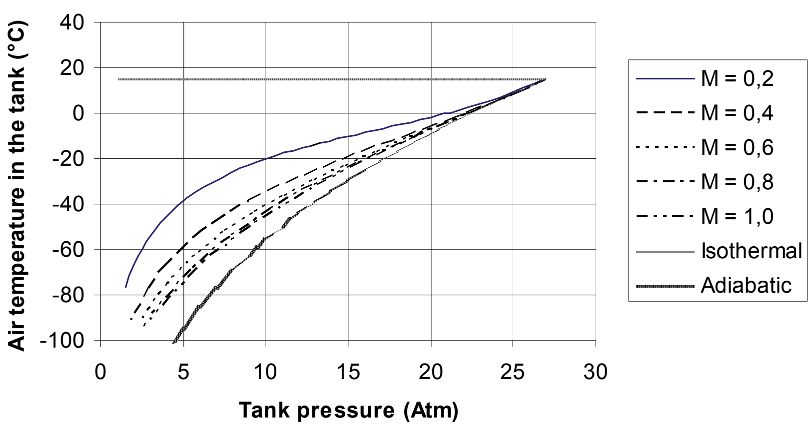

Figure 7: Temperature vs pressure in the tank.

6 Choosing the proper Mach number for obtaining a quasi-isothermal cold stream

Once the desired low temperature has been achieved in the tank during the initial evacuation, the aim is to generate a cold stream with a quasi-constant temperature in which water can be sprayed.

Two opposite effects have to be compensated:

- Expansion makes temperature in the tank to decrease
- The heat flux from the tank walls to the contained air makes temperature to increase

Some cases have been calculated (see Fig. 8) at moderately low Mach numbers:

Temperature in the tank is not constant but if the Mach number of the stream is around 0.15 the temperature variation is limited to few degrees.

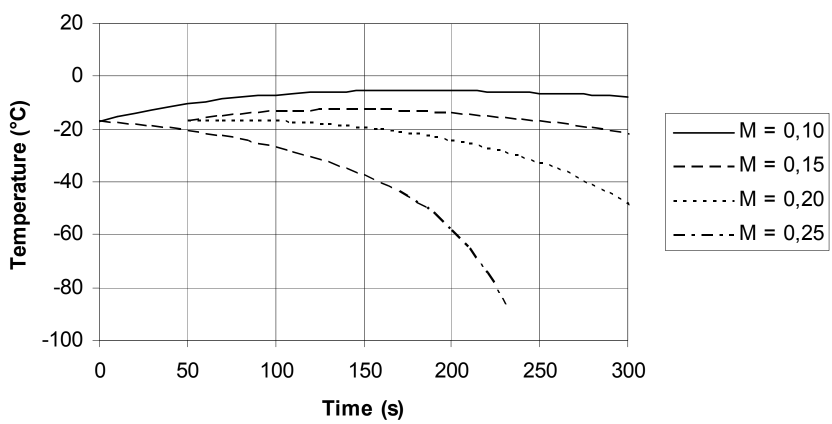

Figure 8: Quasi-isothermal expansion.

From these calculations it is possible to define a “standard test” characterized by the following conditions, see Fig. 9:

- phase of cooling at M =0.6 with a rapid expansion to reach sufficiently low temperatures to allow the formation of ice;
- quasi isothermal flow at M =0.15.

7 Experimental results

In order to obtain a quasi-stationary stream an automatic throttle valve has been inserted downstream the manual valve: a quasi-constant stagnation pressure is obtained in the isothermal phase, see Fig. 10. The oscillations of stagnation pressure during the rapid expansion are due to the inertia of the valve, over dimensioned for the IFF.

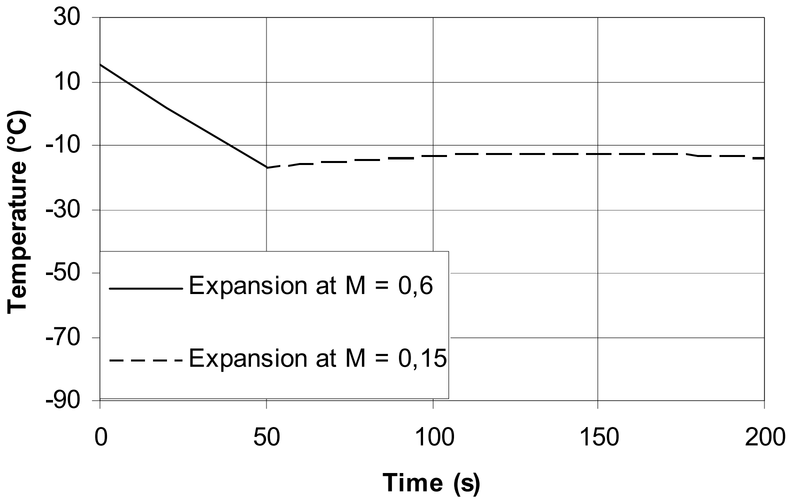

Figure 9: A standard test.

The behavior of the stagnation temperature in the automated test is shown in Fig. 11:

- temperature is kept nearly constant at -20˚C
- a time of around 200s is available for icing simulation.

8 Measuring MVD and LWC

One of most important parameters for the study of the formation of ice is the diameter of water drops in the stream. It is important to evaluate the distribution i.e. the number of particles in function of their dimension according to the measuring technique.

When the distribution of the diameters is known it is possible to calculate some average dimensions as the Median Volumetric Diameter (MVD) that is defined as

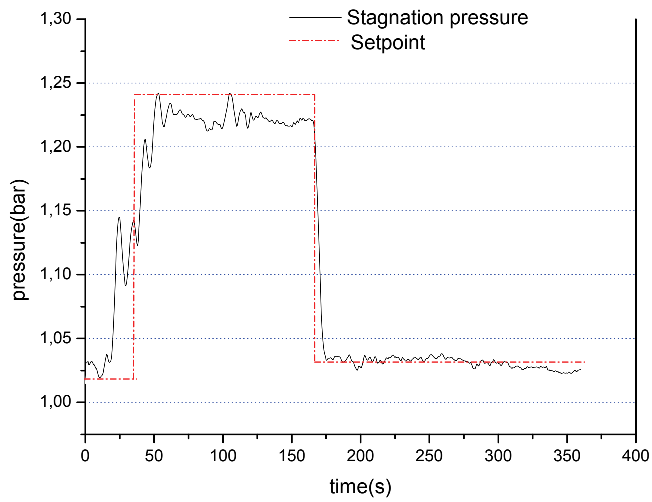

Figure 10: Stagnation pressure in an automated test.

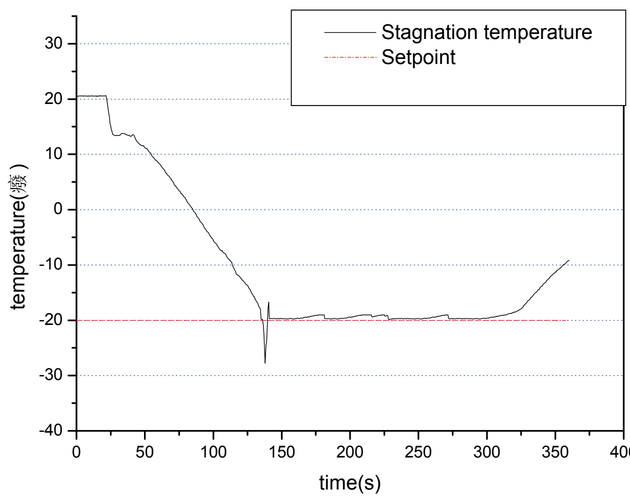

Figure 11: Stagnation temperature in an automated test.

the diameter of the drops such that half of the volume of water analyzed is made of drops of diameter smaller than and the other half is made of drops of diameter larger than the MVD.

The Liquid Water Content (LWC) is expressed in grams of liquid water per cubic meter of air (g/m^3).

In order to measure the liquid water content in the stream and the median volumetric diameter of the drops, both invasive techniques (Oil Slide Technique, Icing Rotating Cylinder and Icing Blade Technique) and an optical instrumentation (Phase Doppler Particle Analyzer, PDPA) have been used.

In the Oil Slide Technique [SAE–ARP-5905] a glass slide covered with silicone oil, is exposed perpendicularly to the direction of the stream. The liquid drops that hit the relatively warm slide are captured by the silicone oil. The slide is immediately examined with a microscope, see Fig 12; the image is sent to a PC where the dimensions of the drops are measured using the software JAVA Image-J; then the MVD can be calculated.

This measuring technique is based on the premise that the drops captured preserve their spherical shape after impacting the slide and that the examined specimen is representative of the whole cloud.

For the determination of the Liquid Water Content (LWC), two invasive techniques have been tested:

- the Icing Rotating Cylinder (according to the formulation of J. R. Stallabrass) [SAE–AIR-4906];
- the Icing Calibration Blade [SAE–AIR-4906].

In the first case a rotating circular cylinder is introduced for a given time in the stream in order to achieve an uniform growth of ice, see Fig. 13.

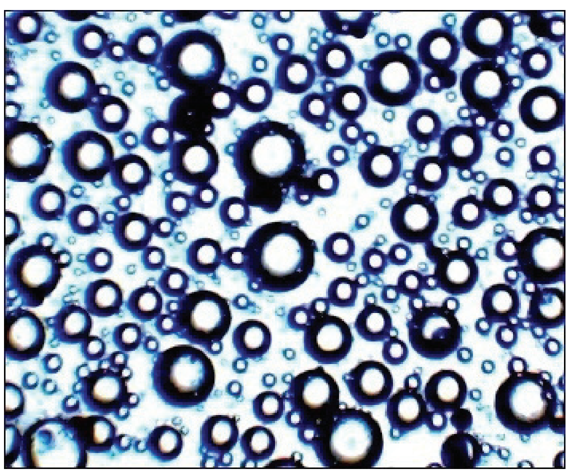

Figure 12: Microscope view of water drops collected on an oil slide.

Figure 13: The iced cylinder.

The LWC can be calculated with the equation of Stallabrass:

$$LWC = \frac{\pi\Psi_{ice}\left(r_f - r_i\right)}{EtV} \tag{7}$$

where:
Ψ_{ice}=gensity of ice;
r_i = initial radius of cylinder;
r_f = final radius of cylinder + ice;
E = efficiency of collection of the cylinder;
V = speed;
t = time of exposition of the cylinder to the flow.
Expressing the final radius r_f as a function of the mass of formed ice m_{ice} (Kg)

$$r_f = \sqrt{\frac{m_{ice}}{E\Psi_{ice}l} + r_i^2} \tag{8}$$

where l is the length of the iced part of the cylinder. Combining equations (7) and (8)

$$LWC = \frac{\pi\Psi_{ice}\left(\sqrt{\frac{m_{ice}}{E\Psi_{ice}l} + r_i^2} - r_i\right)}{ETv} \tag{9}$$

In the second technique a metallic blade (50mm x 150mm x 3mm) is put parallel to the stream for a given time: afterwards the developed thickness of ice is measured by means of a cold micrometer in order to prevent melting of ice before measurement.

The time of exposure to the stream, t_e, has to be sufficient for growing of ice up to a thickness of 1,5 ÷ 5 mm. The Liquid Water Content is computed from:

$$LWC = \frac{\rho_{ice}\Delta s}{E_b v t_e} \tag{10}$$

with:
ρ_{ice}: density of ice;
Δs: average thickness of ice on the blade;
E_b: efficiency of collection of the blade (dimensionless) as provided by a NASA numerical code for droplets trajectory calculation;
v: speed of the flow in the test section;
t_e: time of exposure of the blade to the stream.

Besides the aforementioned invasive techniques measurements were made also with a Phase Doppler Particle Analyzer (PDPA), see Fig 14.

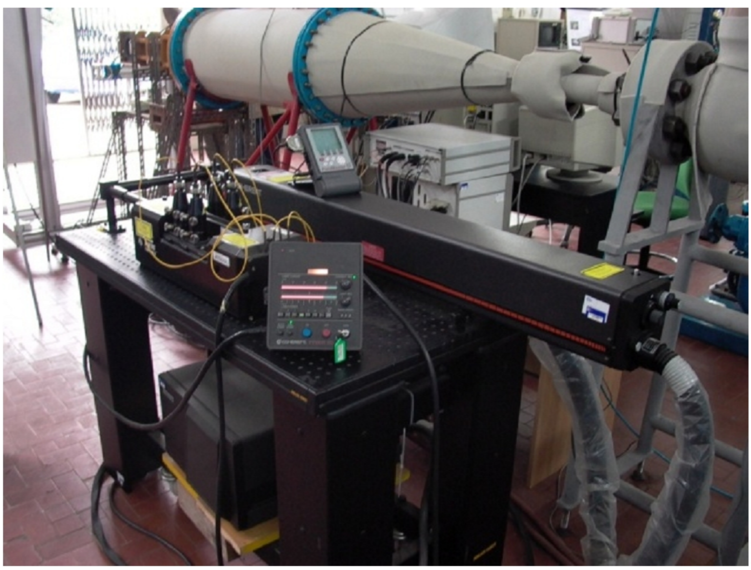

Figure 14: Phase Doppler Particle Analyzer (PDPA)

In the PDPA [Bachalo and Houser, 1984] a system of lens, mirrors and optical fibers called "Fiber Drive" (FD) splits the original beam emitted by a 5W Argon-ion laser in 3 couples of rays, since 3 components of velocity are to be measured.

In each couple the first ray of order zero and the second one of order one are shifted by a frequency of 40 MHz through a "Bragg Cell". Thanks to the frequency shift between the two beams the interference fringes move in the volume of measure allowing the measure of null or negative components of velocity. All the beams are sent, through the optical fibers, to the transmission optics that put them into focus in the volume of measure.

Table 1

Φ (mm)	**A** (mm^2)	$\bar{t}_s$ (s)	$\dot{m}$ (g/s)	**V** (m/s)
0.4	0.126	103	1.94	15.4
0.6	0.283	96	2.08	7.35
0.8	0.503	74	2.70	5.37

In the reception optics the signal scattered by the particles passing in the volume of measure is sent to three photomultipliers The light signal, transformed in electric analog signal by each photomultiplier, is firstly filtered from the low frequency component due to the Gaussian shape of light intensity in the volume of measure (frequency of pedestal) and therefore mixed (procedure of down mixing) with another signal in order to subtract the component of frequency introduced by the Bragg Cell so that the resultant frequency is the Doppler frequency proportional to the speed of the particles passed in the volume of measure. Each photomultiplier points out therefore the same signal shifted this time in phase because of their relative distance.

Thanks to the method of the PDPA, utilizing the linear theory of geometrical optics, from the measure of the phase difference between the signals of each photomultiplier is possible to determine the diameter of each drop.

The PDPA can therefore provide both the LWC and the MVD of the drops.

9 Ice due to condensation of residual humidity

In order to gain confidence with the different measuring techniques a preliminary evaluation of the LWC and of the MVD of the drops has been made in the cloud generated by the residual humidity in the air stored in the tank. The results are:

Liquid water content:

Icing rotating cylinder LWC = 0,06 g/m^3
PDPA LWC = 0,042 $\div$ 0,134 g/m^3

Average Diameter

Oil slide technique MVD = 13 $\div$ 50μm
PDPA D_{20} = 24,2 $\div$ 38,5

Where $D_{20} = \frac{1}{n}\sqrt{\sum_{1}^{n} d_i^2}$ is the **mean surface diameter.**

10 The water spraying system

An electric gun atomizer available off the shelf (Power Plus, model POW 750) was used as a spray-system. Water contained in a small tank is inhaled by a volumetric pump and sent to an atomizer nozzle.

Three nozzles are available with nominal diameters Φ = 0.4 mm, 0.6 mm, 0.8 mm. For every nozzle an average mass flow rate has been calculated measuring the time needed to atomize 200 ml of water. The results averaged on ten tests are reported in Table 1:

The Φ = 0,6 mm spray-nozzle has been installed in the middle of the stagnation chamber: in this way a sufficient time of exposure of the drops to the low temperatures and a good uniformity of the stream can be obtained. These measurements were made only with the invasive techniques.

Liquid water content:

Icing rotating cylinder LWC = 0,87 $\div$ 1,27 g/m^3
Icing blade technique LWC = 0,78 $\div$ 1,45 g/m^3

Average Diameter:

Oil slide technique MVD =20 $\div$ 50 μm

With respect to the results obtained without the spray system the values of the MVD are similar, the LWC is about one order of magnitude larger.

Various geometries have been tested at typical IFF set-point (200s at -20°C with LWC=1,2 g/m^3) resulting in various type of ice accretion. For instance an impressive result has been achieved by a blunt cylinder (see Fig. 15) resulting in a very streamlined milky rime ice accretion.

11 Conclusions

A low-cost icing wind tunnel (IFF) was built up by modification of a blow-down supersonic wind tunnel using a quasi-stationary technique to achieve typical icing conditions encountered in real clouds. The facility has shown a repeatable capability to generate a flow at -20°C for a useful duration of about 200s with an LWC content ranging 0,6 to 1,2 [g/m^3] and super-cooled droplets whose MVD ranged 20 to 50 [μm]. The IFF has been proven to be a reliable and cost-effective tool for ice shape accretion and evaluation, calibration of probes, testing of spray nozzles and validation of measuring techniques. Nevertheless the IFF has shown potential improvement capabilities allowing for lower temperatures, better stability and longer

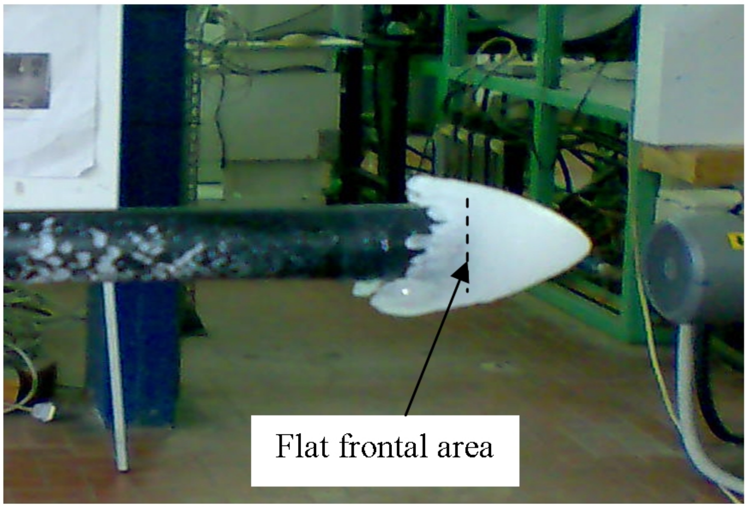

Figure 15: Rime ice on a disk

duration which will be object of future developments.

References

Bachalo W. D., Houser M. J. (1984): Analysis and Testing of New Method for Drop Size Measurement Using Laser Light Scattering Interferometry", NASA CR-174636.

Cimino M., Esposito A., Mastroianni A., Pinto A., Renis R., Russo G. P. (2005): Studio di fattibilità per la realizzazione di una galleria pilota a ghiaccio 60° Congresso Nazionale Associazione Termotecnica Italiana, Roma, Settembre 2005.

Cimino M., Esposito A., Esposito B., Minieri G., Renis R., Russo G.P. (2007): Messa a punto e calibrazione di una galleria blow-down per la simulazione delle condizioni di ghiaccio presenti in volo XIX Congresso Nazionale AIDAA, Forli, 17-21 Settembre 2007.

SAE – AIR - 4906 Droplet Size Instrumentation Used in Icing Facilities.

SAE – ARP - 5905 Calibration and Acceptance of Icing Wind Tunnels.