EXPERIMENTAL STUDY OF SPRAY CHARACTERISTICS AND ITS UNIFORMITY UNDER DIFFERENT ICING CONDITIONS

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***Abstract**:* An experimental study was conducted to investigate the spray characteristics in a horizontal low-speed icing research wind tunnel where two-phase air/dispersed water flows were produced to simulate atmospheric icing processes. The variations of the liquid water content (LWC), droplet size distribution (DSD), and droplet velocity were studied in the vertical and streamwise directions in the CIGELE tunnel test section for different free-stream velocities and initial DSDs (DSD at nozzle outlet). An integrated system for icing studies was used to measure DSD and LWC, and Particle Image Velocimetry was used for droplet velocity measurements. Nozzle dynamic parameters were varied in the tests in order to produce clouds with different DSDs and LWCs to simulate different icing conditions. The results show that droplet size and LWC increase downwardly for low air velocities (below 10 m/s) due to gravity effects. On the other hand, the uniformity of DSD and LWC is improved considerably for higher velocities (above 20 m/s). The limit for obtaining a uniform cloud depends strongly on air velocity and droplet size, and consequently, on icing conditions.

1. INTRODUCTION

Atmospheric icing is a major problem in cold climate regions, which can cause serious damage to structures, such as overhead power networks. Types of icing are related to either flowing or stationary aerosol clouds. The DSD of an aerosol cloud together with its temperature, the free stream velocity and the LWC are among the most important factors affecting icing processes [1]. The size and dynamics of the droplets are influenced by a number of parameters and physical phenomena, including aerodynamic drag, gravity, and turbulence of the carrying phase [2]. Other processes involved are evaporation and cooling, discussed in [3], but which are out of the scope of this study.

The main goal of this investigation is to study LWC and DSD uniformity in the streamwise and vertical directions. It is also important to obtain droplet velocity vectors depending on nozzle dynamic parameters and air velocity for other purposes such as calculating aerodynamic coefficients and exerted force on the icing objects. An integrated system for icing studies was used to measure LWC and DSD. Particle Image Velocimetry, with the use of laser technique, was utilized to measure the velocity and direction of droplets.

2. RESULTS AND DISCUSSION

The droplet median volume diameter (MVD) is approximately constant for the smallest differential pressures, and then increases until reaching a maximum which is followed by a decreasing tendency. The MVD at a specific height decreases along the streamwise direction, because the larger droplets tend to move toward the bottom of test section due to the effect of gravity effects. Also, as velocity increases, droplet separation according to their size occurs only in clouds with the larger droplets. Quantitatively, this separation occurs for aerosol clouds with MVD of 20 μm or greater when air velocity is the lowest, and only for aerosol clouds with MVD of at least 50 μm when air velocity is the highest. The dependence of LWC on differential pressure is similar to the MVD – differential pressure relationship, except that the LWC increases even with the smallest differential pressures. Also, the LWC decreases in the streamwise direction for 5 m/s, and this tendency is the same for higher velocities at mid-height, but it will be reversed for 28 m/s at $y = -7$ cm. Droplet size and the vertical component of droplet velocity increases vertically from the top to the bottom of the tunnel due to the gravity effects on larger droplets.

3. CONCLUSION

The gravity effects on a spray produced in a horizontal wind tunnel are more significant than drag effect at low air velocity. Hence, MVD increases downward vertically and decreases along the streamwise direction at a specific height. However, when the velocity increases, the drag effect becomes more significant than the gravity effect, and droplet separation according to their size occurs only for clouds with the larger droplets.

This information is essential for aerodynamic studies when samples with complex geometry are mounted in different orientations and different wind angles of attack.

4. REFERENCES

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Abstract—An experimental study was conducted to investigate the spray characteristics in a horizontal low-speed icing research wind tunnel where two-phase air/dispersed water flows were produced to simulate atmospheric icing processes. The variations of the liquid water content (LWC), droplet size distribution (DSD), and droplet velocity were studied in the vertical and streamwise directions in the CIGELE tunnel test section for different free-stream velocities and initial DSDs (DSD at nozzle outlet). An integrated system for icing studies was used to measure DSD and LWC, and Particle Image Velocimetry was used for droplet velocity measurements. Nozzle dynamic parameters were varied in the tests in order to produce clouds with different DSDs and LWCs to simulate different icing conditions. The results show that droplet size and LWC increase downwardly for low air velocities (below 10 m/s) due to gravity effects. On the other hand, the uniformity of DSD and LWC is improved considerably for higher velocities (above 20 m/s). The limit for obtaining a uniform cloud depends strongly on air velocity and droplet size, and consequently, on icing conditions.

Keywords-aerodynamic coefficients, droplet size distribution, liquid water content, wind tunnel.

I. INTRODUCTION

Atmospheric icing is a major problem in cold climate regions, which can cause serious damage to exposed structures, such as overhead power networks. Icing precipitations are of different types like, glaze ice, wet snow, which are related to either flowing or stationary aerosol clouds characterized by different meteorological conditions. The droplet size distribution (DSD) of an aerosol cloud together with its temperature, the free stream velocity and the liquid water content (LWC) are among the most important factors affecting icing processes [1-5]. The size and dynamics of the droplets are influenced by a number of parameters and physical phenomena, including aerodynamic drag, gravity, and turbulence of the carrying phase [6]. Further influencing processes are evaporation and cooling which are discussed in [7], but are out of the scope of the present study.

Aerosol clouds under icing conditions may be simulated in an icing wind tunnel by injecting water droplets into a cold air stream. The zone of uniformity of aerosol clouds produced in horizontal wind tunnels may vary considerably in the streamwise and vertical directions. This information is essential for aerodynamic studies when samples are mounted in different orientations and are exposed to different wind angles of attack in the tunnel test section. The applied samples may possess simple geometry, such as a bar, or complex geometry like truss shapes which are used frequently in tower construction. In the latter case, the vertical or streamwise dimension of the sample is considerable, so that the spray characteristics at different locations appear as basic information when modeling icing on objects with complex geometry. The LWC and DSD of an aerosol cloud together as well as their uniformity are affected by nozzle dynamic parameters such as nozzle water pressure and air pressure which are able with the control panel. The nonuniformity of DSD is mainly caused by the effect of gravity which leads to droplet separation in horizontal wind tunnels according to the diameter of the droplets. In the modeling of low airspeeds (below 20m/s), which is common during atmospheric icing processes [3], gravity deflects droplet trajectory significantly as the droplets move from the spray bar to the test section. This problem can be optimized by adjusting nozzle dynamic parameters and air speed, but it will be more complicated when the icing object possesses complex geometry such as truss shape or bar.

The main goal of this investigation is to study LWC and DSD uniformity in the streamwise and vertical directions in the test section of a horizontal icing wind tunnel in order to find conditions how complex icing objects can be exposed to a satisfactorily uniform cloud in the test section. It is also important to obtain droplet velocity vectors depending on nozzle dynamic parameters and air velocity for other purposes such as calculating aerodynamic coefficients and exerted force on the icing objects which are mounted in the test section.

II. EXPERIMENTAL SET-UP

A. *Test Facility*

Experimental data were collected in the CIGELE atmospheric icing research wind tunnel (CAIRWT). The CAIRWT is a closed-loop, low-speed icing wind tunnel 30m in length, including a 3-m-long horizontal test section whose rectangular cross section measures 0.46m in height and 0.92m in width. The height and width of the settling chamber where a horizontal spray bar is located are 1.7m and 1.14m, respectively. An accepted standard technique is used at CAIRWT to simulate atmospheric icing processes and involves injecting water at room temperature into a cold air stream through air-assisted nozzles located at the trailing edge of a horizontal spray bar [8]. The latter is shaped like a NACA-0012 air-foil and is installed at the height of the tunnel center line, immediately downstream from the honeycomb panel. The present spray bar system uses three nozzles located at the centerline. A distance of 4.4m separates the spray bar and the midpoint of the test section where the icing structure being analyzed is usually placed.

The air-assisted nozzles can produce widely different droplet spectra. These nozzles are manufactured by Spraying Systems Co. (Carol Stream, Illinois, USA) and use a model 2050 stainless steel water cap and a model 67147 stainless steel air cap. These nozzles produce a round spray pattern with a spray angle of around 15º.

B. *Instrumentation*

An integrated system for icing studies was manufactured by Droplet Measurement Technologies, which is applicable for LWC and DSD measurements. This instrument has two probes for droplet size measurement, the Cloud Imaging Probe (CIP) and the Cloud Droplet Probe (CDP), whose operation is based on optical imaging techniques. The CDP is designed to measure particles with diameters between 3 and 50 μm, whereas the CIP measures particles ranging in size from 25 to 1550 μm. The CIP is a combination probe incorporating several basic measuring instruments to characterize cloud parameters, also including a hot-wire LWC sensor, an air temperature sensor and a Pitot tube air speed sensor. The measured data are displayed by the particle analysis and collection system (PACS) which has an intuitive graphical user interface at the host computer and provides powerful control of the measured parameters while simultaneously displaying real-time size distributions and derived parameters.

The PIV technique, which has been widely described [9,10,11], was used to obtain droplet velocity vectors. The most commonly used method is to take at least two constructive images from small tracer particles suspended in the flow under investigation. By measuring the particle image displacement, the two dimensional projections of the local velocity vector can be calculated using the time between the two pulses from the laser. The technique is based on the measurement of the particle displacements, because the seeding particles accurately follow the air flow pattern [12]. In parallel it is fundamental to obtain a high uniform seeding density in the region of interest. The seeding particles for PIV investigation of two phase flows in icing wind tunnel are water particles, which are generated by means of 3 nozzles. The light source for illumination of the particles is a double cavity Nd:YAG laser and relative harmonic generator (HG) and harmonic separator (HS) supplying the near-IR light into green. Nd:YAG laser produces light with a wavelength of 1064nm, but the HG and HS changes this to 532nm, and the interval between the two pulses can be set between 4 and 10ns.

The recording system includes a CCD camera, a PC for image acquisition and a synchronisation unit. The camera is a full frame interlines CCD technology, capable of acquiring two frames with minimum delay of 1 μs and a CCD resolution of 1024 by 1280 pixels.

C. *Experimental Procedure*

The integrated system described in the previous section was used to measure LWC and DSD in the vertical and streamwise directions in the tunnel test section for different free-stream velocities and initial DSDs (DSD at nozzle outlet). Through the tests, the temperature was set at 15℃ and the duration of each measurement was 30s. The measurements were done for four air velocities; V_a = 5, 10 20, and 28m/s. The droplet size was determined by adjusting the pressure of the nozzle water and air lines. The water pressure, p_w, was set at 450 kPa, and the air pressure, p_a, was varied from 180 to 620 kPa. Thereby aerosol clouds were produced with varying DSD and LWC so that they simulated different icing conditions including in-cloud icing and freezing drizzle. These measurements were repeated for three vertical positions with 7cm increments and four horizontal positions with 50cm increments. The adopted co-ordinate system was as follows:

- The origin was at the center point of the test section.
- The *x*-axis was coincident with the tunnel longitudinal center line and it was oriented in the direction of the free-stream velocity.
- The *y*-axis was placed vertically and oriented upward.

Thus, measurements were made at the following positions: x = –1, –0.5, 0, +0.5 m; y = –0.07, 0, +0.07 m.

The PIV technique was used in order to determine the magnitude and direction of droplet velocities. The PIV set-up and its components were installed in three vertical positions, y = –0.07, 0, +0.07 m, and in two horizontal positions, x = –0.5, +0.5 m to illuminate and capture seeding particles. The air velocity and nozzle dynamic parameters were the same as for the DSD/LWC measurements. In all regions, a Canon lens with aperture opening of 1.4 was used. All the area was dimensioned to observe the flow across the test section.

PIV data analysis started with the displacement field calculations, obtained by the evaluation software based on cross-correlation analysis using small interrogation windows. To get all information out of the image, two consecutive interrogation windows were two-fold overlapped (50%).

III. TEST RESULTS

The experimental results are presented and discussed in this section. The quantity of data obtained is large because of the considerable amount of tests carried out at different streamwise and vertical positions, for different air velocities, and for different nozzle pressures. Therefore, only some of the results are reported here, which will be sufficient to show the effect of the parameters studied.

It was revealed in a former study that a combination of nozzle water and air pressures, so called the differential pressure, $\Delta p = p_w - p_a$, is a key parameter in determining LWC and DSD [8]. Thus, the LWC and the median volume diameter (MVD) will be presented as functions of the differential pressure with an additional varied parameter in each figure. Figures 1 and 2 present the MVD variations along the streamwise direction at y = –7 cm for the lowest and highest velocities applied in these tests. The MVD is approximately constant for the smaller differential pressures (up to about –100 kPa when the air velocity is 5 m/s, and up to about –50 kPa for 28 m/s), and then it increases until reaching a maximum which is followed by a decreasing tendency. This maximum appears around 100-150 kPa for 5 m/s, and this differential pressure increases with air velocity. It should be above 300 kPa for 28 m/s, as may be assumed from Fig. 2.

According to Fig. 1, the gravity effect is more significant than the drag effect for low air velocity. Hence, the MVD at a specific height (y = –7 cm in Figs. 1 and 2) decreases along the streamwise direction, because the larger droplets go toward the bottom of test section. When the velocity increases, the drag effect become more significant than the gravity effect, and droplet separation according to their size occurs only for clouds with the larger droplets. Quantitatively, this separation occurs for aerosol clouds with MVD of 20 μm or greater when air velocity is the lowest, and only for aerosol clouds with MVD of at least 50 μm when air velocity is the highest (see the minimum MVD where the curves are distinguishable in Figs. 1 and 2).

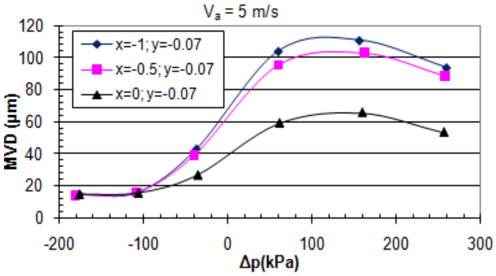

Figure 1. MVD as a function of differential pressure for different positions in the streamwise direction with air velocity of 5m/s

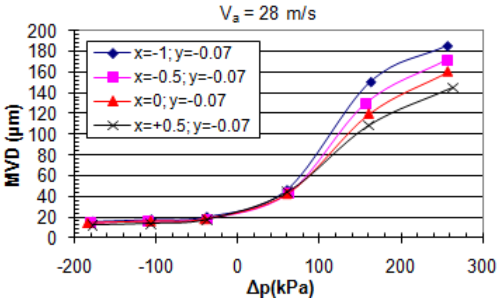

Figure 2. MVD as a function of differential pressure for different positions in the streamwise direction with air velocity of 28m/s

Figures 3 and 4 show that the dependence of LWC on the differential pressure is similar to that of MVD, except that the LWC increases even with the smallest differential pressures. Also, the LWC at the height of y = –7 cm decreases in the streamwise direction at 5 m/s, which is reversed at 28 m/s. The curves obtained for different streamwise positions appear closer and closer to each other with increasing air velocity until LWC becomes constant along the streamwise direction for an air velocity between 10 and 20 m/s. Then, the curves appear farther and farther from each other when the air velocity is further increased, but their order becomes reversed. This behavior may be explained by the fact that when the air velocity is high, the cloud is not much extended vertically at the beginning of the test section, but more and more droplets reach the vertical position of y = –7 cm as they move forward in the test section. This explanation is also confirmed by the fact that a similar reverse tendency was not observed at y = 0 cm. Most of the cloud was around mid-height at the beginning of the test section even at the highest air velocity, so that LWC at this height does not increase in the streamwise direction.

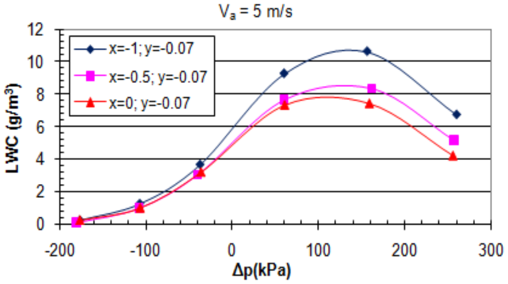

Figure 3. LWC as a function of differential pressure for different positions in the streamwise direction with air velocity of 5m/s

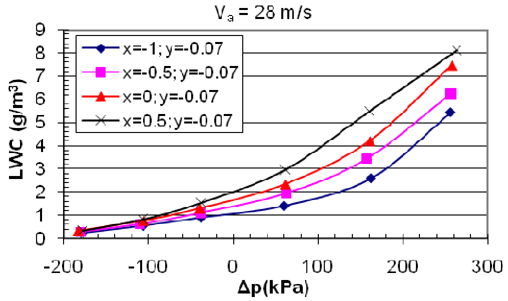

Figure 4. LWC as a function of differential pressure for different positions in the streamwise direction with air velocity of 28m/s

Figures 5 and 6 present the variation of MVD in the vertical direction. MVD decreases from top to bottom for high enough differential pressures. The difference between MVD values at the top (y = +7 cm) and at the bottom (y = –7 cm) is visible in Fig. 5 for 20 μm MVD at 5 m/s, whereas this difference becomes considerable for MVD values greater than 40 μm at 28 m/s (see Fig. 6).

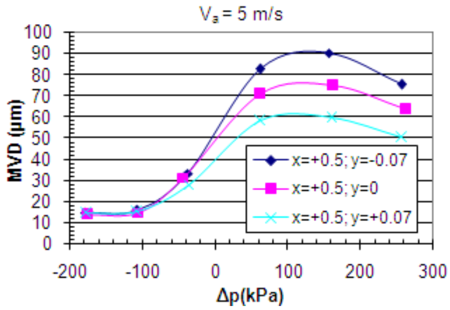

Figure 5. MVD as a function of differential pressure for different positions in the vertical direction with air velocity of 5m/s

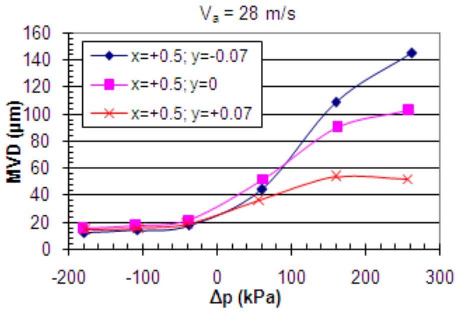

Figure 6. MVD as a function of differential pressure for different positions in the vertical direction with air velocity of 28m/s

The droplet velocity vectors were determined at different positions and under different ambient conditions. The horizontal component of droplet velocities is approximately the same as air velocity, but the vertical component varies with the measurement position and ambient conditions. Figure 7 shows how the vertical component increases toward the bottom of the tunnel at the same vertical cross section. The average of these measured vertical components are –0.05 m/s, –0.13 m/s and –0.30 m/s at the vertical positions of y = +7 cm, y = 0 cm and y = –7 cm, respectively. As was discussed earlier, droplets are larger at the bottom of the section. The gravity effect on these droplets is more important, so that the vertical component of their velocity is higher.

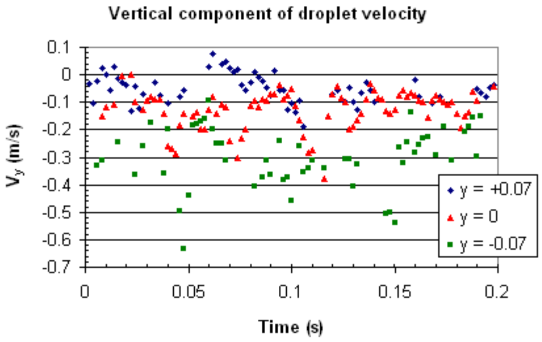

Figure 7. Vertical component of droplet velocities measured at different vertical positions. Further conditions: x = +0.5 m, V_a = 20 m/s, p_w = 450 kPa, p_a = 180 kPa

IV. CONCLUSION

The variations of spray characteristics in the streamwise and vertical directions in the test section of a horizontal wind tunnel were studied experimentally. It was found that the gravity effect is more significant than the drag effect for low air velocity. As a result, the MVD increased downward vertically and decreased along the streamwise direction at a specific height. However, when the velocity increased, the drag effect became more significant than gravity effect, and droplet separation according to their size occurred only for clouds with the larger droplets.

This information is essential for aerodynamic studies when samples with complex geometry are mounted in different orientations and are exposed to different wind angles of attack in a tunnel test section. This is because such samples can have considerable vertical and streamwise dimensions exceeding the zone of cloud uniformity. Based on these results, it is recommended for future work to increase the number of nuzzles in both horizontal and vertical directions and also to try improving the position of the nozzles in the vertical direction to obtain better uniformity in the middle of the test section of the tunnel.

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