Laboratory Measurements of Turbulence in an Icing Wind Tunnel using a Hot-Wire Anemometer

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Abstract—**A hot-wire anemometry technique was used to measure free stream turbulence levels in an icing wind tunnel. Spatial distributions of the turbulence levels in the cross-section of the icing wind tunnel were investigated in view of their influence on the mixing of aerosol cloud and correspondingly on the uniformity of the liquid water content (LWC) field. The distribution of the turbulence level was checked for different dynamic conditions in the wind tunnel starting from 5 m·s^{-1} up to 30 m·s^{-1}. The potential influence of the thermal factor in a single-phase air flow with the nozzles off was also investigated in various frequency ranges.**

The influence of pressures in the air and water lines, as well as of air temperature in the spray-bar system was investigated. Even with the single spray-bar system considered in this investigation the influence of these factors was found to be considerable, in particular for the lower air speed investigated, *i.e.* 5 m·s^{-1}. Pressure in the air lines of the nozzles was found to be the most crucial factor affecting the level of turbulence in the test section. The solutions to the problems arising with the loading of the flowing gas phase are presented and discussed.

I. INTRODUCTION

MOST of the industrial heat- and mass- transfer processes occurring in flowing fluids are related to the fundamental flow property called turbulence. Transfer coefficients, which are usually used to describe heat- and mass- exchange between a body and fluid flow, generally depend to a greater degree on the flow properties than on the body properties [1]. As the level of free-stream turbulence increases, the role of the fluid properties continuously becomes more and more dominant. Reliable information concerning the free-stream turbulence level in a flowing fluid is thus one of the major factors defining specific heat- and mass- transfer processes [2]. During natural atmospheric icing processes (AIPs) occurring in the planetary boundary layer (PBL), the sources of air turbulence are buoyancy and wind shear; while during the experimental modeling of AIPs in an icing-wind-tunnel controlled environment, the free stream turbulence is produced by the tunnel configuration [3]. It may also be enhanced by the air jet used for atomizing the water in the nozzles [4] and by the presence of nozzle-bearing spray-bars [5]. Henze [4] also considered the effects of heated air and water pressure in the nozzles, while Oleskiw et al. [6] recorded the relationship between the increased levels of axial turbulence and local flow angularity. Considerable amount of work regarding free-stream turbulence is done during the aerodynamic surveys [7] or droplet-cloud calibrations [8] of the icing wind tunnels. Despite the need of the experimenters to attain a decreased level of turbulence while working with fluid flow in icing wind tunnels, more often than not the level of turbulence in a wind tunnel is higher than that registered under natural conditions. The increased free stream turbulence in an icing wind tunnel tends to raise the uniformity level of the LWC field [9, 10], although it tends to complicate the heat- and mass-exchange processes, producing unnatural ice accretion shapes and increased ice accretion load [11]. Marek and Olsen Jr. [5] also insisted on the importance of a minimum level of turbulence required for the optimum mixing of droplets in an aerosol cloud.

The main goal of this investigation was to define free-stream turbulence in an icing wind tunnel as a function of (i) various thermodynamic parameters maintained inside a wind tunnel; (ii) pressures in air and water lines of the nozzle system used for atomizing the water; and, (iii) position in the cross-section of the tunnel test section. Subsidiary goals of the present investigation were to compare the profiles of the horizontal and vertical distributions of free stream turbulence inside the two segments of the CIGELE Atmospheric Icing Research Wind Tunnel (CAIRWT): settling and test sections; and to verify hereby the effectiveness of the converging bell section of the tunnel. A brief description of this tunnel is provided in the next section, considering that it is central to the discussion of the problem under investigation.

II. EXPERIMENTAL SET-UP

A. Experimental Facility

The CAIRWT is a horizontal closed-loop low-speed icing wind tunnel 30 meters in length, including a 3-meter long test section whose rectangular cross-section measures H_{TS}=0.46 m in height and L_{TS}=0.92 m in width. 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. The latter is shaped like a NACA-0012 airfoil and is installed at the height of the tunnel centerline, in the settling section, immediately downstream from the honeycomb panel. The present spray-bar system uses three nozzles located at the centerline, and 0.2 m left and right of it, respectively. A distance of 4.4 m separates the spray-bar and the mid-point of the test section where the icing structure being analyzed is usually placed. This distance is sufficient that an aerosol cloud undergoes noticeable transformation due to both heat- and mass-transfer, thereby becoming supercooled. Simultaneously, an additional water vapour in the gas phase is produced. The CAIRWT is a wind tunnel with the rectangular cross-sections in both settling and test sections and different contraction ratios in the horizontal and vertical planes. Contraction ratio in the vertical plane, which is defined as $R_h = H_{SB}/H_{TS}$ =2.52:1 is greater than contraction ratio in the horizontal plane defined as $R_l = L_{SB}/L_{TS}$ = 1.89:1. In the formulae presented *H* and *L* stand for the height and length of the corresponding section of the tunnel, respectively, while the subscripts SB and TS stand for spray-bar, *i.e.* settling section, and test section, respectively. Maximum attainable air speed in the CAIRWT is of Mach 0.09 (*i.e.* 30 $m \cdot s^{-1}$). The results of the aerosol cloud calibration in the test section of the CAIRWT are presented in [12], while this paper deals with the results of aerodynamic calibration measurements.

B. Experimental Instrumentation

The hot-wire anemometry (HWA) is an excellent means for a pointed evaluation of the fine structures in turbulent fluid flows. We refer readers the investigation by Henze [3] for an in-depth discussion of state-of-the-art of HWA evaluation and the presentation of both advantages and disadvantages of this method. The turbulence data in present research were collected in a single-phase air flow using a TSI hot-wire anemometer IFA300 at stations separated 4.4 m apart inside the tunnel: in the settling section, at the location of the spray-bar, and in the test section, at the usual location of icing body. This study made use of three single hot-film probes, model 1210, located at the tunnel centerline, and 0.2 m left and right of it, respectively. The effective air speed was always formed by the streamwise and lateral components.

Some preliminary results of the measurements of air turbulence levels in a single-phase air flow will be presented hereafter as the functions of different groups of parameters pinpointed earlier in the Introduction as having a considerable effect on the local turbulence distribution. Finally, some conclusions will be given concerning the importance of the corresponding group of parameters in view of the turbulence level variations.

III. Preliminary Results and Discussion

A. Thermodynamic parameters

The air turbulence level was measured as a function of two thermodynamic parameters: air speed and air ambient temperature. Five values of air speed were selected for measurements V_a=5, 10, 15, 20 and 30 $m \cdot s^{-1}$; and for each selected value, the four values of air temperature were chosen: T_a=-15, -5, 0 and 20 ^oC. The first two values of air temperature were chosen as the most appropriate ones for characterization of in-cloud icing and freezing rain atmospheric icing phenomena, respectively. The choice of the last two values of air temperature was dictated by the necessity to find out the behaviour of air turbulence at the indifferent, *i.e.* equal to the water fusion temperature T_a=T_0=0^{o}C, and warm air temperatures. The influence of overheat ratio changes, related to the variations of ambient air temperature, is negligible, since the operational temperature of the hot-films is noticeably higher, T_w=250 ^{o}C. In this first series of experiments the turbulence was measured only at the three locations in the test section: (i) geometrical center of the tunnel test section; (ii) 0.2 m left of the geometrical center, as seen from streamwise position; and, (iii) 0.2 m right of it. Depending on the position relatively to the centerline, the distribution of air free-stream turbulence as a function of air speed and air ambient temperature was found to be considerably different. The free-stream turbulence data acquired at the geometrical center of the tunnel test section and 0.2 m left of it, as seen from the streamwise position, are presented in a 3-D scattering diagram in Fig. 1 and Fig. 2, respectively.

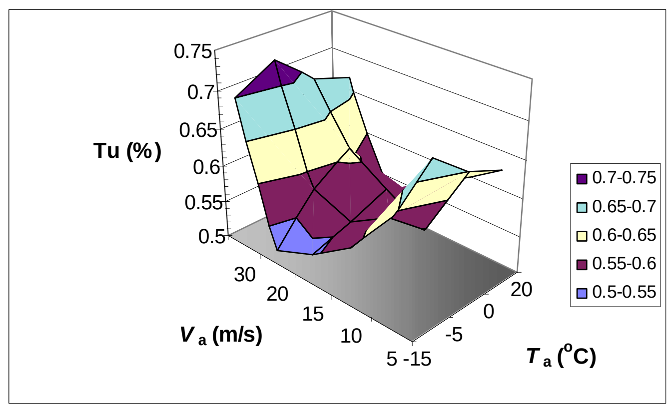

Fig. 1. The turbulence levels measured at the geometrical center of the tunnel test section as a function of air speed and ambient air temperature.

The objective of this comparison is to show to which extent the effect of the converging bell is successful in view of the suppression of the air turbulence at different locations in the test section. At the geometrical center of the tunnel test section (Fig. 1), the dependence of the free-stream turbulence level, *Tu* (%), on air speed and ambient air temperature has a noticeably expressed saddle shape. Although both low and high air speeds favour the increase of free-stream turbulence, the sources of the turbulence in both cases, however, are different. In the first case, it is a consequence of the relatively weak acceleration of air flow in the converging bell, *i.e.* relatively low contraction ratio for low air speed, while in the second case it is a result of the weak reduction of free-stream turbulence by the honeycombs and near the turning vanes locations. The reason of a slight dependence on air ambient temperature with a peak around 0 ^{o}C, has not been well documented to date and should be verified in the supplementary series of experiments. To the best of our knowledge, there is no experimental investigation concerning the influence of the temperature factor on the level of free-stream turbulence. The present research sheds thus some more light on the area of experimental physics dealing with the turbulence properties of a flowing fluid. The dependence of the free-stream turbulence level on air speed and air ambient temperature is quite different at the location of 0.2 m left of the geometrical center of the test section (Fig. 2). At this location the intensity of free-stream turbulence increases rather linearly with air speed, while the dependence on air ambient temperature almost does not exist. The behavior of the turbulence intensity level recorded at this location is caused by the increased initial level of free-stream turbulence near the honeycombs at this side and, as a consequence, a non-entire damping of turbulence by the converging bell. As will be seen in the subsection C, the increased level of free-stream turbulence, produced by non-uniformity of the air speed distribution was, indeed, recorded at the left side in settling section, i.e. near the spray-bar, during the turbulence profiling series.

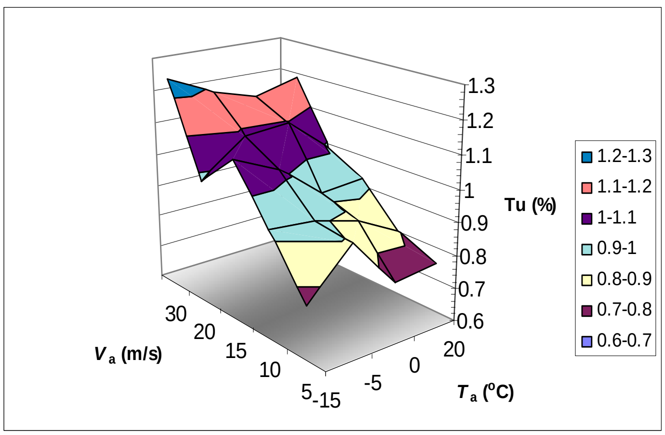

Fig. 2. The turbulence levels measured at the distance 0.2 m left of the geometrical center of the test section as a function of air speed and ambient air temperature.

B. Aerosol-creating system

This series of the experiments was designed in order to find out the effect of variation of nozzle pressures in air and water lines of the aerosol-creating system on the level of free-stream turbulence in the test section. The air jet and water dispersed under pressure create the additional sources of turbulence in the settling (i.e. spray-bar) section, which may be registered in the test section. During modelling of various atmospheric icing conditions in the CAIRWT, the pressures in air, P_{al} (kPa), and water, P_{wl} (kPa), lines of the aerosol-creating system may vary within the considerable wide ranges: $103.4\,kPa \le P_{al} \le 413.6\,kPa$ and $69\,kPa \le P_{wl} \le 551\,kPa$. In this series of the experiments, the turbulence level was recorded in the test section as a function of the varying nozzle air and, subsequently, water pressures within the above-mentioned ranges for the five values of air speed in the tunnel, V_a=5, 10, 15, 20 and 30 $m \cdot s^{-1}$. The step for varying the air and water pressures was set at 69 kPa. During the evaluation of the effect of the pressure in the first line, *i.e.* either the air or water line, the second one was kept at 0 kPa. Also, the effect of pressure in the water line was investigated by sending air in the line instead of water. This was necessary in order to avoid eventual damage of the hot-films by impinging aerosol droplets. Again, the turbulence level was measured at the three locations in the test section: (i) geometrical center of the tunnel test section; (ii) 0.2 m left of the geometrical center, as seen from streamwise position; and, (iii) 0.2 m right of it. Only the data recorded at the geometrical center of the test section will be presented in the present study. The results of the measurements of the turbulence level as a function of pressure in the nozzle air line for various air speeds are presented in Fig. 3, while Fig. 4 shows the corresponding turbulence data as a function of pressure in the nozzle water line.

For the highest air speed investigated in this research (V_a=30 $m \cdot s^{-1}$), the raise in the level of turbulence produced by the increase of pressure in the water line of the nozzle system from 0 to 413.6 kPa (Fig. 4, cross symbols) was found to lie within a range of accuracy of measurements and may thus be disregarded.

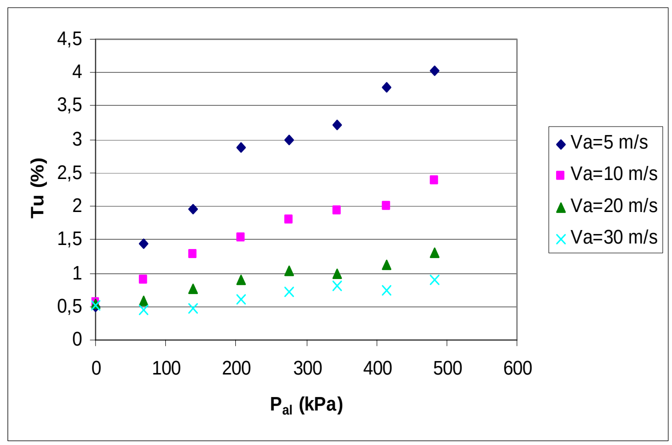

Fig. 3. The free-stream turbulence level at the geometrical center of the test section as a function of pressure in air line of aerosol-creating system.

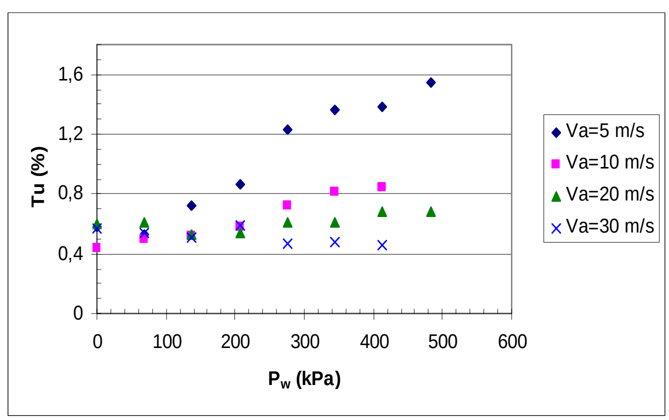

Fig. 4. The free-stream turbulence level at the geometrical center of the test section as a function of pressure in water line of aerosol-creating system.

At the same air speed, the corresponding raise in the level of turbulence produced by the increase of pressure in the air line from 0 to 482.6 kPa was found to be significant, up to 80% of the initial non-disturbed value (Fig. 3, cross symbols). A dramatic raise in the level of turbulence produced by the increase of pressure in the water and particularly in the air lines of the nozzle system was found at the lowest air speed considered in this research (V_a=5 m·s^{-1}). When the pressure in the water line of the nozzle system increased from 0 to 413.6 kPa, the level of turbulence raised up to 3 to 4 times of its initial value (Fig. 4, diamond symbols). This result is particularly surprising, since a relatively small number of nozzles (*n*=3) was used for forming the aerosol cloud in all experiments. The data collected on both sides of the tunnel centerline in the test section, which are not presented here, reveal a discordance between the values recorded at the outer wall from the one hand and the values recorded at the center. As the pressure in the investigated line rises, this discordance is found to be preserved. Again at the lowest air speed, the level of turbulence produced by the increase of pressure in the air line from 0 to 482.6 kPa was found to be even more important, having a value up to 7 (!!!) times higher than the initial value of turbulence (Fig. 3, diamond symbols). The depth of this influence may be evaluated from the fact that the difference between levels of turbulence at the right and left sides of the tunnel under such an influence may disappear. The turbulence data recorded reveal thus a profound dependence between the free-stream turbulence level and pressures in both the air and water lines of the aerosol-creating system. By using the method of least squares, the parabolic dependence of the turbulence intensity at the geometrical center on the nozzle air pressure was defined as follows:

$$Tu = \left(6\cdot 10^{-6}\ln V_a - 2\cdot 10^{-5}\right)P_{al}^2 + 0.193V_a^{-1.65} + 0.76V_a^{-0.14} \quad (1)$$

The corresponding dependence on the nozzle water pressure is found to be linear and states as follows:

$$Tu = \left(-0.0014\ln V_a + 0.0045\right)P_{wl} + 0.0056V_a + 0.41 \quad (2)$$

As may be seen from both expressions, the level of free-stream turbulence in both cases depends on air speed.

C. Non-Uniformity of Horizontal Distributions of Turbulence in a Single-Phase Flow

The horizontal and vertical distributions of the level of free-stream turbulence in an air flow inside the settling (*i.e.* near the spray-bar) and test sections were obtained in this last series of experiments. Only the turbulence data concerning the measurements of horizontal distribution of turbulence intensity will be presented in this communication. Figure 5 compares the profiles of turbulence levels in the horizontal direction inside (i) the settling section (i.e. near the spray-bar) and (ii) the test section, at its geometrical center, at an air speed of 30 m.s^{-1}. An important issue arising from a comparison of turbulence levels over the spray-bar and at the geometrical center of the test section is the lack of symmetry with the centerline at both sites. The turbulence level near the inner wall of the circuit is considerably higher than it is near the outer wall. This feature results in a different degree of mixing in the aerosol cloud on each side of the centerline [12]. Comparison of the absolute values of turbulence for both curves from Fig. 5 reveals that the one representing the geometrical center of the test section shows a high degree of laminar flow at the center, since the level of turbulence there may be as low as 0.5 %. This laminarity is optimal for obtaining reliable results for the experimental investigation of atmospheric icing. Several peaks in turbulence distribution near the spray-bar are related to the locations of the vertical cylindrical supports for the honeycomb panel.

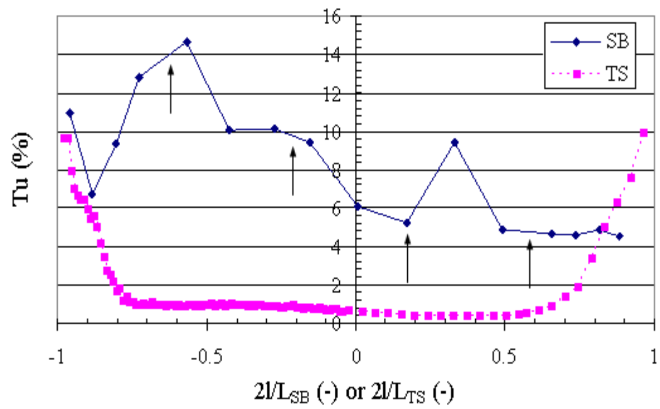

Fig. 5. Horizontal turbulence profile for average velocity in the test section, $\overline{V}_{a,TS} = 30\ \text{m}\cdot\text{s}^{-1}$, SB at the spray bar, TS in the test section. Arrows show the position of the vertical cylindrical supports of the honeycomb panel. (Adopted from [12]).

Figure 6 compares horizontal profiles of the velocity field in the settling section, i.e. over the spray-bar, $V_{a,SB}$, and in the test section, $V_{a,TS}$, for three different average velocities in the test section: 5, 20, and 30 m·s^{-1}.

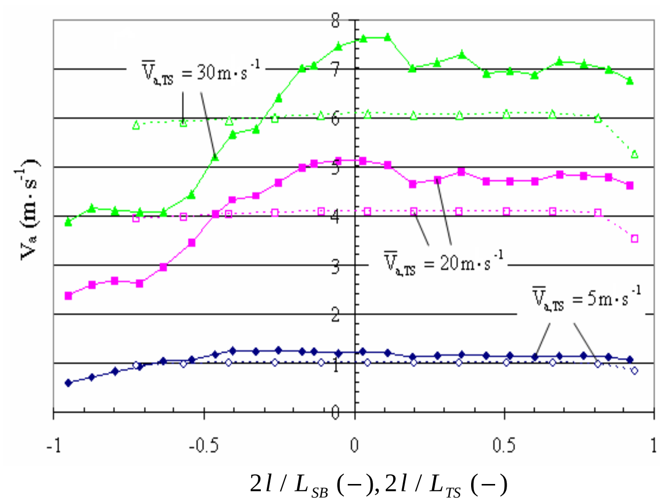

Fig. 6. Horizontal velocity profile for three different average velocities in the test section, $\overline{V}_{a,TS}$. Continuous lines: local velocity at the spray bar, $V_{a,SB}$; dotted lines: local velocity in the test section divided by the product of the horizontal and vertical contraction ratio, $V_{a,TS}/(R_hR_v)$. (Adopted from

[12]).

In order to use the same scale for both sites, local velocity in the test section is divided by the product of the horizontal and vertical contraction ratio, $R_l R_h$. It may be observed that, due to a higher energy loss near the inner wall when the main air jet turns at the corners, the velocity head suffers from non-uniformity on the left side, when observed from the position of the honeycombs. The non-uniformity observed is considerable at an air speed of $V_{a,TS}$=30 m.s^{-1} (around 35 %), and almost negligible at $V_{a,TS}$=5 m.s^{-1}. The non-uniformity in air speed distribution on the left side is not, however, observed in the test section (compare left sides of continuous and dotted lines in the same figure). The relevant contraction in the horizontal plane, R_l=1.89, is clearly sufficient for the initial non-uniformity to disappear in the test section. The consequence of this non-uniformity may be observed in the dissimilar behaviour of the turbulence level at the centerline and left of it, as was reported previously in the Subsection A. Such a non-uniformity in the distribution of the turbulence level results in the relatively different aerosol characteristics on the left- and right-hand sides [12].

IV. Conclusions

It was shown in this experimental study that the level of free-stream turbulence, as recorded in a single-phase air flow, may be considerably disturbed when modeling AIPs phenomena. Three very important issues concerning the sources of appearance of additional free-stream turbulence were addressed in the present study. First, the specifics of the tunnel design may account for up to 30 % of an additional increase in the free-stream turbulence level which has so far been disregarded. Second, the most crucial factor affecting the level of turbulence in the tunnel test section is the pressure change in the air lines of the nozzles. Loading of the flowing gas phase by a dispersed phase with prescribed properties is always related to the appearance of nozzle air jets and water dispersed under pressure. The increase in pressure of the air and water lines of the nozzle system causes an important increase in the free-stream turbulence level of air flow. A calibration of the turbulence fields is thus required when loading a single-phase flow. Third, the non-uniformity of air speed distribution in the settling section may be a source for noticeably different local behavior of the turbulent fields with the change of thermodynamic parameters. It may be concluded that an additional spatial calibration of the turbulence fields is needed with all three groups of parameters considered in the present research.

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VI. References

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