THERMO-ANEMOMETRIC DETERMINATION OF LIQUID WATER CONTENT IN WET AIRSTREAM

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DOI: 10.19062/2247-3173.2016.18.1.45

Abstract: *The paper is focused on the experimental study of possibilities of the thermo-anemometric analysis for determination of the liquid water content in the stream of wet air. The developed method is based on the measurement and comparison of stream velocity of wet and dry air by the hot-wire thermal anemometric probe. Experiments were performed in the small icing wind tunnel using the standard thermal anemometer Testo 425. There was found the correlation between the liquid water content and the difference in measured velocity of the wet and dry airstreams. The conclusion of the paper pays attention for the interpretation and formulation the final analyses and recommendations.*

Keywords: *liquid water content, aircraft icing, hot-wire sensor.*

1. INTRODUCTION

The liquid water content (*LWC*) is a measure of the amount of water contained in the amount of dry air, usually expressed by grams of water per cubic meter of air (g/m^3). The *LWC* is used for determining of the water content in a cloud. Clouds may contain *LWC* values from of 0.03 g/m^3 for cirrus clouds up to 3 g/m^3 for cumulonimbus clouds. Clouds contain wide range of water droplet sizes with different diameters. The range of diameters usually extends from 15 to 40 μm. Clouds below freezing often contain a mixture of supercooled liquid droplets and small ice crystals. Freezing drizzle size droplets normally extend from 40 to 400 μm. Freezing rain droplets are larger still, extending up to several millimeters in diameter.

The liquid water content, along with airspeed, air temperature, and water droplet size is one of the important parameters that affects icing on aircraft. Therefore, it is crucial to determine a suitable method for measuring the liquid water content in natural clouds or in the stream of air in an icing wind tunnel.

2. MEASURING TECHNIQUES

There are several ways that can be used to measure the liquid water content in clouds or in the flowing airstream.

One way involves cloud remote-sensing techniques. The most known are weather radars. Operational radars were not specifically designed for icing detection, but they may yield information that, when combined with that from other sources such as numerical weather prediction models, satellite imagery, or surface observations, provides clues to the location and intensity of icing [1].

Cloud water can also be retrieved from passive microwave measurements because of its strong spectral signature and polarization signature. Clouds are semi-transparent allowing for measurement of the total columnar absorption. The absorption is related to the total amount of liquid water in the viewing path, after accounting for oxygen and water vapor absorption [2].

A laser disdrometer measures the reduction of total signal as a hydrometeor passes through a horizontally oriented laser-beam. This signal is proportional to the linear extent of the beam blocked by the hydrometer at this instant in time [3].

The icing blade and rotating cylinder, which are commonly used to measure *LWC* in icing wind tunnels, although there are very simple devices can provide accurate measurements in an icing spray cloud with a median volume diameter less than 50 μm. Both are based on the measure of thickness of ice accreting on the probe surface during the appropriate exposure time [4].

The iso-kinetic probe is less sensitive to droplet splashing, because droplets are drawn iso-kinetically into the probe. The amount of collected water is then weighed to provide a direct *LWC* measurement. The iso-kinetic condition defines a cylindrical stream tube in a spray cloud with a cross-sectional area equal to the probe's inlet area, hence, each measurement represents a discrete point in a spray cloud distribution [5].

Another way is in situ airborne measurements providing the most accurate information about cloud characteristics and detection of icing conditions.

The forward scattering spectrometer probe is an instrument developed for the measurement of cloud droplet size distributions and concentration. This probe detects single particles and size them by measuring the intensity of light that the particle scatters when passing through a focused laser beam. The instrument can size particles from 1 to 50 μm and it is capable of sizing particles having velocities from 20 to 175 m/s [6].

Optical array probe for in situ cloud droplet measurements uses the definition of the cross-sectional sample area within which droplets are detected. The sample volume is derived by multiplying the sample area by the flow velocity and the sample duration. Therefore, a bias in the sample area or in the flow velocity translates directly to a bias in measured droplet concentrations and calculated *LWC*. This probe is used for measure droplets in the range of dimeters from 15 to 450 μm [7].

The hot-wire liquid water sensors are frequently used. The wire is attached to the power supply and is situated on the outside of the airplane. As it moves through a cloud, water droplets hit the wire and evaporate, reducing the temperature of the wire. The resistance of the sensing coil is directly proportional to its temperature. Therefore, the control circuit maintains the sensor at constant temperature by maintaining it at constant resistance. A Wheatstone bridge is formed of four resistances, of which the master coil sensor is one. The power dissipated by the sensor is the product of the current through the sensor and the voltage drop across it. The power dissipation due solely to vaporization can then be estimated, which in turn gives an estimate of liquid water content.

The Johnson-Williams instrument uses two heated wires in a balanced bridge circuit. The main sensing wire is 0.55 mm in diameter and is mounted perpendicular to the airstream. It is heated at a constant voltage to a temperature above the boiling point of water. Cloud droplets impinging on the wire are evaporated, causing the wire to cool and its electrical resistance to decrease. This change in resistance causes an imbalance in the bridge circuit; the degree of imbalance is related to the *LWC*. The second wire is mounted to the airstream and is shielded from droplet impingement. This wire is connected to the opposite side of the bridge and compensates for small changes in air temperature, air density and speed [4].

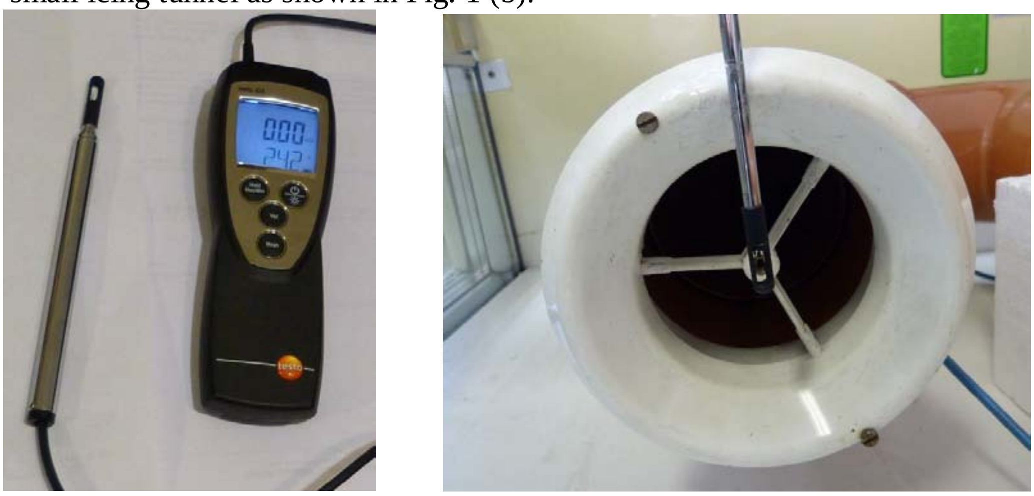
The CSIRO-King instrument employs a sensor composed of three wire coils wound around a small hollow tube. The total heat transfer rate from the coil is determined from the power required to keep the sensor coil at a constant temperature. This heat transfer rate is composed of the "dry" term, which is a function of airflow velocity, air density and air temperature, and a "wet" term, which is a function of airflow velocity and *LWC* [4].

The Nevzorov instrument is also a constant temperature device which consists of two separate hot-wire sensor systems that are intended to measure liquid water content and total water content. The sensing elements are mounted on a vane that is designed to keep the sensors aligned into the airflow. Each sensor system consists of two heated wires a sensing wire and a compensating wire. The liquid water content sensor is mounted on the leading edge of the vane and the compensating wire mounted on the trailing edge of the vane. The total water sensor consists of a wire mounted inside a cylindrical cone and the compensating wire wound in a groove around the cylinder. Each set of wires is controlled and monitored by its own set of electronics [4].

3. METHOD OF MEASUREMENT

Prices of the above mentioned systems are too high for using in the small icing wind tunnel, that is used at the University of Defence [8]. Therefore, we were seeking for some simple and less expensive sensor for determining of the liquid water content in the stream of wet air. Hot-wire anemometers have been used extensively for many years as a research tool in fluid mechanics. Measurement of fluid flow velocity is based on the fact that the probe's resistance is proportional to the temperature of the hot wire, which is influenced by the fluid convective heat transfer. If water droplets are present in an airstream, it is supposed that the impacting droplets should substantially increase the hot-wire probe cooling. This phenomenon is then indicated by increasing the measured airflow velocity. This increase in velocity due to water droplets in the wet airstream is examined for various liquid water contents, airflow velocities and temperatures.

The common commercial thermal anemometer Testo 425 was chosen as the instrument for measuring flow velocities and temperatures by means of a permanently connected hot-wire probe. View of the instrument is show in Fig. 1 (a). The hot-wire probe of the thermal anemometer Testo 425 was attached in the center of the test section of the small icing tunnel as shown in Fig. 1 (b).



(a) (b)

FIG. 1. Thermal anemometer Testo 425 (a), hot-wire probe attached in test section (b)

The one nozzle sprayer has been used for the injection of the distilled water into the annular air duct of diameter 120 mm. The resulting liquid water content in the stream of wet air is determined by: the mass of injected water, the duration of water injection, the airflow velocity, and the air duct of diameter. It yields

$$LWC = \frac{\Delta m}{v\,A\,\Delta\tau}, \tag{1}$$

where Δm is the mass (g) of water consumed in a sprayer and $\Delta\tau$ is the time (s) of this consumption, v is the airflow velocity (m/s) and A is the flow cross-sectional area (m^2).

The experiment was performed in such a way that it is possible to find a dependence between the liquid water content and the difference in velocity of the wet and dry airstreams. Differences in velocities of airstreams with and without water droplets injection were examined for various injector modes ensuring LWC values from zero to 8 g/m^3. A set of measurements were performed for three airflow velocities v = 5, 8 and 11 m/s and for two air temperatures 0 °C and 24 °C.

4. RESULTS OF EXPERIMENT

Results of measurement as the courses of difference in velocity Δv of the wet and dry airstreams versus the liquid water content LWC for three dry airstream velocities v are given in Fig. 2 at the temperature 24 °C and in Fig. 3 at the temperature 0 °C.

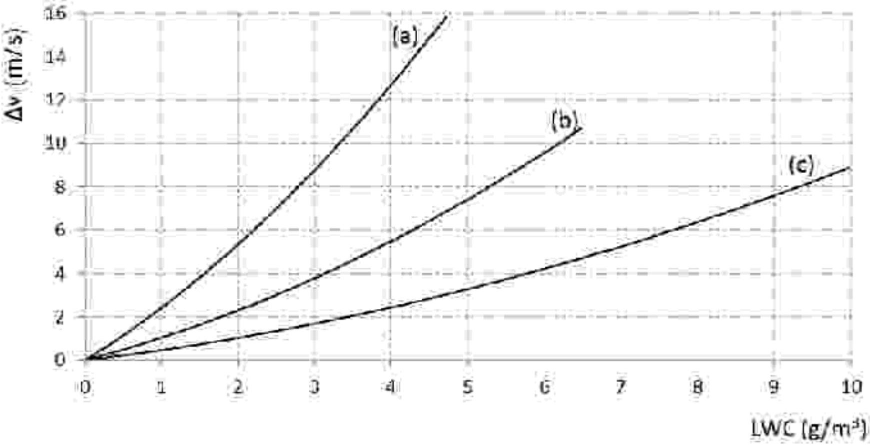


FIG. 2. Difference in velocity of wet and dry airstreams versus liquid water content at temperature 24 °C for airflow velocities: (a) 11 m/s, (b) 8 m/s, (c) 5 m/s

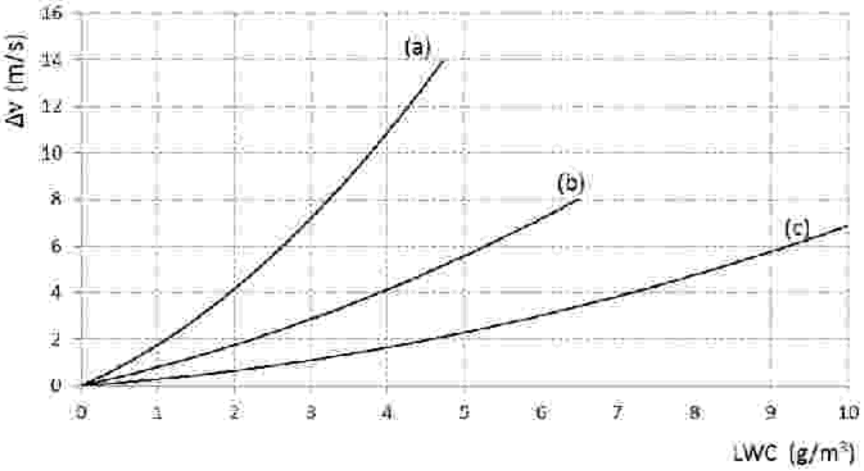


FIG. 3. Difference in velocity of wet and dry airstreams versus liquid water content at temperature 0 °C for airflow velocities: (a) 11 m/s, (b) 8 m/s, (c) 5 m/s

Presented results of measurement show us that the difference in velocity of wet and dry airstreams is a suitable parameter for the determination of the liquid water content with a substantial increase for higher airstream velocities. The influence of the temperature is fairly low.

If we are looking for the correlation between the liquid water content and the given difference in measured velocity, it seems to be rather complicated as seen in Fig. 2 and Fig. 3. However, if we express the difference in measured velocity Δv related to the airflow kinetic energy by $\Delta v/v^2$, we do obtain nearly identical courses for all airflow velocities as shown in Fig. 4. These slight differences are probably given by the measurement accuracy.

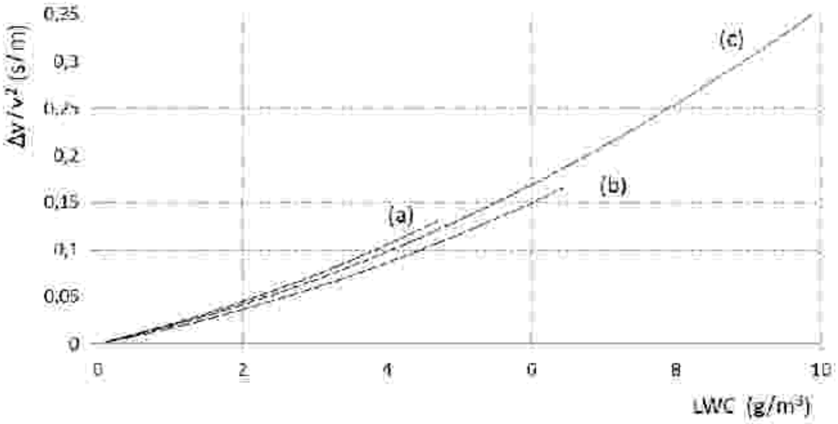


FIG. 4. Difference in velocity of wet and dry airstreams related to airflow kinetic energy versus liquid water content at temperature 24 °C for airflow velocities: (a) 11 m/s, (b) 8 m/s, (c) 5 m/s

5. APPROXIMATION OF RESULTS

An approximation of the measurement results is useful for a computer processing. The dependence of *LWC* versus $\Delta v/v^2$ is plotted for two air temperatures in Fig. 5.

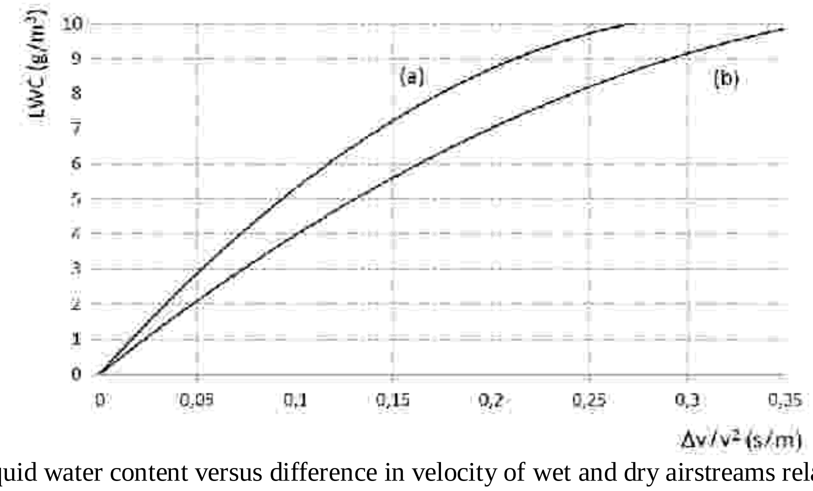


FIG. 5. Liquid water content versus difference in velocity of wet and dry airstreams related to airflow kinetic energy for air temperatures: (a) 0 °C, (b) 24 °C

The best candidate for the approximation of measured results seems to be the polynomial equation in form

$$LWC = x_1\, T^{y_1} \frac{\Delta v}{v^2} + x_2\, T^{y_2} \left(\frac{\Delta v}{v^2} \right)^2, \tag{2}$$

where T is the absolute air temperature (K).

By applying the approximation equation (2) for results of measurement, we can obtain by using the Excel processor the dependence of the liquid water content *LWC* on the difference in measured velocity of the wet and dry airstreams Δv, the airflow velocity v, and the absolute air temperature T valid for the thermal anemometer Testo 425 in form

$$LWC = 4.454\,10^{11}\ T^{-4.045}\ \frac{\Delta v}{v^2} + 2.727\,10^{22}\ T^{-8.4}\left(\frac{\Delta v}{v^2}\right)^2. \tag{3}$$

CONCLUSIONS

The low cost method for the liquid water content quantification in the stream of wet air using the thermal anemometer Testo 425 has been developed. It is possible to use this method for determination of *LWC* in an icing tunnel from differences in measured velocities of airstreams with and without water droplets spray injection.

In principle, it is possible to use the thermal anemometer also for the in situ airborne measurements, if the hot-wire probe would be placed nearby the pitot tube for determining the airspeed of an aircraft. The difference between measured velocities using the thermal anemometer Testo 425 and the pitot tube would be applied by the same way for the determination of the liquid water content.

Results of measurement and their approximation presented in this paper are valid for the given one nozzle water sprayer. The type of water sprayer determines the droplet size diameter. In future, further testing for another water sprayers is supposed.

ACKNOWLEDGMENT

The work presented in this paper has been supported by the institutional funding DZRO K 201 “VÝZBROJ” and by the specific research project of Faculty of Military Technology SV16-216.

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