Global Rainbow Technique: Temperature evolution measurements of super-cold droplets

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Abstract

Recreate the natural icing condition in a wind tunnel is a challenge, with a lot of industrial applications (plane security, turbojet, wind turbine, electric cable icing, etc,.). A major difficulty is the determination of the water droplet temperature. In nature, the water droplets are in the atmosphere during a long time. Accordingly the droplet temperature can be supposed equal to the air temperature. In a wind tunnel, the droplet must be injected at a positive temperature, then travel only on few meters, corresponding to a short residence time, limiting the heat exchange with the air. Therefore, the *in situ* measurement of the droplets temperature and size distribution is crucial for icing characterization.

To carry out such measurements ***RainbowVision*** has developed a device, based on the concept of Global Rainbow Technique (GRT). In this paper, droplets temperature measurements are validated as well as the associated droplet size distributions. Then, for the first time, GRT has been applied in the real icing wind tunnel PAG at the DGA-EP to measure the droplet temperature and size distribution behavior. These promising preliminary results are reported and discussed.

Keywords: Spray, Icing, Droplet temperature measurement, Droplet size distribution, Icing Wind Tunnel.

Introduction

Sprays are classically characterized by geometrical parameters as: the size distribution, velocity distribution, density, size/velocity correlation, etc. Nevertheless, thermo-chemical parameters as the spray temperature and the spray composition are also very important. These parameters are necessary for understanding physical phenomena as well as mastering a large number of industrial processes such as evaporation process.

Temperature and composition affect the refractive index value of droplets in a spray. Then, the measurement of the refractive index is a measurement of these two quantities. Accordingly, Global Rainbow Technique (GRT) has been developed [1] to measure simultaneously the refractive index (therefore temperature and/or composition) as well as the droplet size distribution. By analyzing the light scattered by the droplet around rainbow angle, the refractive index can be extracted from the rainbow position, whereas the droplet size distribution can be extracted from the global rainbow shape [2, 3, 4].

The Global Rainbow Technique has been successfully used in different applications such as in liquid combustion field where the fuel droplets temperature evolutions in the vicinity of the front flame have been measured [5]. The evaporation of the multi component fuel has been also quantified by measuring the evaporation rate and droplet composition [6]. In the chemical field, the chemical extend of the reaction between a gas and a reactive liquid can be determined, for example the characterization of CO_2 capture by a spray of Monoethanolamine (MEA) [7].

Another potential domain for the GRT application is Icing Wind Tunnels (IWT). IWT are used to study the icing and deicing for plane safety, electric cable icing, wind turbine, etc. In this particular field, the measurement of droplet temperature is critical. Indeed, in the natural environment the water droplet are in air during a long time permitting to assume that the droplet temperature is equal to the air temperature. On the contrary, in an IWT, the droplets are injected at a positive temperature and the residence time is limited. Then the droplets do not have always the time to be in thermic equilibrium with air for all the IWT working conditions. Therefore, the measurement of the droplet temperature in IWT is a challenge to be able to master icing condition.

This paper is organized as follow. The first section describes briefly GRT principle. The following section presents the validation of the GRT measurements which pay particular attention to the dependence of the water refractive index on the temperature. The next section shows preliminary results of super-cooled temperature behavior measurement in the real IWT (PAG at DGA-EP). Finally, our conclusions are presented.

Global rainbow technique (GRT) background

Rainbow techniques are based on the recording of the light scattered by droplets around the rainbow angle. By analyzing this angular light distribution, refractive index and particle size are estimated. Standard rainbow technique refers to the case where the recorded light is issued from a single droplet or from droplets assumed identical and at the same location. Standard rainbow techniques are very accurate, permitting to measure accurately the refractive index, the size and evaporation rate but in very restrictive configurations [3]. Meanwhile, Global rainbow technique (GRT) refers to the case where the recorded light is issued from different droplets randomly located in the control volume. The technique is less sensitive to the particle shape compare to standard rainbow technique. GRT permits to measure in situ and simultaneously an average refractive index value (therefore temperature) and size distribution in realistic sprays. It has been proved that the average refractive index value is weighted by the droplet size in $d^{7/3}$[8].

GRT measurement validation

GRT measures simultaneously an average refractive index and a size distribution from recorded global rainbow images. These two measurement values must be validated.

Refractive index (temperature) measurement validation

There are two main steps to extract the droplet temperature by using GRT. First the average refractive index is accurately extracted from the global rainbow images. Second, the average refractive index is transform to average temperature by using the appropriate relationship.

To validate the refractive index measurement, standard solutions of water and ethanol for different concentrations have been used. Figure 1 plots the index of refraction measured by GRT on spray versus the index of refraction measured by a classical refractometer [9] on bulk liquid. The result demonstrates that the GRT measurement have an accuracy equivalent to classical refractometer. It will be noted that a change as small as 0.0001 on the average refractive index is measurable.

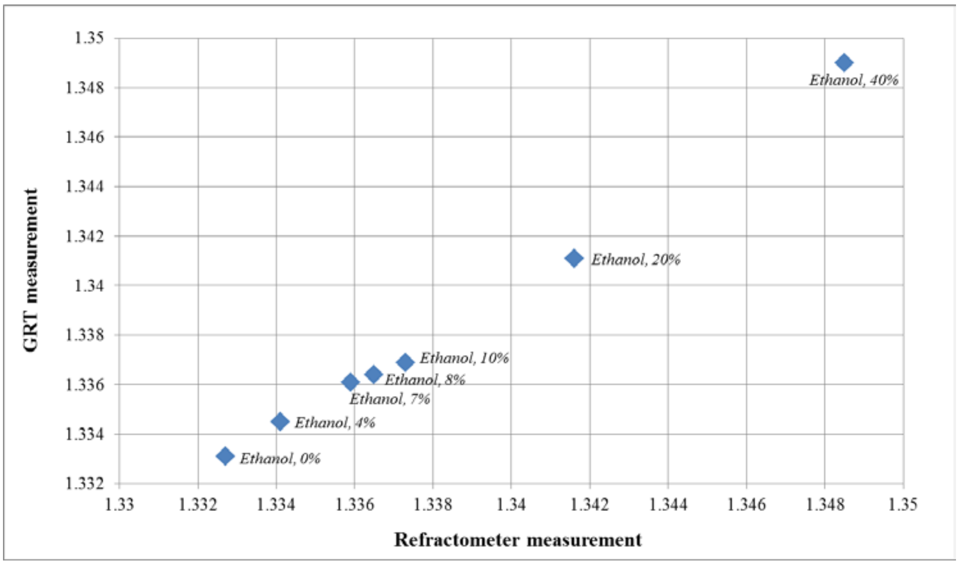
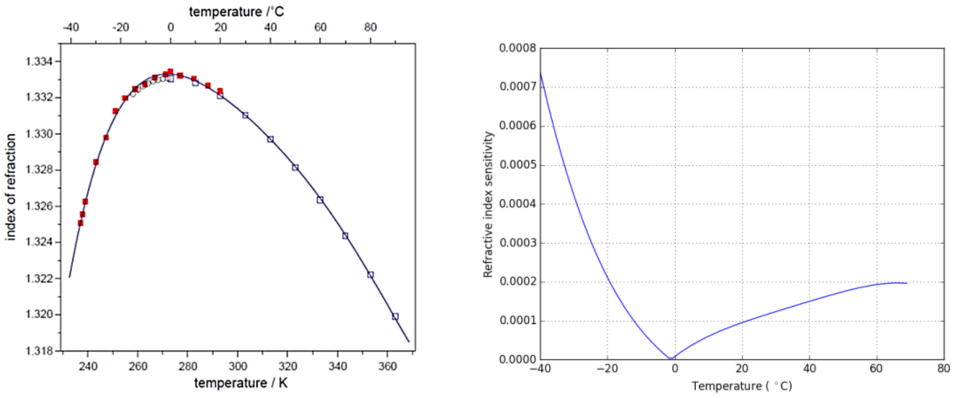


Figure 1 Comparison of refractive index measurement between GRT and refractometer for different liquid sprays.

In the super cooled condition, it is not possible to use the classical refractometer to obtain the relationship between temperature and refractive index. Then to transform water droplet refractive index to temperature, the relationship proposed by Duft and Leisner [10] is used. According to Duft and Leisner, the dependence of the water refractive index on temperature is clearly exemplified in Figure 2-a. Figure 2-a shows that the maximum value of the refraction index is obtained at a temperature of 0°C. Then, for both negative and positive temperatures, the values of the refractive index decrease. Accordingly, one measure of the refractive index value corresponds to two possible values of the temperature. Figure 2-b plots the variation of the refractive index value for a change of the temperature of 1°C between -40°C and + 70°C.

This curve underlines the facts that:

- Lowest sensitivity of temperature measurement is for droplets around 0°C.
- High sensitivity of temperature measurement is for droplets temperature lower than -20°C.

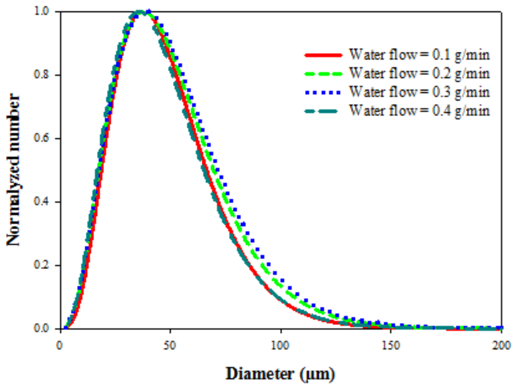


(a) **(b)**

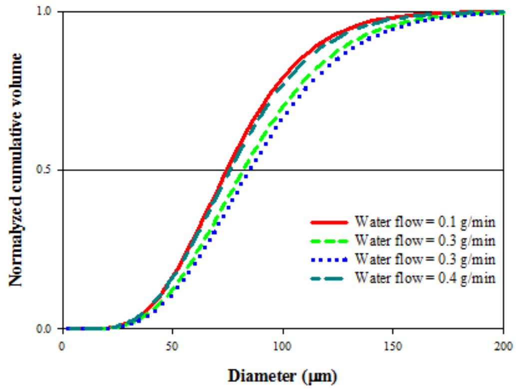
Figure 2 The relationship between index of refraction and temperature from Duft and Leisner results [9].

Size distribution validation

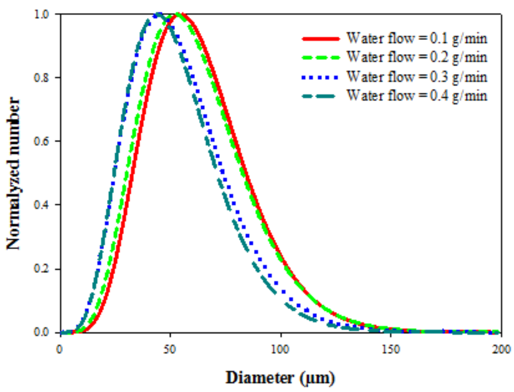
Phase Doppler Anemometry (PDA) in the Dual mode configuration from DANTEC is used to compare the size measurements by GRT technique. Standard sprays created by an ultra-sonic injector (Sonics, VCX 130, 45 kHz) with different liquid flow rates are investigated. The measurements are carried out along the spray axis, at about 5 cm from the nozzle orifice. The PDA and GRT measurements have been carried out simultaneously.



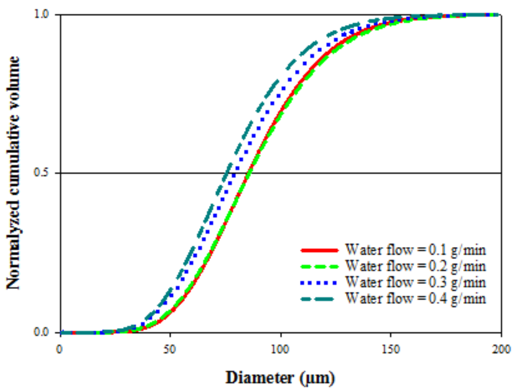
(a) Normalized size distribution by PDA



(b) Normalized cumulative volume by PDA



(c) Normalized size distribution by GRT



(d) Normalized cumulative volume by GRT

Figure 3 Comparison between PDA and GRT for size distribution measurements.

However, the measurement positions of these two techniques are shifted by 4 mm along the spray longitudinal axis. Each PDA measurement corresponds to 50,000 droplets while each GRT measurement corresponds to an average size distribution on 100 images (one image corresponds an exposure of 100 ms). The measured size distributions by PDA and GRT have been fitted by gamma function. Then, the normalized volume distributions have been computed from these gamma fitted size distributions.

Figure 3 compiles the obtained size distribution as well as the associated volume distribution for the PDA and GRT measurements. The curves are not identical but the obtained behaviors are close. The comparison of the size measurement between two techniques for different liquid flow rates is exemplified in Table 1. Table 1 compiles the maximum of the fitted size distribution (D_{max}) and the Mean Volume Diameter obtained from the fitted distribution (MVD_g). In IWT, a key parameter is MVD. This study shows that MVD_g measurements by PDA and GRT are in agreement with a difference smaller than 15%.

	PDA Measurement		GRT Measurement	
Flowrate (g/s)	**D_{max}** (µm)	**MVD_g** (µm)	**D_{max}** (µm)	**MVD_g** (µm)
0.1	37.43	75.20	54.78	85.10
0.2	37.06	82.14	52.26	85.10
0.3	36.49	84.90	45.27	79.10
0.4	35.48	76.03	44.01	75.26

Table 1 Comparisons between PDA and GRT measurements for maximum diameter (D_{max}) and MVD_g.

IWT exemplifying results

To evaluate the potential of GRT temperature measurement for icing studies in an IWT, a series of measurements have been performed at the PAG wind tunnel from DGA-EP, supported by UM-AMS. Figure 4 is a schematic view of the PAG facility while the table 2 compiles the principal performances of the PAG icing wind tunnel.

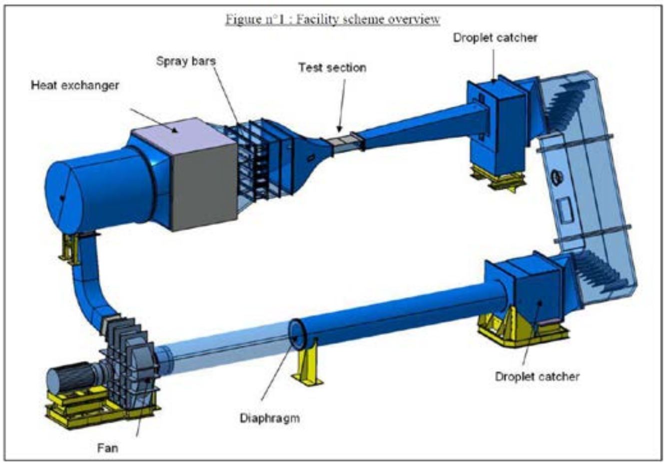


Figure 4 Scheme of the PAG facility at DGA-EP.

Test section	200 x 200 mm
Air mass flow rate	2 to 10 kg/s
Speed (empty test section)	50 to 220 m/s
Mach number (with -15°C)	0.70
Liquid Water Content	0.15 to 3 g/m^3
Total Air temperature	-40 to +15 °C
Median Volume Diameter	15 to 50 µm

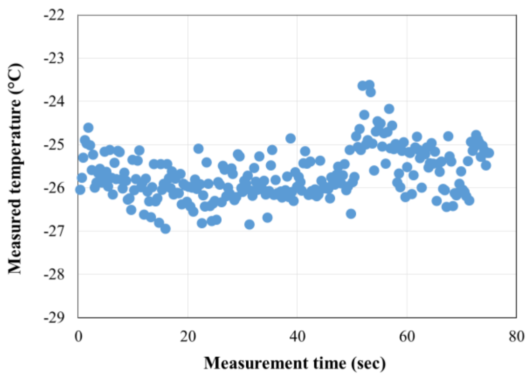
Table 2 The principal performances of PAG facility.

Figure 5-a displays the behavior of the droplets temperature versus the time for three different values of hygrometry (100, 150 and 200 %). It will be noted that, for this particular configuration, the droplet temperature looks to be independent of the hygrometry level.

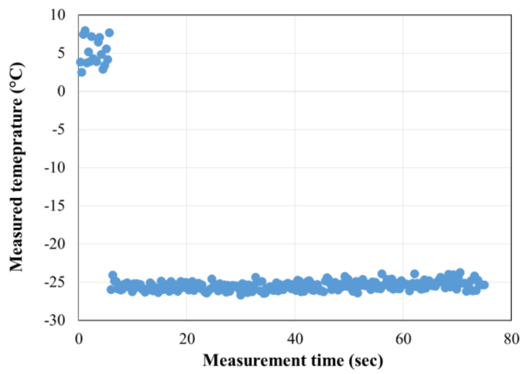
Figure 5-b displays the behavior of the droplets temperature versus the time for two values of the MVD. It is evident that the droplet temperature depends strongly on the droplet size. The decreasing of the droplet size from a MVD equal to 40 µm to a MVD equal to 20 µm leads to the decreasing temperature of about 20°C.

Figure 5-c displays the behavior of the droplets (MVD = 20 µm) temperature versus the time when the air velocity is increased progressively from 150 m/s to 200 m/s. The shape of the curve is the same than the shape of the curve of the velocity. It will be noted than in that case, the droplets temperature increases of about 12 °C.

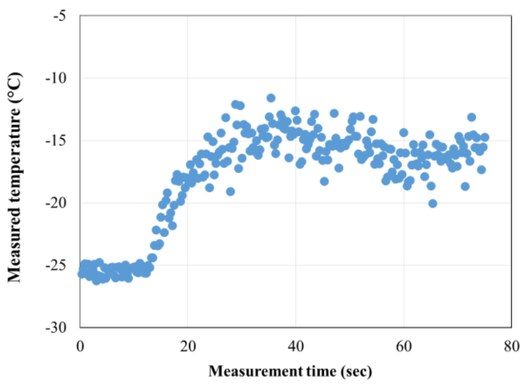
Figure 5-d displays the behavior of the droplet refractive index measurement when the liquid droplets are freezing according with a modification of the IWT working point. This behavior can be sorted in three zones. In a first zone, the droplets are liquid. The refractive index is stable corresponding to a stable temperature of about -15°C. Then, the IWT working condition is changed to create ice crystal. In a second zone, the droplets temperature decreases rapidly. Finally, in a third zone, the rainbow structures of the scattered light disappear leading to misinterpretation by the inversion code. Accordingly, the measured refractive index values present a chaotic behavior with large and fast variations. This behavior is a signature of frosts particles with a non-spherical shape.



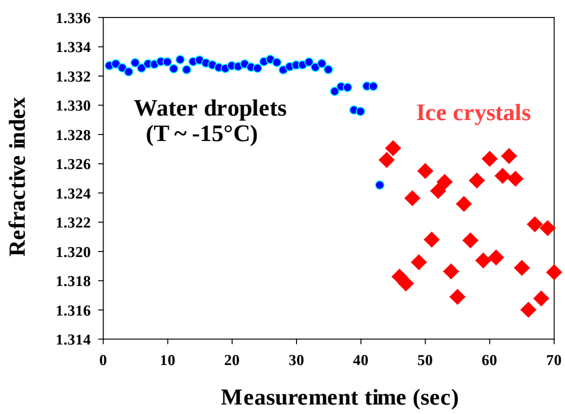
(a) Vary hygrometry (100, 150 and 200 %)



(b) Vary droplets size (MVD from 40 to 20 µm)



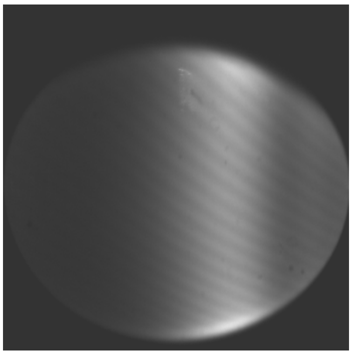
(c) Vary flow velocity (150 to 200 m/s)



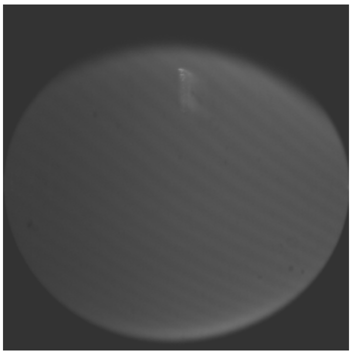
(d) Water droplets state change (from liquid water→ice→water)

Figure 5 Temporal evolution of the droplet temperature versus time for different configurations of the wind tunnel.

This analysis is supported by the observation of the recorded images of the scattered light distribution at rainbow angle as displays in figure 6. Figure 6-a displays the recorded light scattering for a spherical liquid droplet. The rainbow pattern is clearly visible. On the contrary, figure 6-b displays the recorded light scattering for a frozen droplet. The light distribution is essentially ‘uniform’; no rainbow pattern can be identified.



(a) Global rainbow image for liquid droplets



(b) Global rainbow image for iced droplets.

Figure 6 Examples of the light scattered by liquid droplets and by iced crystal at the rainbow angle.

Summary and Conclusions

The measurement of droplet temperature in an Icing Wind Tunnel (IWT) is a challenge. In this presentation, it is demonstrated that the Global Rainbow Technique (GRT) is a potential technique to answer this challenge.

In a first part of the contribution, it is proved that the GRT measures accurately refractive index with the accuracy on the 4^{th} decimal. This measurement accuracy is sufficient to measure the droplet temperature with an accuracy of better than few degree for droplets temperature lower that -20°C. Moreover, the measured size distribution by GRT is in agreement with PDA. The comparison of means volume diameter (MVD) between PDA and GRT is better 15%.

In a second part, the GRT device has been successfully applied in a real IWT (PAG IWT at DGA-EP, Paris). The dependences of the droplet temperature with the droplet size, air flow velocity, and hygrometry have been quantified as well as the water phase change from liquid to ice.

The challenge now is to extend the working condition to lower liquid water content (LWC).

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