GLOBAL RAINBOW THERMOMETRY APPLIED TO A FLASHING TWO-PHASE R134-A JET

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ABSTRACT

Two-phase flows hold an interest in many areas of science and engineering. In the safety field, one such topic is the accidental release of flammable and toxic pressure-liquefied gases. In case of such a release, a flashing vapor explosion takes place resulting in a very dense two-phase cloud. In particular, if the released substance is flammable, this cloud can be combustible and can lead to deflagration or detonation. For understanding the source processes of flashing and risk assessment, data related to cloud characteristics (i.e. droplet size, velocity, temperature) is needed especially in the near region of the release. Due to the non-equilibrium nature of the near field regions accurate data measurement is not possible with intrusive techniques. Therefore, laser-based optical techniques like Global rainbow Thermometry (GRT) and Phase Doppler Anemometry (PDA) are tempted. The main object of the present work is to assess the mean size and temperature evolution along a flashing two phase R134A jet. GRT gives a smaller mean diameter than PDA because GRT measures only the most spherical thus smaller droplets. The temperature evolution by GRT differs much from thermocouple measurements.

1. INTRODUCTION

Wide ranges of industrial processes operate at high pressures such that the process fluids are in supercritical state with respect to the ambient surroundings. Hazardous situations can occur in the case of accidental release caused by equipment and/or operator failure. In case of such a release, a flashing vapor explosion takes place resulting in a very dense two-phase cloud. In particular, if the released substance is flammable, this cloud can be inflammable and can lead to deflagration or detonation.

Thermal non-equilibrium is necessarily present in flashing situations, i.e. when changes in the system pressure result in superheating of the liquid and production of vapor. Under adiabatic conditions, the vapor formed can obtain its latent heat of vaporization only at the expense of the sensible heat of the remaining liquid. Because of the relatively large vapor pressure of the material, a combination of fluid dynamics and thermodynamics instabilities will then lead to break-up into small droplets. Equilibrium will be reached when the fraction of the liquid converted to vapor has extracted enough energy from the residual liquid. This creates drastic temperature changes along the flow field. The harsh experimental environment leads us to apply techniques like Global rainbow Thermometry (GRT), which is non-intrusive and gives information both about the droplet size and temperature. In 1999, van Beeck et al. (1999), have presented the principle of the GRT technique. GRT aims at measuring the mean size and temperature of spray droplets. In this paper, the local mean values measured in a flashing spray will be presented. The results are compared to that of Phase Doppler Anemometry and thermocouple measurements.

2. FLASHING MECHANISM

When a liquid is at a temperature above the saturation temperature for its pressure, it is superheated and is out of thermodynamic equilibrium. In a static situation and under carefully controlled conditions (pure substance, perfectly clean and smooth vessel and no physical disturbances) it is possible for a liquid to be maintained in this meta-stable state. Under most practical circumstances, however, the ideal conditions cannot be met and the meta-stable liquid will return to its equilibrium condition through evaporation, thus releasing its superheat as latent heat.

Thermal non-equilibrium is necessarily present in flashing situations. Under adiabatic conditions, the vapor formed can obtain its latent heat of vaporization only at the expense of the sensible heat of the remaining liquid. A liquid at its saturation temperature and pressure can gain superheat in one of two ways: it can be heated to a higher temperature while its pressure is maintained, or it can be depressurized rapidly so that its thermal inertia ensures the internal temperature remains nearly constant and above its new saturation temperature. In the former case, the higher temperature will be at the interface of the

liquid and its surroundings, and evaporation, when it occurs, will be at the interface. In the latter case, the highest temperature will be inside the liquid and evaporation will tend to be from within.

As claimed by Owen (1991), if the superheat within the depressurized liquid can be conducted to the liquid surface, the latent heat will be released through surface evaporation. If, however, the heat cannot be conducted at a sufficiently high rate to the surface, evaporation will occur within the liquid through bubble growth. This process can be extremely violent and explosive. Because of the relatively large vapor pressure of the material, a combination of fluid dynamics and thermodynamics instabilities will then lead to break-up into small droplets. Figure 1 shows a general view of a two-phase flashing jet. Equilibrium will be reached when the fraction of the liquid converted to vapor has extracted enough energy from the residual liquid.

Figure 1 A general view of the two-phase flashing jet

The initial, flashing stage of the jet, where the system is furthest from an equilibrium is least understood and there is a need for accurate and reliable data in order to generate and/or refine useful mathematical models and computer codes. Due to the non-equilibrium nature of the near-field regions accurate data measurement is not possible with intrusive techniques such as thermocouples. Non-intrusive methods, such as laser-based techniques present the only possibility for obtaining accurate data measurements in this environment even though dense particle concentration can obscure seriously optical access.
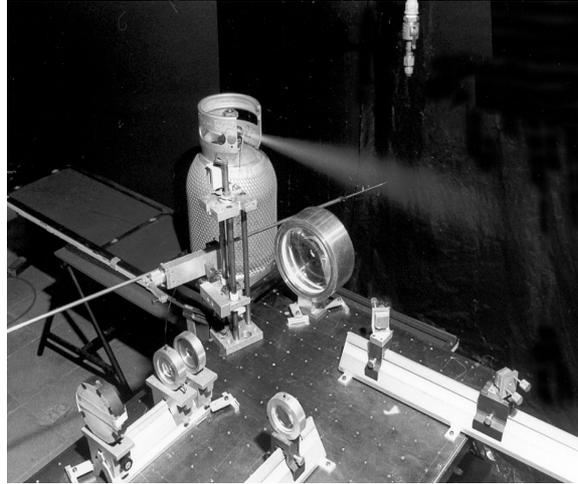
3. GLOBAL RAINBOW THERMOMETRY

Since 1988, rainbow thermometry has been investigated by Roth et al. (1988), Sankar et al.(1993), van Beeck and Riethmuller (1994). Up to now, the rainbow technique measures the temperature and size of individual droplets. Even though the technique has been applied in the field of spray combustion by Sankar et al (1996), confidence could not be established because of major problems. These are related to the temperature gradient inside the droplet (Massoli (1998), Anders et al. (1995), Corbin et al. (1996)), droplet nonspericity (vanBeeck and Riethmuller (1995)) and a ripple structure that strongly perturbs the rainbow interference pattern, from which one deduces the droplet parameters (Massoli (1998)).The last two problems are solved by global rainbow thermometry. Especially the fact that there is a solution for the nonsphericity problem is an important innovation, because until now a droplet nonsphericity of 1% could lead to an error in the temperature measurement of 40° C. During the passed years, several algorithms for detection of spherical droplets were proposed but neither of them were sufficiently general. (Sankar et al. (1996), van Beeck and Riethmuller (1996))

Global Rainbow Thermometry is presented. It is a new technique for measuring average size and temperature of spray droplets. For data inversion a global rainbow pattern is employed, which is formed by constructive interference of laser light scattered by an ensemble of spherical droplets. The non-spherical droplets and liquid ligaments provide a uniform background and thus do not influence the interference pattern from which average size and temperature are derived. This is a large improvement with respect to standard rainbow thermometry, investigated since 1988, which is strongly influenced by particle shape. Moreover, the technique is applicable for smaller droplets than the standard technique because the global pattern is not spoiled by a ripple structure.

Global rainbow thermometry (GRT) primarily aims at eliminating the non-sphericity effects that exists for the rainbow technique since its invention in 1988. The basic principles of GRT have been published by (van Beeck et al., 1999).

3.1 Experimental set-up

Figure 2 shows a picture of the experimental setup. A vessel that was pressurized under 6.6 bars at 25ºC is used to create a two-phase flashing jet at atmospheric pressure. The measurements are taken along the jet axis. The nozzle diameter is 5mm. A CW Argon-ion laser beam is expanded and directed towards the R134-A flashing spray by a system of lenses and mirrors. The typical laser power for this spray is 100 mW and the beam is expanded to a thickness of 15 mm. A large-diameter lens receives the back-scattered light of all the droplets that cross the laser beam. At the image plane of this lens a pinhole spatially filters the laser beam and thus selects a probe volume of about ± 1 cm^3. Only the droplets passing this volume will contribute to the rainbow that is projected on a semi-transparent screen, which is recorded from the other side by a digital video camera. The use of a transparent screen makes the alignment of the video camera to a minor issue. To calibrate the magnification factor of the camera, one records a millimeter paper that is attached to the screen. Subsequently, the relationship between pixel number and the scattering angle is found via the focal length of the lens system.

Figure 2 Experimental setup of Global Rainbow Thermometry and thermocouple

The position of the rainbow on the screen depends on the refractive index of the droplets, thus on their temperature. The interference fringes that are seen in the rainbow pattern can be related to the droplet size without prior knowledge of droplet temperature. As such, both parameters can be obtained quasi-independent from each other.

3.2 Principles of GRT

A typical global rainbow interference pattern created through a water spray is seen in Figure 3. The pattern is recorded while the probe volume is positioned in the core of the spray. One can observe several Airy fringes, also called supernumerary bows, which are formed through interference of internally-reflected rays. The pattern of Figure 3 is stable, i.e. the Airy fringes are not moving in time. This should imply that the pattern is formed by constructive interference of the spherical droplets, because for each of them the rainbow position is identical. Destructive interference occurs for the non-spherical droplets and liquid ligaments, because their respective rainbow patterns are randomly oriented and thus yield a uniform background. Consequently, there is no need for complex selection criteria to look for rainbow patterns from spherical droplets. The selection of spherical droplets is done automatically, just like the rainbow in the sky, which is a static phenomenon, even though numerous raindrops are not spherical.
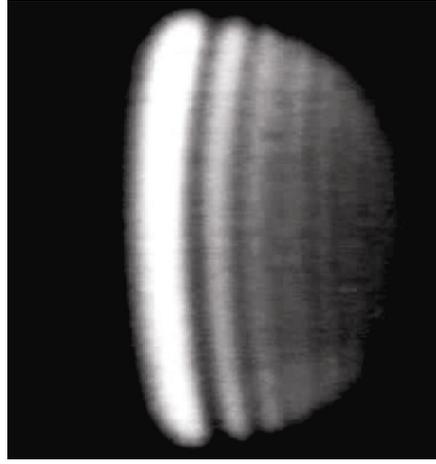
Figure 3 A typical global rainbow interference pattern created through a water spray

Besides the fact that the global rainbow pattern is formed by spherical droplets only, it is interesting to notice that the visibility of this pattern is reduced compared to that formed by a single droplet. Ripple structures cannot be observed at all in the global rainbow patterns. These ripple structures contain no temperature information and thus can only deteriorate the accuracy of the temperature measurement; for a single droplet smaller than 30μm, the uncertainty in the temperature measurement exceeds already ± 6ºC when using standard rainbow thermometry (Sankar et al.(1996)). Therefore, the fact the ripple structure does not appear in the global rainbow pattern is very favorable for an accurate detection of the Airy fringes, from which droplet size and temperature are derived. The disappearance of the ripple structure has already been discussed by Roth et al. (Roth et al. (1991), Roth et al. (1992)). These authors studied the mean scattering diagram of a polydispersed burning droplet stream. A droplet size variation of less than 1μm made the ripple structure to vanish completely. However, the authors made no comments on the natural selection of spherical droplets by means of this global interference pattern.

Data inversion algorithm

From the simulations of the global rainbow pattern using the Airy theory (van Beeck et al. (2001)), one can evaluate what kind of mean diameter and temperature is obtained from the global rainbow. The aim is to look for a data inversion algorithm that is independent of the spray-dispersion parameter σ. Different schemes have been studied in the past. They vary in the characteristic information deduced from the signal. The most interesting results are obtained for the data inversion algorithm based on the inflection points around the main rainbow maximum (see Figure 4), i.e. θ_{inf1} and θ_{inf2}. The relationship between these points and $D_{rainbow}$ and θ_{rg} can be constructed analytically from the Airy theory applied to a single droplet (vanBeeck 1997). For a R134a droplet, whose refraction index *m* is equal to 1.206, in air it follows:

$$D_{rainbow} = 823.14 \cdot \lambda \cdot \left(\theta_{\inf 2} - \theta_{\inf 1}\right)^{-3/2}$$

$$\theta_{rg} = \theta_{\inf 1} - 18.62 \cdot \left(\lambda / D_{rainbow}\right)^{2/3}$$

θ_{rg} is the so-called geometrical rainbow angle, which depends only on the refractive index, thus on the droplet temperature, and is therefore an important parameter for the rainbow technique. Roth and al. (Roth 1996) already noted that θ_{inf1} lies very close to θ_{rg}; hence the first inflection point is a good indicator for the droplet temperature, especially when corrected for the (small) diameter effect. Note again that the diameter determination is independent of the droplet temperature. One hopes that above formulas do not only apply to a single droplet but also to an ensemble of droplets. This means that $D_{rainbow}$ and θ_{rg} should yield physically meaningful average quantities, which is addressed hereafter.
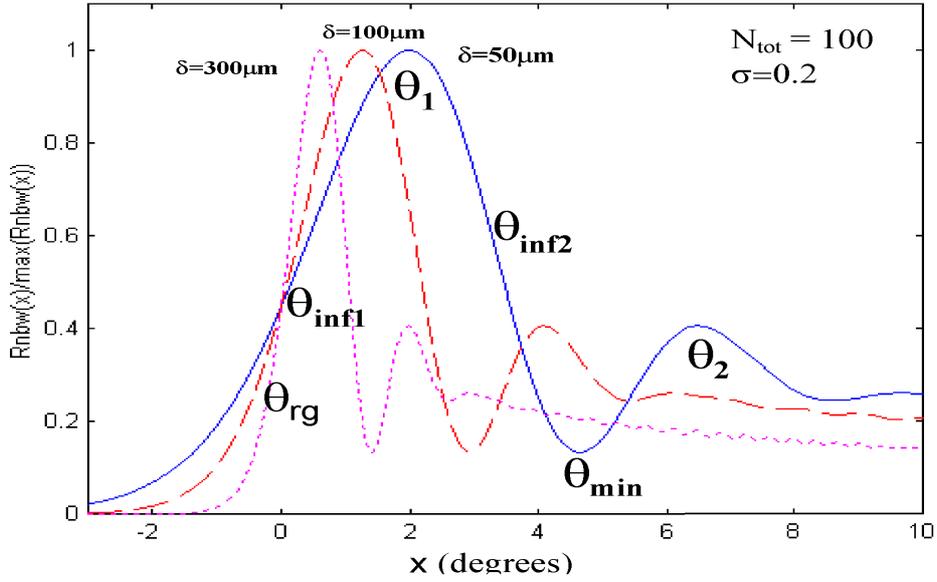
Figure 4 Simulations of global rainbow patterns for different mean diameters at constant dispersion σ. Furthermore, x=θ-θ$_{rg}$. The two inflection points θ$_{inf1}$ and θ$_{inf2}$ serve to find the droplet diameter D$_{rainbow}$ and θ$_{rg}$, thus the droplet temperature

Figure 5 shows $D_{rainbow}$ as a function of σ for δ=100 μm. $D_{rainbow}$ exceeds the Sauter mean diameter D$_{32}$ considerably. This is related to the decrease of the width of the principal rainbow maximum when σ increases(van Beeck et al.,2001a). Figure 6 depicts for different diameters the deviation of θ_{rg} from its value at σ=0 . This deviation is never larger than 0.025˚,which means that algorithm ensures an accuracy in the temperature measurement of less than ± 1ºC, in case of water droplets, and even less for e.g. Diesel sprays.

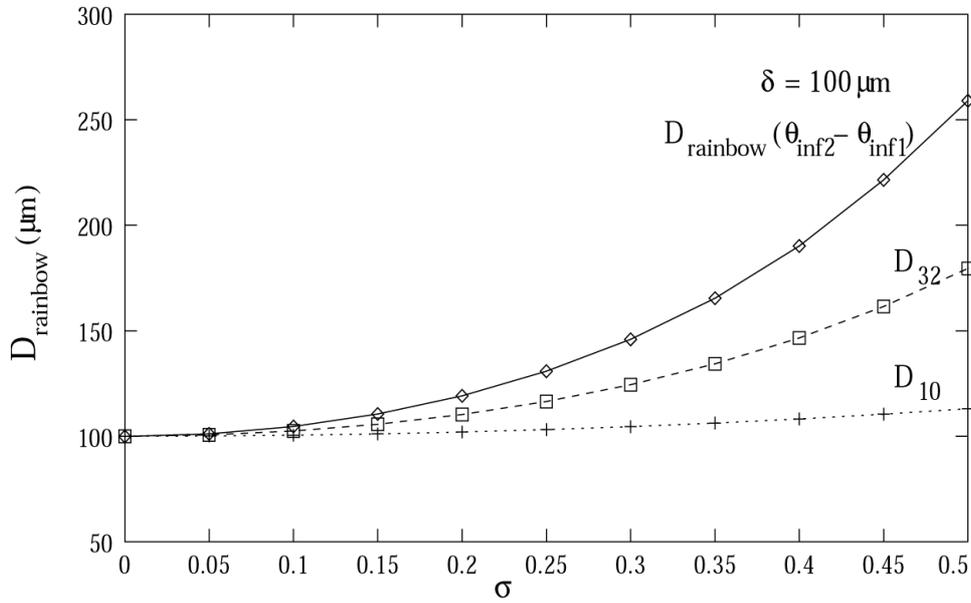Figure 5 *The rainbow diameter, computed from the θ$_{inf2}$-θ$_{inf1}$, as a function of spray dispersion σ for various amount of droplets, N$_{tot}$.*
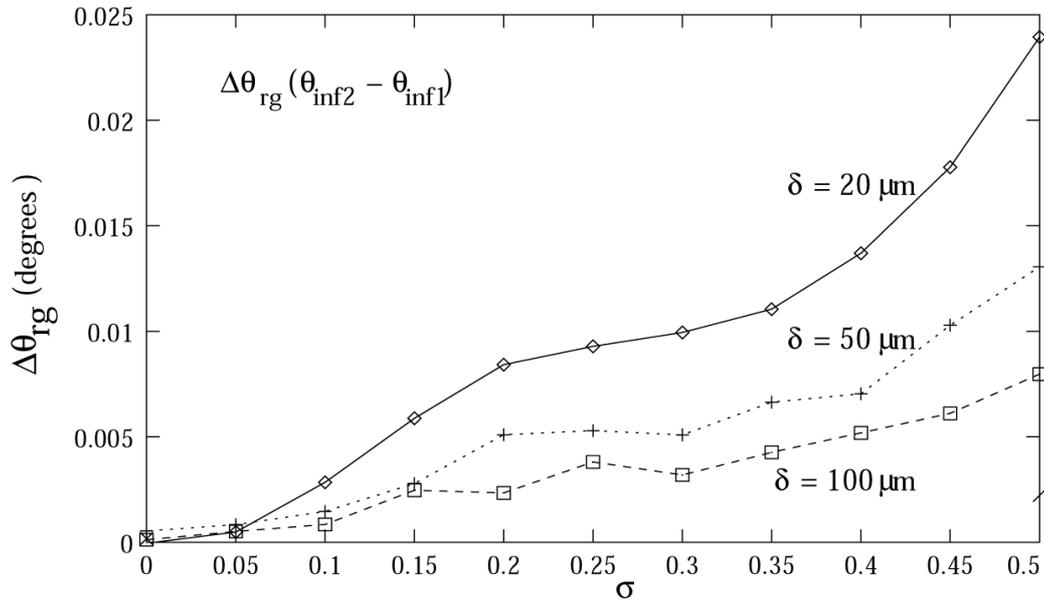
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Figure 6 The deviation of θ_{rg}, based on θ_{inf2} and θ_{inf1}, from its value at $\sigma=0$, as a function of σ for different mean diameters δ

4- RESULTS

A spray from R134a was analyzed for centerline drop size and temperature information using Global Rainbow Thermometry, Phase Doppler Anemometry (PDA) and thermocouples.

Figure 7(a) shows the global rainbow pattern of a flashing R134a jet at 8 cm far away from the nozzle. Comparing the image to the water spray global rainbow pattern in Figure 3, it is easily seen that the Airy fringes are hardly seen due to the large range in droplet sizes. Figure 7(b) shows a GRT pattern at 40 cm far from the nozzle generated by a single droplet.
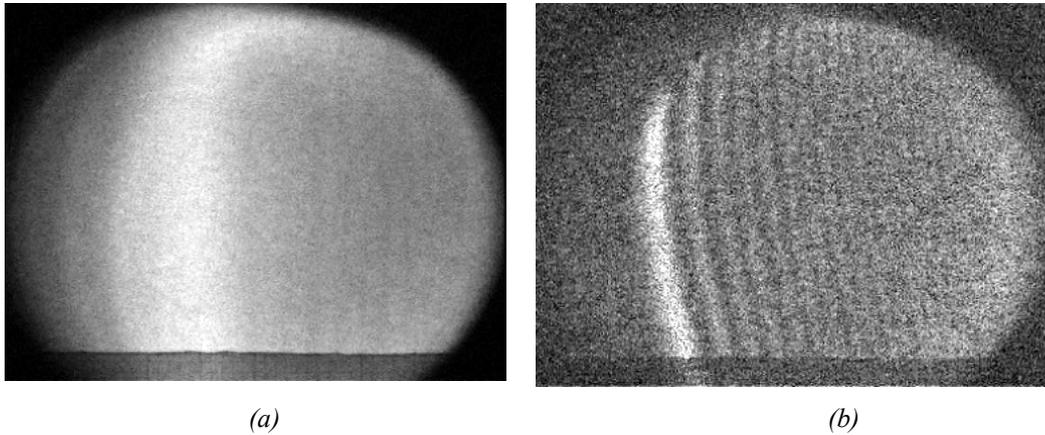

(a)   *(b)*

Figure 7 R134A global rainbow pattern close to the nozzle (a) and at 40 cm from the nozzle(b)

Figure 8 shows the rainbow profiles at different axial locations from the nozzle starting from 8 to 40 cm. The droplet temperature is deduced from the inflection points of the main peak in the rainbow pattern. Assuming a lognormal droplet size distribution, GRT measures a mean diameter that should be larger than the Sauter mean diameter, D_{32}, provided all droplets are spherical. (Figure 5)
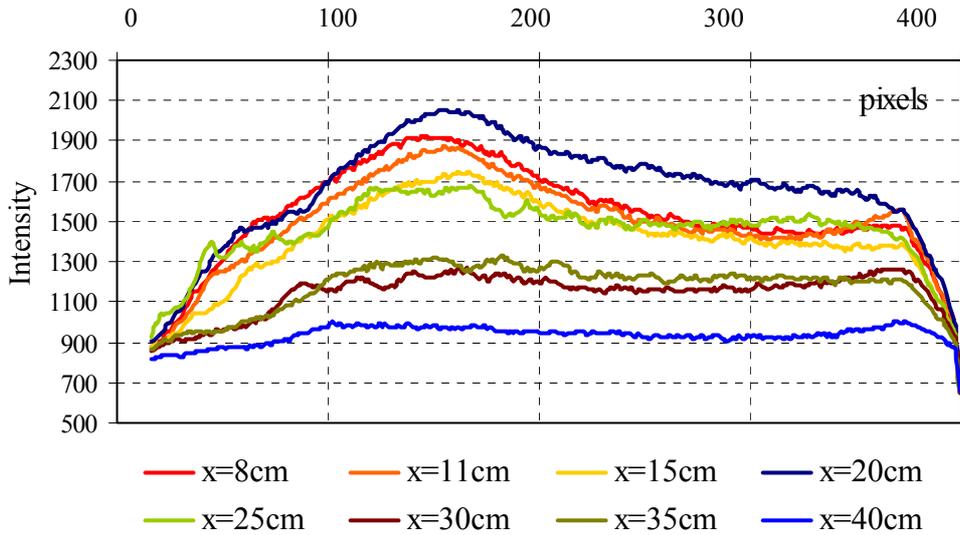
Figure 8 Global rainbow patterns at different positions from the nozzle

Figure 9 shows the behavior of the droplet diameters on the jet axis in comparison between PDA and GRT concerning the arithmetic mean diameter D_{10} and D_{32}. PDA results show that D_{32} and D_{10} approach each other, i.e. the droplet size distribution becomes narrower. The mean diameter obtained by GRT is closer to D_{32} further away from the nozzle, but is always smaller than the value measured by PDA. This is in agreement with previous results in a water spray (De Giorgi et al. (2001)), where it was shown that only the most spherical, thus smaller droplets were measured by GRT. Obviously, droplets tend to be more spherical further from the nozzle.
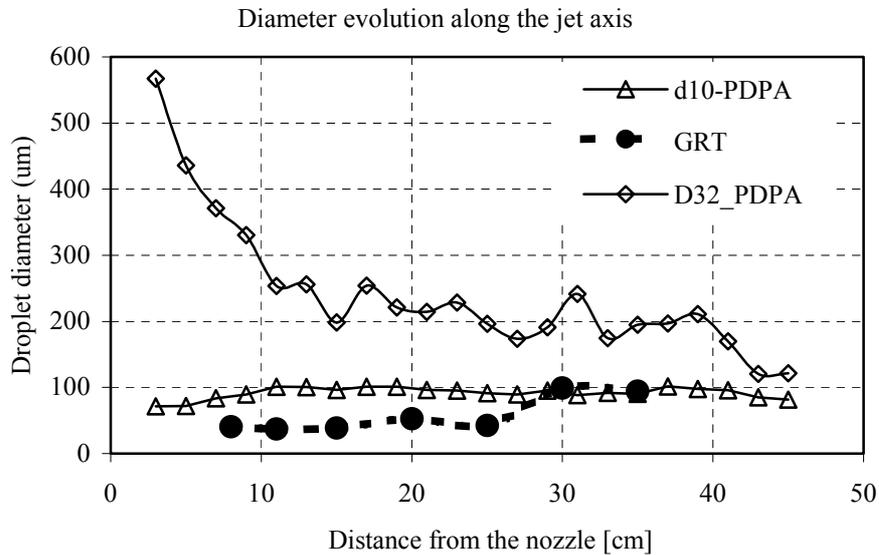

Figure 9 Comparison between Global Rainbow Thermometry (GRT) and Phase Doppler Anemometry (PDA) in terms of D_{10} and D_{32}

Figure 10 compares GRT with thermocouple measurements for a high and low flow rate. The GRT measurement points furtherst downstream are fitted to the thermocouple measurements due to the present lack of absolute temperature measurement by GRT. For both flow rates, the temperature evolutions are opposite to the thermocouple measurements. The uncertainty in the inflection point determination results in a temperature uncertainty of ± 20ºC, which is however not sufficient to explain the opposite trend. The explanation is believed to be related to the internal temperature gradient inside the droplet, to which Rainbow Thermometry is very sensitive and apparently also GRT. This gradient is present especially during the initial rapid cooling phase of the droplet, which is more important for the low mass flow rate.

This can be explained by the fact that for this flow rate, the droplet size is bigger, hence temperature inhomogeneities are less quickly leveled out. Similar problems with rainbow thermometry have been encountered in the initial heating phase of a burning fuel droplet stream. (van Beeck et al, 2001b). More measurements should be performed to quantify the gradient effect in GRT in order to cure it.
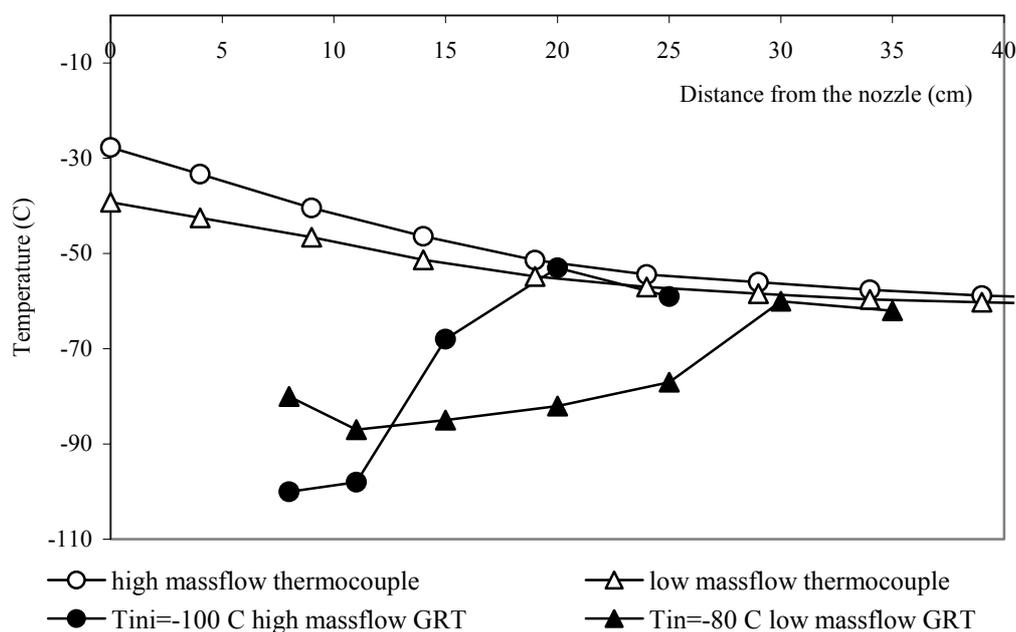

Figure 10 Relative temperature obtain with Global Rainbow Thermometry

5. CONCLUSIONS

Global Rainbow Thermometry gives a means to perform instantaneous measurements of global spray parameters. Applications of the rainbow technique lie in domains where an alternative to PDA size measurements is looked for and where a temperature uncertainty of a few degrees Kelvin is acceptable, like in flashing flows and spray combustion research. The technique is based on the processing of a rainbow formed by a local ensemble of droplets. GRT can be applied in harsh environments where non-spherical droplets and/or liquid ligaments are encountered. However, this paper has shown that GRT does not solve the high measurement uncertainty related to strong internal temperature gradients encountered in big droplets. Also is the general trend that the droplet size measurement by GRT is smaller than that by PDA due to the fact that GRT sees only the most spherical, thus the smaller droplets.

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