Global Rainbow Thermometry in a liquid-liquid suspension

M. R. Vetrano, J.P.A.J. van Beeck

Von Karman Institute for Fluid Dynamics, Chaussée de Waterloo 72, B – 1640 Rhode Saint Genèse, Belgium

Abstract

This paper is dedicated to show the application of the Global Rainbow Thermometry technique to liquid-liquid suspension. Moreover, the experimental validation of the Global Rainbow Thermometry (GRT) technique will be shown. This validation has been performed through an original experiment, in which the droplet size and temperature of liquid droplets, suspended in a liquid bulk, can be independently measured.

1. Introduction

The Global Rainbow Thermometry (GRT) technique is used to measure some characterising parameters of particular two-phase flows. As matter of fact, the GRT technique can be used to measure the diameter and temperature distribution of liquid droplets suspended in a liquid or gaseous environment. One of the requirements to apply the technique is to provide that the relative index of refraction between the guest and the host is grater than one. The liquids transparency and the immiscibility rate in the case of a liquid-liquid suspension are also important for the technique application. One has to find the Rainbow Thermometry technique principle in the light scattering phenomenon. As well known, the rainbow in the sky is a natural phenomenon produced by the interaction between the sunlight and the water droplets present in the atmosphere. The sunlight is scattered and decomposed in its spectral components by the droplets producing seven bands of different colours. In the laboratory tests the rainbow assumes a different aspect.

When a monochromatic laser beam illuminates a water droplet, suspended in air, an interference pattern can be observed if one looks at infinity along a specified angle range called '*scattering angular range*'. The fringe pattern moves along the scattering angular range as a consequence of changes in the droplet temperature while the width of the fringes depends only on the droplet diameter. The technique that permits the determination of the droplet temperature and size from the interference fringe analysis is called Standard Rainbow Thermometry (SRT) [1]. The GRT technique represents the extension of the SRT to multiple droplets. Some improvements to the standard technique can be found in the global one. In the SRT technique the light reflected by the droplet surface generates a ripple structure that for very small droplets represents a big perturbation in the pattern analysis. Also the possible non–sphericity of the droplets constitutes an important challenge of the

standard technique. The effect of a non–spherical droplet on the standard pattern is to shift and distort it, making the analysis of the interference pattern impossible [2].
The GRT technique has been already applied to characterize water sprays [3]. Other applications can be considered such as the characterization of spray flame in which mean size and temperature of fuel droplets can be measured in complex spray flames. This would allow to validate advanced theoretical spray combustion models that are used in the design of fuel-efficient combustors. Application of the GRT to liquid–liquid dispersions like those used in liquid-liquid extraction processes are also possible. In this paper the GRT technique will be applied to liquid-liquid suspension and new efforts in the validation of the technique will be presented.

2. Theory

The theoretical approach used is a hybrid one in which geometrical optics is used to study the interaction of laser light with liquid droplets and the Airy theory is employed to study the rainbow interference fringes.
In this paper we will not go in the details of the theoretical approach, only the basic equations will be presented. A complete discussion can be found in the reference [4].
Using the Airy theory the light intensity of the fringe pattern generated by each droplet in the observation point, Ω^2_{Rnbw}, can be expressed using equation 1,

$$\Omega^2_{Rnbw}(z(\theta)) = \left| 2 \cdot c \cdot Airy\left(\left(\frac{12}{\pi^2} \right)^{1/3} \cdot z(\theta) \right) \right|^2 , \quad (1)$$

The quantity z(θ) is a non dimensional parameter denoting the normalized angular deviation from the geometric rainbow angle. In the extension of this theory to multiple droplets hypotheses on the probability distributions of the physical properties of the droplets are necessary.
In the present case the probability distribution for the droplet size is assumed to be lognormal, while for the droplet temperature and non-sphericity a Gaussian distribution is used. The GRT signal can be expressed by equation 2,

$$Rnbw(\theta, D, \sigma_D, T, \sigma_T, \sigma_R) = \sum_{k,i,j} \Omega^2_{Rnbw}(z(\theta, D_j, R_i, T_k)) \cdot D_j^{7/3} \cdot \xi(T_k)_{\overline{T},\sigma_T} \cdot \zeta(R_i)_{\overline{R},\sigma_R} \Delta T \Delta R . \quad (2)$$

Simulations have been performed in order to analyse the effects of the mean value and the dispersion factor of the probability distributions assigned to the variables D, T and R. These simulations demonstrate how the changes of the mean value of the probability distribution result in a shift of the simulated GRT pattern while the variations of the probability distribution dispersion factor produce a smoothing effect on the pattern. The data inversion algorithm uses the least square fit method to compare the experimental rainbow pattern with the simulated one minimizing the square of the difference between the two signals.
From this minimization process the distribution for the temperature, the size and the non-sphericity of the droplets can be directly found.

3. Liquid suspension

The Global Rainbow Thermometry technique has been applied to liquid-liquid suspensions in order to measure the diameter and temperature distributions of droplets generated by agitation in a mixture of two immiscible liquids. The liquids that have been used are respectively water for the host and silicon oil for the guest. The results obtained with the

GRT technique have been validated using other measurement techniques. The liquid-liquid suspension is in isothermal conditions, so the droplets temperature can be measured by means of a thermocouple immersed in the liquid bulk, while the droplet size can be measured by direct observation with a camera. Using these techniques the validation of the Standard Rainbow Thermometry technique, in a liquid-liquid suspension, was already been performed [5]. The Global Rainbow Thermometry measurements have been performed using the experimental set-up depicted in fig.1. An Argon laser beam, expanded by means of two lenses, illuminates a squared reservoir filled with a mixture of water and silicon oil. A stirring agitator placed inside the mixture creates the suspension. 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 an aperture, is placed in order to select a probe volume. The droplets passing this volume will contribute to the rainbow image that is projected on a semi-transparent screen and recorded by a CCD camera. The mixture temperature is measured by means of a thermocouple.

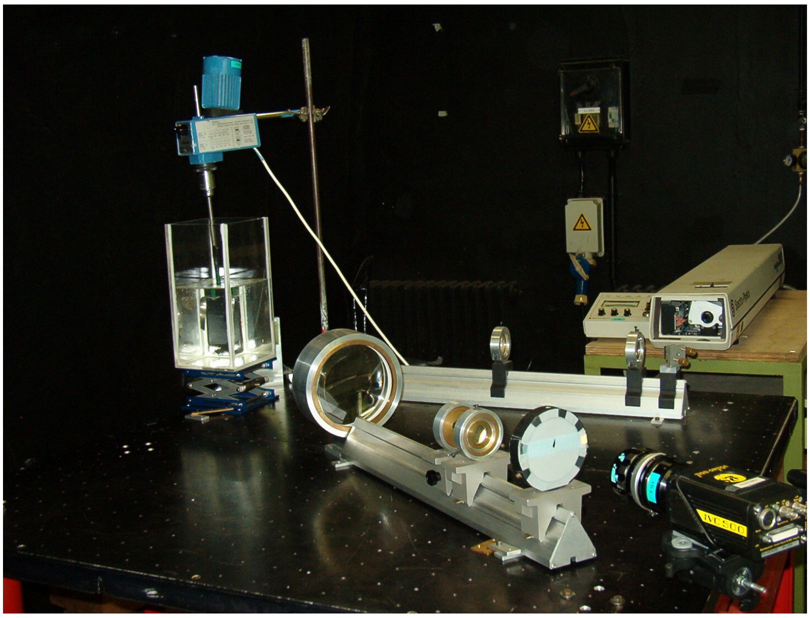


Fig.1 –GRT set-up for liquid-liquid suspension characterization

In this paper results on the temperature and size distribution of two different suspensions will be presented. These two differ for the guest liquid viscosity. In one case, silicon oil of 50cSt of viscosity has been used; in the other the oil has a viscosity of 100 cSt. These two oils correspond respectively to a refractive index of 1.404 and 1.405 at 20°C. An example of rainbow interference fringes produced using the GRT technique is shown on figure 2. On such interference figure the relative intensity pattern is represented.
The post processing of the interference images consist in the subtraction of the background light and in the evaluation of the intensity levels along one pixel line. The intensity pattern is filtered in order to cut the noise and through an angular calibration, that takes into account the deformation of the interference image due to the shape of the container, the absolute angular position of the rainbow image in the space can be obtained. The patterns obtained have been simulated with the algorithm proposed in the previous section. The values of the droplet diameter and temperature are directly extrapolated by the optimised simulated pattern. On figure 3 the comparison between the experimental GRT pattern and the optimised simulated one is presented.

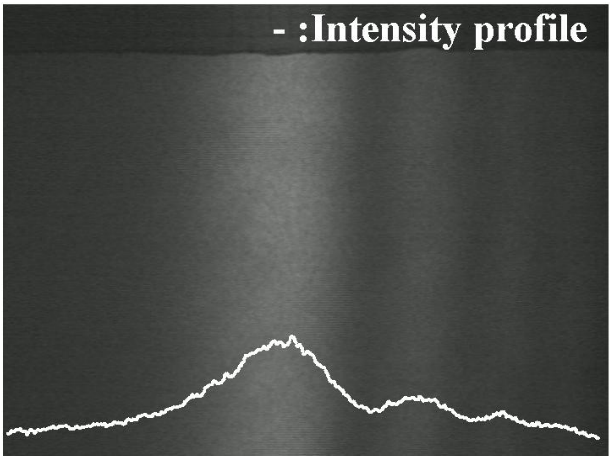
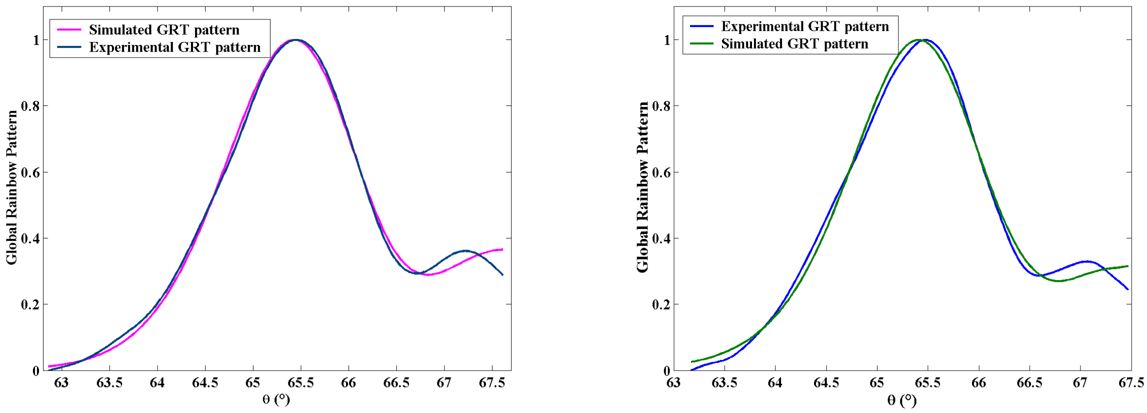


Fig.2 – GRT interference fringes and relative intensity pattern



(a) (b)

Fig.3 – Experimental-simulation comparison for two different mixtures: a)ν=50 cSt, b))ν=100 cSt.

4. Global Rainbow Thermometry validation

In order to validate the results obtained for the size distribution with the GRT technique, images of the oil droplets have been taken using a back light scattering technique. An additional camera has been used in the set-up. This one is a camera with a shutter time up to 100 μs. A so small shutter time has been used in order to provide still images of the oil droplets. After having been checked that the probe volume observed by the high shutter camera was the same used for the GRT, the camera has been calibrated taking a picture of a ruler put in the object plane.

In figure 4 an example of such images is presented.

A series of droplets images have been taken in order to have a good statistic for the droplet size distribution. During the post-processing of the images only the droplets in focus have been taken in account and through numerical filters their diameters have been obtained. On figure 5 the diameter distribution of the silicon oil droplets that generate the GRT fringe pattern of figure 3 is represented. The statistics are made on 270 droplets. As it is possible to see, the droplet size distribution is mostly Gaussian and corresponds to a mean value of 783.5 μm and a dispersion factor around it of 260 μm.

The diameters, obtained through the post processing of the droplet images are referred to the horizontal one, no matter the possible droplet non-sphericity.

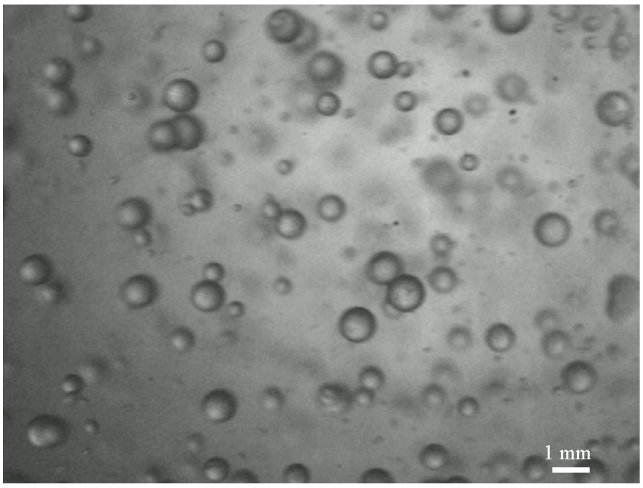


Fig.4 – Image of silicon oil droplets suspended in a water bulk

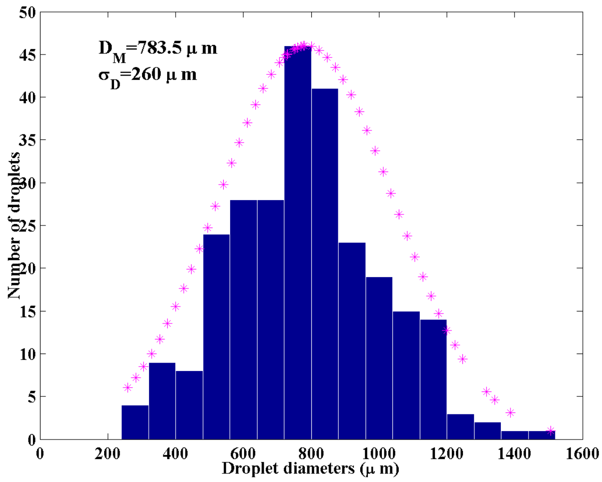


Fig.5 – Droplet size distribution

In table 1 the results for the droplets size distribution obtained with GRT technique are presented. The results obtained for the silicon oil of 100 cSt of viscosity through the droplets image analysis have also been reported.

Oil viscosity	D_{Rnbw} [μm]	D_{DO} [μm]	σ_{DRnbw} [μm]	σ_{DDO} [μm]
50 cSt	813.7		0.36	
100 cSt	738.9	783.5	445.8	260

Table.1 – Experimental results for the droplets diameter

The results agreement regarding the droplet size mean value is good (~94%) while a bigger discrepancy can be seen for the dispersion factor; here the agreement reduces to the 58 %. The higher size dispersion factor, obtained from the fringe analysis, is due to a decreasing visibility of the signal attributable to other effects that the variation in droplet diameters.

In table 2 the results for the droplet temperature distribution are presented.

Oil viscosity	T_{Rnbw} [°C]	T_{TC} [°C]	σ_{TRnbw} [°C]	σ_{TTC} [°C]
50 cSt	18.2	16.9	$2 \cdot 10^{-4}$	~0
100 cSt	21.8	19.9	$1 \cdot 10^{-4}$	~0

Table.2 – Experimental results for the droplets temperature

The experiments have been made at ambient temperature and in isothermal condition. The possible heat absorption due to the interaction between the continuous laser light (P~2Watt) and the mixture is considered negligible. This consideration is confirmed also by the fact that the dispersion factor of the droplet temperature distribution is very close to zero. The results regarding the mean droplets temperature are also in a good agreement (~92% for both mixtures). The discrepancy can be due to a statistical error performed during the measurement of the reference angle used to evaluate the absolute scattering angle range. Future research is focused on the improvements of the experimental measurement of the reference angle.
On figure 6 the comparison between the GRT signal, achieved through the analysis of the Rainbow fringes, and the intensity signal obtained adding all the Standard Rainbow Signals obtained with the droplet diameters is presented. The shift between the two signal is thus due to the systematic error on the reference angle determination.

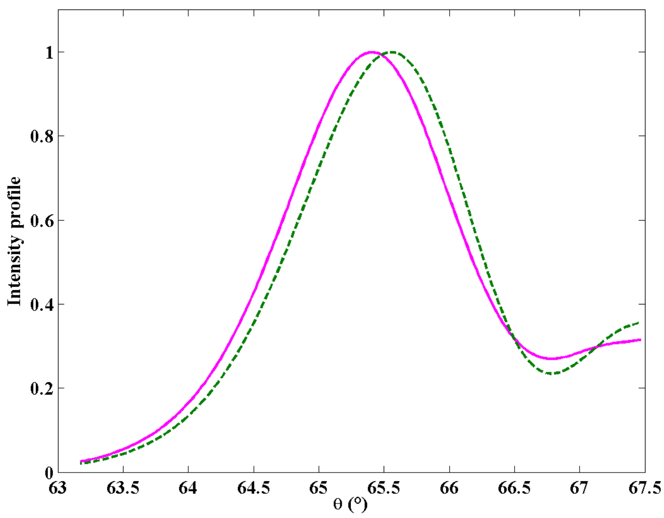


Fig.6 – Comparison between the GRT pattern obtained from the fringe analysis (-) and the one obtained from the droplets size values (---)

5. Conclusions

In this paper results concerning the application of the Global Rainbow Thermometry technique to liquid-liquid suspension have been presented. The results obtained with the GRT technique have been validated, in the case of one of the two mixtures used, through conventional measurement techniques like thermocouple measurements and direct observation. Back light scattering technique has been exploited to take images of the oil droplets. The results between the different techniques agree around the 93% both for the size and the temperature determination.

Acknowledgements

M. R. V. acknowledges financial support from the “Fonds pour la formation a la Recherche dans l’Industrie et dans l’Agriculture (F.R.I.A.).”

References

[1] Roth N. Anders K. and Frohn A. : “Simultaneous measurement of temperature and size of droplets in the micrometric range”, *Journal of Laser Applications*, Vol. 2, No. 1, (1990), pp 37-42.

[2] van Beeck J.P.A.J., “Rainbow phenomena: development of a laser-based, non-intrusive technique for measuring droplet size, temperature and velocity”, *Ph.D-thesis*, Eindhoven University of Technology, ISN 90-386-0557-9, 1997.

[3] van Beeck J.P.A.J., Giannoulis D., Zimmer L., Riethmuller M.L. : “*Global Rainbow Thermometry for droplet-temperature measurement.* ”, Optics Letters, Vol. 24 Issue 23 Page 1696 (1999).

[4] Vetrano M. R., van Beeck J.P.A.J., Riethmuller M. L.: “Experimental validation of Global Rainbow Thermometry simulations”, Optical technology and Image processing For Fluids and Solids Diagnostics, SPIE-Beijing, September 2002.

[5] Vetrano M. R., van Beeck J.P.A.J., Riethmuller M. L.: “Global Rainbow Thermometry validation in liquid-liquid suspension”, Photonics in Mechanical and Industrial Processes, Louvain-la-Neuve, Belgium, February 20-21, 2003.