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# APPLICATION OF LASER AND WHITE-LIGHT SPECKLE PHOTOGRAPHY FOR LIQUID DIFFUSION STUDIES

Ambrosini D.*, Paoletti D. and Galli G**.
*Author for correspondence
DIMEG, University of L'Aquila,
Via G. Gronchi 18, 67100 L'Aquila
Italy
E-mail: dario.ambrosini@univaq.it
**DIAEE, University of Roma "La Sapienza", Italy

## ABSTRACT

Optical techniques have a long tradition in flow visualization, allowing both qualitative and quantitative analysis. In particular, speckle photography, introduced in 1968, has been extensively used and applied to many heat and mass transfer problems.

The aim of this work is to compare white-light speckle photography and laser speckle photography techniques in the evaluation of liquid diffusion coefficients. White-light speckle photography (WLSP), recently proposed in natural convection heat transfer problems, has several advantages with respect to laser speckle photography, which makes it a more robust method. Basic theory as well as some experimental results are given. A comparison of the data provided by the two speckle photography techniques, processed with the same algorithms, with values available in literature shows a satisfactory agreement.

## INTRODUCTION

The diffusion process plays an important role in many applications of chemical and mechanical engineering, and in pollution control and biological systems [1]. It is generally recognized that optical techniques are powerful tools to investigate fluid flow phenomena in transparent media because they enable the simultaneous, real-time analysis of large regions to be performed non-invasively.

Optical methods can provide both qualitative and quantitative data, which can be used to develop a more complete phenomenological theory and for comparison with previous analytical, numerical and experimental investigations. As a matter of fact, optical techniques have been used in diffusion measurements since the 19th century: a recent account of the current status of advancement can be found in [2].

Traditional interferometers (Jamin, Mach-Zender, Rayleigh and Gouy) have been routinely employed and are considered among the most precise methods for measuring diffusion coefficients in liquids. Since the 1970's years, the advent of holographic interferometric techniques, although not yielding the same precision, offers some advantages over the classic interferometry.

Speckle photography techniques, introduced at the beginning of the 1970's years, are well known in fluid mechanics and heat transfer problems. In diffusivity measurements, speckle-based methods involve mostly ESPI (Electronic Speckle Pattern Interferometry), which can be considered a type of holographic interferometry [2]. Also speckle-based deflection techniques have been considered [3-5].

In particular, laser speckle photography is based on the deflection, induced on a travelling laser beam, by a non uniform refractive index. This beam deflection can be treated as a geometrical displacement of the speckle pattern, from which the desired information can be obtained [3].

White-light speckle photography, recently proposed in natural convection heat transfer problems [4], has several advantages with respect to traditional speckle photography, which makes it a more robust method. The experimental setup is based on a speckle pattern recorded on a holographic plate.

## NOMENCLATURE

| | | |
|---|---|---|
| $D$ | [$m^2 s^{-1}$] | Diffusion coefficient |
| $n$ | [-] | Index of refraction |
| $t$ | [s] | Time from the beginning of diffusion |
| $x$ | [m] | Cartesian axis direction |
| $w$ | [m] | Separation of characteristic extremes in $\Delta n$ |
| Special characters | | |
| $\Delta$ | [-] | Indicates a difference |
| Subscripts | | |
| $a$ | | Characteristic extreme in $\Delta n$ |
| $b$ | | Characteristic extreme in $\Delta n$ |

The white light is passed through a transparent test section, where the heat transfer process occurs. Two different exposures, recorded on a photosensor, are taken. The features of the technique are low cost, simple setup, simple run procedure and low mechanical stability requirements. Main disadvantage lies in reduced sensitivity and accuracy with respect to holographic interferometry and ESPI. Very recently, white-light speckle photography was extended to diffusivity measurements [5].

The aim of this work is to compare white-light speckle photography and laser speckle photography techniques in the evaluation of liquid diffusion coefficients.

Speckle images are evaluated by using algorithms based on the package MatPIV 1.6.1 by Sveen. This package was chosen for several reasons: it is free; it is Open Source; it works in the MATLAB® environment, thus sharing its capabilities of technical calculations and data visualizations.

Preliminary experimental measurements were performed considering the diffusion of a 1.75 M (moles/l) aqueous solution of common salt (NaCl) in pure water. A data comparison with values available in literature shows a satisfactory agreement.

## SPECKLE PHOTOGRAPHY FOR DIFFUSION STUDY

As said, speckle photography is based on the light beam deflection induced by a non uniform refractive index. This deflection can be treated as a geometrical displacement of the speckle pattern, from which the desired information can be obtained [6].

Diffusion measurements by speckle photography can be performed using coherent (laser) [3] or non-coherent (white-light) sources [5]. The relative experimental setups, which are very similar, are shown below.

### Laser speckle photography

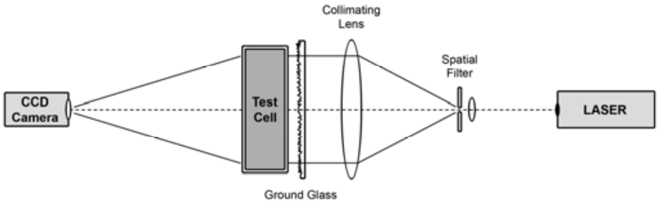

**Figure 1** The laser speckle photography experimental setup

The experimental arrangement is depicted schematically in Figure 1. The spectrophotometric glass diffusion cell (10 mm × 10 mm × 45 mm) is equipped with a Teflon shutting device to avoid evaporation phenomena. The cell, filled through a capillary tube from the bottom to minimize turbulence and mixing, is illuminated by an expanded and collimated laser beam by means of a diffuser (ground glass). The light source is a laser diode (Lasiris by StockerYale, wavelength 638.5 nm, output power 5 mW).

The light rays diffracted by the ground glass, form a speckle pattern on the photosensor of a CCD video camera which images the diffuser. The video signal is finally processed by a frame grabber that allows arithmetic operations on images in real-time.

The TV camera was a Silicon Video® 9T001C with PIXCI® D2X imaging board by EPIX Inc., with a resolution of 2048 × 1536 pixels. The camera was equipped with a TEC-55 55mm F/2.8 Telecentric Computar Lens, which reduces viewing angle error and magnification error while providing good resolution and contrast with low distortion.

### White-light speckle photography

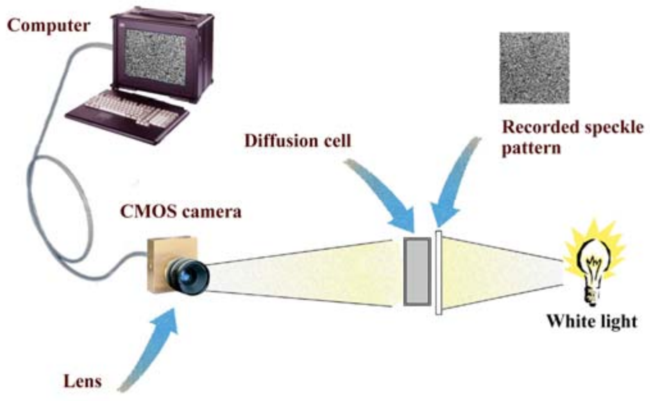

**Figure 2** Schematic overview of WLSP for diffusivity measurement.

The experimental setup for WLSP is shown in Figure 2. The system is based on a recorded speckle pattern illuminated by a 50 W white halogen lamp. The light is then passed through a transparent test section, in which the diffusion process occurs. The diffusion cell and the image acquisition system are the same of Figure 1. In practice, the setup for WLSP can be obtained from the scheme in Figure 1 as follows:

1. Replace the laser source with a white light source
2. Remove spatial filter, collimating lens and ground glass
3. Insert a recorded speckle pattern.

As the source is non-coherent, the white-light speckle method relies on a random pattern, which could be naturally present or must be artificially created, on the test object. In this work, speckle patterns with different speckle sizes were created by exposing holographic plates to a speckle pattern obtained by illuminating a diffuse glass plate with a laser beam.

The method evolved from Moiré and laser speckle techniques. Because of its simplicity and versatility, it was applied to deformation measurements [7]. WLSP is an interesting technique because, in many cases, provides better results than laser speckle photography [8], even if it usually exhibits lower sensitivity [7].

WLSP is similar to “synthetic schlieren”, presented by Dalziel et al. [9] and to “Background Oriented Schlieren” (BOS) by Richard & Raffel [10].

**The diffusion phenomenon**

If refractive index $n$ in the test section is non-uniform, the rays through the test object will be deflected. In other words, if the refractive index changes, the deflection angle will also change. The change of the deflection angle can be regarded as a local translation of the speckle pattern and this displacement is proportional to the derivative of the refractive index [6].

During an isothermal diffusion process, the change in the index of refraction $\Delta n(x,t_1,t_2) = n(x,t_2) - n(x,t_1)$, for two given times $t_1$ and $t_2 > t_1$ has two characteristic extremes (say $x_A$ and $x_B$) [2], see Figure 3, whose separation, say *w*, can be used to obtain the diffusion coefficient *D*. In fact, the following relation holds:

$$D = \frac{w^2\left[(1/t_1) - (1/t_2)\right]}{8\ln(t_2/t_1)} \tag{1}$$

Equation (1), first obtained by Bochner and Pipman, was widely used in holographic interferometry and ESPI measurements [11].

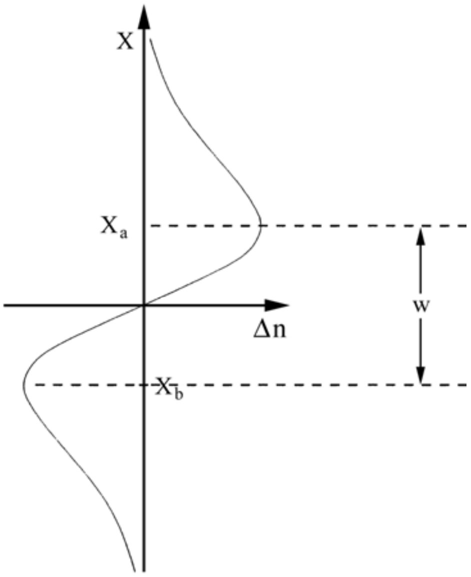

**Figure 3** Graphic reconstruction of the refractive index variation curve in the diffusion cell

## DATA PROCESSING

There are only three experimental variables in equation (1): the times $t_1$ and $t_2$ and the distance *w*. Furthermore, equation (1) is independent of the wavelength of the light, the concentration of the solution and the value of the refractive index as long as concentration and refractive index are linearly related. It does not depend on the size of the cell. And most important, it does not depend on identification of the initial boundary between the solutions.

The zero of time could be a possible source of error. However, the usual procedure [11], in which the cell is filled through a capillary tube from the bottom to minimize turbulence and mixing, has proven capable to give an accuracy of the order of 1-2% (respectively, using holographic interferometry and ESPI), therefore we may consider as the most important source of errors the separation *w*.

The speckle pattern displacement can be obtained by using a cross-correlation approach of the PIV (Particle Image Velocimetry) type [12]: sub-images are extracted from the first image (time $t_1$) and the second image (time $t_2$), then the correlation surface is obtained using suitable correlation filters. The peak location in the correlation surface gives the relative displacement between the two sub-images.

It can be shown [13] that $x_A$ and $x_B$ are object points not exhibiting speckle displacement, therefore their separation *w* can be easily obtained also from the PIV mode displacement map, see Figure 4 right.

Data processing by correlation algorithms is powerful and it is also relatively simple, due to the possibility of using existing PIV software with only minor modifications.

In the following, pattern displacements are evaluated using correlation algorithms based on the MATLAB® toolbox MatPIV 1.6.1 by J.K. Sveen [14], probably the largest presently available free (under the GNU General Public License) PIV toolbox.

## RESULTS AND DISCUSSION

Some measurements were performed considering the diffusion of a 1.75 M (moles $l^{-1}$) aqueous solution of common salt (NaCl) in pure water at 26 °C. Unfortunately, there are few data available to check results: Riquelme *et al.* [15] recalculated previous data obtaining a diffusion coefficient of 1.538 u, u being defined to be $10^{-9}$ $m^2$ $s^{-1}$ for conciseness. More interestingly, they gave several experimental results for different diffusion times, which, with some caution, can be used for comparison here.

Caution is required because, as outlined by the authors themselves [15], the data by Riquelme *et al.* did not match perfectly with the previous ones and some systematic error may exist.

Both laser speckle photography (LSP) and white-light speckle photography (WLSP) were applied. Cross-correlation was calculated in the simplest way, with a single iteration through the images and a 50% overlap of the interrogation windows. The dimension of the interrogating window was 32 pixels.

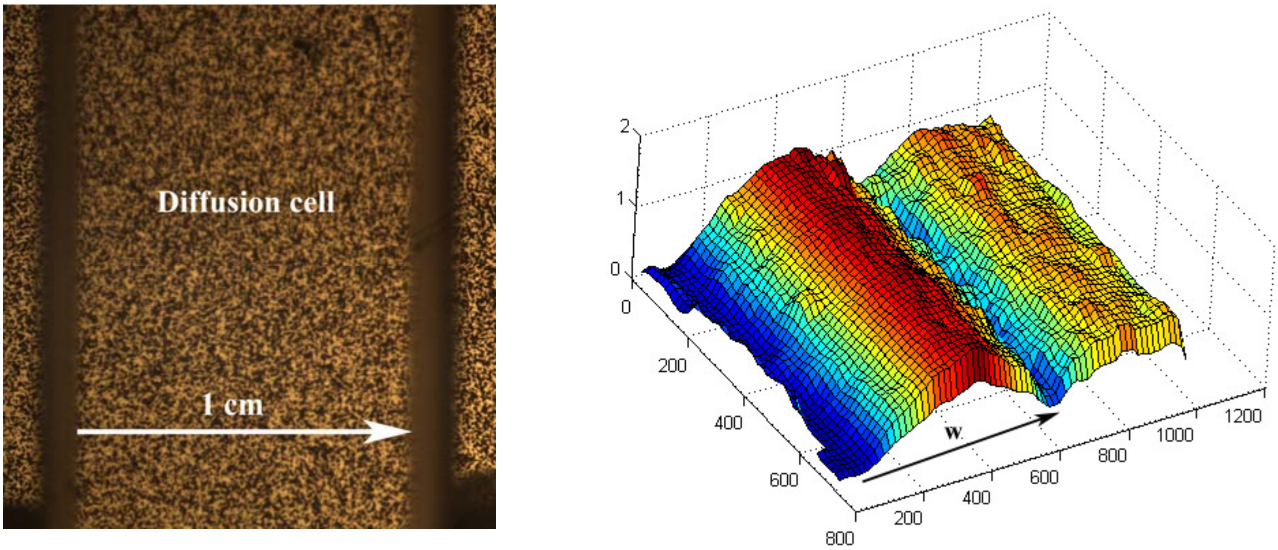

**Figure 4** (left) A typical white-light speckle pattern, seen through the diffusion cell; (right) a typical speckle displacement map

| $t_1$ [s] | $t_2$ [s] | **D LSP** | **D WLSP** | **D Ref. [15]** |
|---|---|---|---|---|
| 2700 | 3300 | 1.718 | 1.599 | 1.634 |
| 3000 | 3300 | 1.521 | 1.603 | 1.627 |
| 3900 | 4200 | 1.672 | 1.651 | 1.598 |

**Table 1** Diffusion coefficients of NaCl in water at 26 °C in units of $10^{-9}$ $m^2$ $s^{-1}$

Table 1 shows some preliminary experimental results, obtained by processing LSP and WLSP data by MatPIV [14], compared to results from [15] obtained by ESPI.

The values show a percent error, with respect to the data in [15], ranging from about 2.1% (WLSP) to 5.1% (LSP) in the interval 45-55 min, from 1.5% (WLSP) to 6.5% (LSP) in the interval 50-55 min and from 3.3% (WLSP) to 4.6% (LSP) in the interval 65-70 min.

WLSP can give high accuracy if a high-quality artificial speckle pattern is used [8]. This requirement is fulfilled in this system because the speckle pattern is directly recorded on a holographic plate.

As discussed in the Introduction, the sensitivity of the white light speckle methods is usually lower than that of their laser counterpart [7]. This is mainly due to the fact that artificial speckles are usually larger than laser speckles and that even a small defocusing reduces the high frequency content. Both these shortcomings are alleviated in the present experiment.

In fact, as the recorded speckle pattern is a high-resolution copy of a laser speckle pattern, speckle size are practically the same. There is an obvious loss in flexibility, due to the fact that to change the speckle size one has to change the speckle picture.

As regards defocusing, being speckle “freezed”, their size is no longer dependent on the aperture of the lens. Therefore, small apertures (high $f_{\#}$) can be used, thus assuring a high depth of field. Performance is further enhanced by the telecentric lens.

Obviously, more experimental results and comparisons are needed to evaluate correctly accuracy and reproducibility of speckle photography techniques in diffusivity measurements, however these preliminary results are encouraging because of the simplicity of the method and the possibility to automate the measurement using a widely available and open access software.

WLSP, at least in this experiment, performs consistently better than LSP. In any case, both the techniques give results within some percent of error with respect to ESPI measurements. An interesting feature of speckle photography techniques (with respect to holographic interferometry and ESPI) is the absence of reference beam; therefore they should be error-free even if the system may incur some small mechanical disturbance during the test.

Furthermore, the performance could be improved in several manners:

1. Matching carefully speckle size and camera resolution;
2. Improving the sensitivity [4];
3. Increasing quality and resolution of the camera (particularly for WLSP);
4. Improving data processing, using more sophisticated algorithms and smaller interrogation windows.

Some of these improvements are currently under consideration.

## CONCLUSION

In this paper we compare laser speckle photography (LSP) and white-light speckle photography (WLSP) for diffusivity measurements. The features of the techniques are low cost, very simple setup and run procedure and low mechanical stability requirements. Main disadvantage lies in reduced sensitivity and accuracy with respect to holographic interferometry and ESPI.

Data processing was based on correlation algorithms of the PIV type. Preliminary experiments on the diffusion of common salt in water, were performed using the MatPIV package in a MATLAB® environment. A comparison with some experimental values available in literature shows that WLSP generally performs better (errors within 2%).

The performance of the techniques could be enhanced by using a higher resolution TV camera with still better image quality and/or more sophisticated correlation algorithms.

## ACKNOWLEDGEMENT

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