A study of heat transfer in vertical channels by white-light speckle photography

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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. White-light speckle photography has certain advantages which make it a more robust method.
The aim of this work is to apply white-light speckle photography to the investigation of free convection in vertical channels in air.

Key-Words: - white-light, speckle photography, free convection, heat transfer, vertical channels, correlation, visualization

1 Introduction

Convection is a complex process, which transports energy to or from a surface by both molecular conduction processes and gross fluid movement. Flows having a variable fluid density can be visualized with traditional optical methods [1-3].
Speckle photography, introduced by Kopf [4] and Debrus *et al.* [5], is well known in literature [6, 7].
A non uniform refractive index, due for instance to a gradient in temperature, has two basic effects on a light beam:
a) a change in phase;
b) a deflection of the beam.
The latter is the physical effect involved in speckle photography. In particular, it can be shown that the beam deflection can be regarded as a geometrical displacement of a speckle pattern; this displacement is proportional to the temperature gradient.
In speckle photography, the information is obtained from the geometrical displacement of a speckle pattern generated by the interaction of coherent light with a diffusing surface. The speckle displacement is traditionally recorded on photographic film, while the evaluation of the specklegrams is performed by computer. Recently, digital recording of the speckle patterns was introduced [8-10].
The white-light speckle method [11] relies on the random pattern, artificially created or naturally present, on the test object. The method evolved from Moiré and laser speckle techniques. Because of its simplicity and versatility, it was widely applied to deformation measurements [11] but had a much smaller amount of applications in fluid mechanics velocimetry [12, 13].
In many cases, white light speckle patterns provide more accurate results than do laser speckle patterns [14]. However, it should be also stressed that the sensitivity of the white light speckle method is usually lower than that of its laser counterpart [11].
White-light speckle photography (W-LSP) was recently proposed and demonstrated in studying free convection in water [15, 16].

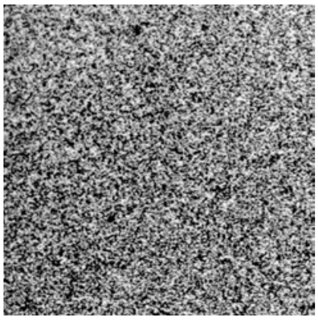

Fig. 1. A typical recorded speckle pattern.

In this paper we use the white-light speckle photography technique to investigate free convection in vertical channels in air. The channel, consisting of two parallel vertical plates at a given spacing value, was asymmetrically heated at uniform wall temperature.
Free convection in channels is encountered in a number of technological applications: most of the existing data are correlated in a classic paper by Bar-Cohen and Rohsenow [17]. A brief description

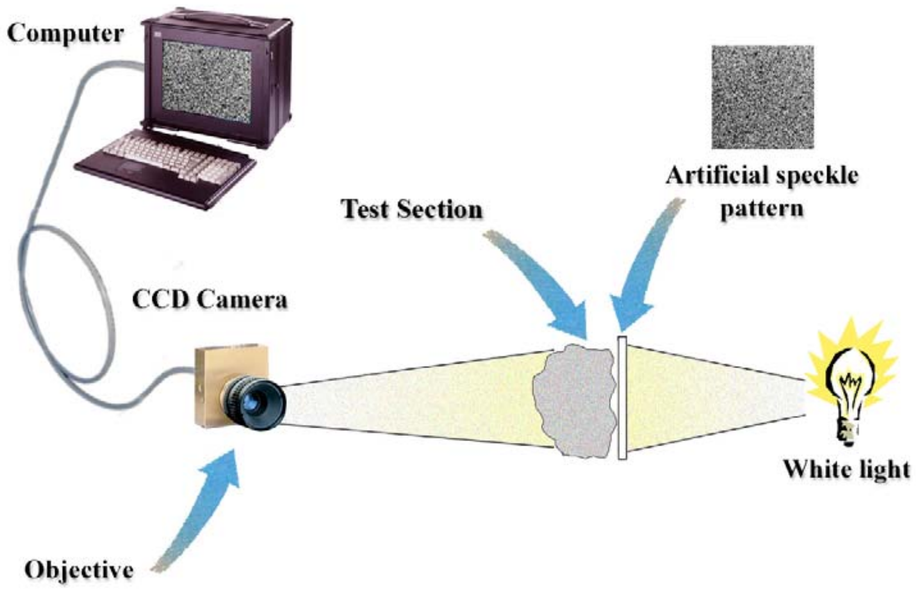

Fig. 2. Experimental setup.

of the technique and some experimental results are given.

2 W-LSP in a nutshell

White-light speckle photography, like traditional speckle photography, is a two-step process: recording of the specklegram and reconstruction (or filtering) of the same specklegram to obtain information on the displacement undergone by the test object.

As white-light is not coherent, speckles must be artificially created. 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. Figure 1 shows a typical recorded speckle pattern. The electro-optical system used in this work is shown schematically in Fig. 2. A detailed description of the technique has been given elsewhere [15, 16].

The system is based on a recorded speckle pattern illuminated by a white-light source. The light is then passed through a transparent test section. Two different exposures, recorded on a photosensor, are taken. The first of the non-refracted pattern, obtained with the test fluid in thermal equilibrium with the surrounding ambient, and the second of the refracted pattern obtained with a temperature gradient in the channel.

The light source is a white halogen lamp of 50 W with a green filter (not shown).

If the test object has a non-uniform refractive index, 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 artificial speckle pattern. In strict analogy with traditional speckle photography [6,7], this speckle displacement is proportional to the temperature gradient. It can be shown [15] that, for a stratified medium,

$$\frac{\partial T(x)}{\partial x} = \Delta_x(x_0)\frac{n(x_0)}{\ell^2}\left[\frac{\partial n(T)}{\partial T}\right]^{-1} \qquad (1)$$

where $\partial T(x)/\partial x$ is the temperature gradient in the direction perpendicular to the propagation axis, ℓ represents the thickness of the test cell, $\Delta_x(x_0)$ is the speckle pattern shift as seen from the TV camera and $n(x_0)$ is the refractive index value at the location at which the ray enters the medium. In literature are available several relations for calculating n and its derivative for different wavelengths and fluids [1-2].

By introducing the local heat transfer coefficient defined as

$$h = -\frac{k}{\left(T_w - T_\infty\right)}\left(\frac{\partial T}{\partial x}\right)_w \tag{2}$$

where k_w is the thermal conductivity of the fluid at the wall temperature, T_w is the wall temperature and T_∞ is the ambient air temperature, and considering Eq. (1) the local heat transfer coefficient can be obtained.

3 Data reduction

One of the key features of digital speckle photography development and success is the possibility to perform computerized image analysis.

In digital speckle photography the speckle displacement can be obtained with the traditional auto-correlation approach (Young's fringes) and with the cross-correlation approach, both digitally performed [10, 15].

Cross-correlation is preferable to auto-correlation because the latter introduces a sign ambiguity and carries decorrelation into the final results [14].

In the cross-correlation approach, sub-images are extracted from the reference image I_R and the deformed image I_D, 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.

As a rule of thumb one can think that the sharper the correlation peak, the more reliable the estimation of its position. This is not completely true, because also noise tolerance is very important [14].

Furthermore, the coarse structure and finite size of the photosensor limit the accuracy in determining the peak position [14].

In this work the images are evaluated using correlation algorithms based on the package MatPIV 1.6.1 by J.K. 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.

4 Experiments

4.1 Test section

The test section consisted of a plate (termed "heated plate"), made up of two aluminium sheets with a plane electrical resistance sandwiched in between, and two shrouding vertical walls. The plate, vertically suspended, is heated by supplying a given amount of power to the resistance. The shrouding walls were smooth, unheated and placed so as to form two adjacent, symmetrical, vertical channels. Aluminium was chosen for its high thermal conductivity, low thermal emittance, and easy machinability.

The dimensions of the heated plate were the following: overall thickness $t = 0.005$ m, height $H = 0.140$ m, length $L = 0.242$ m. The length was set much greater than the other dimensions in order to favour a two-dimensional thermal field in the channels. The spacing S between each unheated wall and the heated plate, set equal on both sides, was chosen in order to yield a channel aspect ratio S/H equal to 0.3. The plate was instrumented with fine-gauge, chromel-alumel thermocouples, calibrated to ± 0.1 K. The ambient air temperature was measured by five shielded thermocouples situated just below the plate array. The plate can be considered isothermal because of aluminium high thermal conductivity.

The radiation heat transfer was expected to be small because of the low thermal emittance of aluminium surfaces.

4.2 Experimental results

White-light speckle photography in natural convection studies was compared to traditional laser speckle photography in [15]. This comparison showed an evident noise reduction if W-LSP is used.

Once the setup was realized (Fig. 2), speckle images were captured without thermal gradients in the test section to assess the performance of the technique.

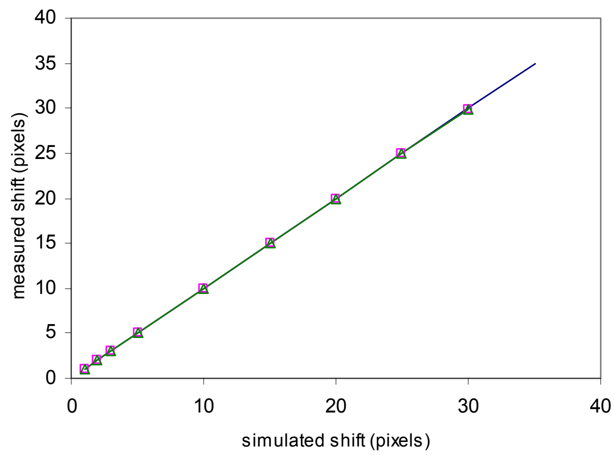

Fig. 3. Measured shifts (B = 64 pixels) speckle size s = 4 pixels (triangles) and s = 6 pixels (squares).

The TV camera was a Silicon Video® 2112 CMOS with PIXCI® D2X imaging board by EPIX Inc., with a resolution of 1288 × 1032 pixels. The camera was equipped with a Micro-Nikkor 55 mm lens and connected to a PC.
As there is no thermal gradient, speckle patterns exhibit no shifts.
Speckle shifts are then digitally introduced so as to be carefully controlled and the images are processed according to the data reduction outlined in Section 3.
Cross-correlation was calculated in the simplest way, with a single iteration through the images and a 50% overlap of the interrogation windows.
Figure 3 shows the recovered displacements obtained with a sub-image size (B) of 64 pixels and two different average speckle sizes (s) of the white-light speckle pattern.
As can be seen, the performance of the data analysis in recovering speckle displacement is good. No significant difference was found in going from B = 64 pixels to B = 128 pixels or in reducing the speckle size s.
Further insight can be gained by considering the relative errors, plotted against the simulated shift, for the two interrogation regions and an average speckle size s = 6 pixels (Fig. 4).
It was found that using a larger interrogation region seems to be marginally better. The behaviour of relative errors for an average speckle size of s = 4 pixels is qualitatively the same.

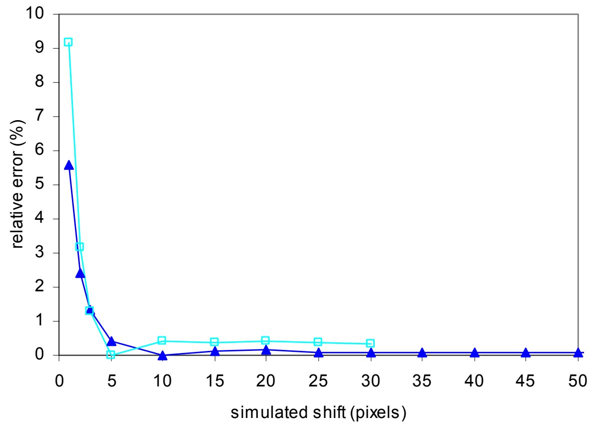

Fig. 4. Relative errors (s = 6 pixels) B = 64 pixels (squares) and B = 128 pixels (triangles).

In analogy with traditional PIV analysis, probability of detecting displacement can be increased by an image offset. This literally shifts the second image with respect to the first by a predetermined integer pixel value. Certain situations may require that the field be analyzed in zones, rather than as a whole, using different image offset [18].
A typical double-exposure hologram is shown in Fig.5. Dark lines represent the interference fringes that directly give the isothermal lines.

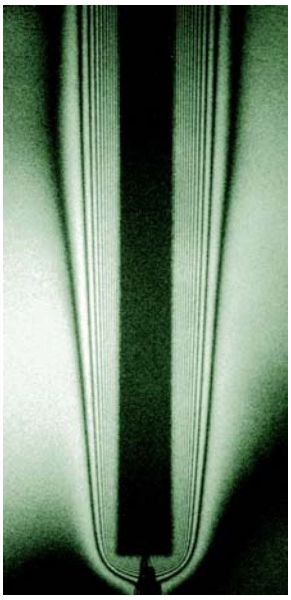

Fig. 5. Typical double exposure hologram showing the isotherms in the channel. S/H = 0.3, ΔT = 28 K.

The flow is symmetrical and laminar; furthermore, non-zero vertical temperature gradients have an influence only in the vicinity of the lower edges of the aluminum plate. With this aspect ratio (0.3) the phenomenon resembles the heat transfer from a single, vertical heated plate.
Then we used W-LSP to check if the technique is suitable to work in air.

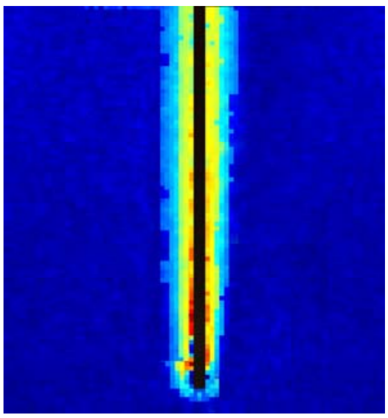

Fig. 6. Speckle displacement in the channel. S/H = 0.3, ΔT = 28 K.

Fig. 7. Vector plot of the speckle displacement in a section halfway along the plate. S/H = 0.3, ΔT = 28 K.

The TV camera was now a Silicon Video® 9T001C with a resolution of 2048 × 1536 pixels.

Two images were acquired, one with the plate at thermal equilibrium with ambient air (295 K) and the second with the heated plate at constant temperature (323 K).

Then the two images were processed according to the data reduction outlined in Section 3.

Figure 6 shows a colour plot of the speckle displacements.

The displacement field (proportional to the temperature gradient field) clearly identifies a laminar region: temperature gradients are not negligible only near the plate; also the development of the laminar region along the plate is clearly detected.

Further information can be gained by examining a vector plot of speckle displacements.

Figure 7 shows this vector plot in a section approximately halfway along the plate.

All displacements are practically horizontal, thus confirming that vertical temperature gradients are non negligible only near the lower edges of heated plate.

To reach satisfying quantitative evaluation, future developments of this work should consider subtleties of correlation algorithms, such as continuous windows shifting and filtering procedures, taking into account that many of the algorithms developed for pattern matching and PIV (Particle Image Velocimetry) could readily be adapted for W-LSP.

5 Conclusion

In this paper we use the white-light speckle photography technique to investigate free convection in vertical channels. The features of the technique were evaluated using a cross-correlation approach, which assures enhanced sensitivity with less noise.

Preliminary experiments were conducted using the MatPIV package in a MATLAB® environment using simulated shifts. Furthermore, experiments were performed in vertical channels with an aspect ratio S/H = 0.3.

The technique has sufficient sensitivity to work in air (previous applications were in water) and was able to detect a number of flow field features as compared with holographic interferometry. Future works will involve a quantitative comparison.

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