SIMULTANEOUS MEASUREMENT OF VELOCITY AND TEMPERATURE FIELD IN THE DOWNSTREAM REGION OF A HEATED CYLINDER

P. Bencs[1*] – Sz. Szabó[1] – D. Oertel[2]

[1]Department of Fluid and Heat Engineering, University of Miskolc, H-3515 Miskolc-Egyetemváros, Miskolc, Hungary
[2]Laboratory of Fluid Dynamics and Technical Flows, University of Magdeburg 'Otto von Guericke', D-39106 Universitätplatz 2., Magdeburg, Germany

ARTICLE INFO

***Article history*:**
Received: 16.01.2013.
Received in revised form: 23.03.2013.
Accepted: 29.03.2013.

Keywords:
Heated cylinder
Schlieren
PIV
Experiment
Velocity field
Temperature field

Abstract:

Simultaneous measurements of the flow velocity and temperature field for a heated bluff body present a typical problem. We attempted to carry out simultaneous measurements using two different methods, Particle Image Velocimetry (PIV) and Schlieren. In this experiment, an electrically heated circular cylinder is placed in a parallel flow, in a wind tunnel. The experimental tests were carried out at low Reynolds numbers (Re<200), therefore, the flow field was approximately two dimensional (the same flow in every normal plane of the heated circular cylinder). Two-dimensional flow and the principle of the Schlieren measurement technique were used to visualize the temperature field. The Z-type Schlieren technique was applied to measure the temperature distribution. Experiments were carried out for forced convection in a 500x500 mm cross-section wind tunnel. The measurement technique and results were shown at different cylinder surface temperatures. The relationship between the vortices shed from the heated cylinder and the heat transfer was determined by relevant numerical simulations. The main objective of the present experimental investigation is to find out whether both velocity and temperature can be measured at the same time. Results are promising and indicate that this aim can probably be met with further refinements of the technique.

1 Introduction

Bluff bodies placed in a flow often have a different temperature compared to that of the surroundings, e.g. in case of the heat exchangers. The structure of the flow around bluff bodies has already been examined in many studies [1-3]. The observed Kármán vortex street has been the subject of numerous experimental and numerical investigations. Nevertheless, it is still unclear how this vortex street might be modified in the case of a heated body. What is the possible influence of heating on the frequency of the detaching vortices, on the structure of those vortices and on the location

* Corresponding author. Tel.: +36 46 565 154; fax: +36 565 471
E-mail address: arambp@uni-miskolc.hu

of their detachment? A further important issue is the heat loss associated with the vortex structures and the forced convection. The objective of the present work is to present the first development steps of a measurement method to allow for a quantitative investigation of these issues.

The development and validation of this method requires a well-defined flow. Therefore, a low Reynolds number flow (Re<200) is to be considered as the first step. Such a flow is mostly two - dimensional, i.e., the flow does not change considerably along the axis of the cylinder.

The employed bluff body is an electrically heated circular cylinder of 10 mm diameter and 500 mm test length. We investigated the wake of the cylinder when placed in an air flow with 0.3 m/s mean velocity and a temperature of 28 ˚C and with imposed cylinder temperatures of 100, 200 and 300 ˚C.

The main innovation of the developed method is the simultaneous and quantitative determination of the velocity and temperature fields. For this purpose, the Z-type Schlieren method is employed to measure temperature along with Particle Image Velocimetry (PIV) for velocity. All recorded images from both methods are processed by commercial software from TSI® and Matlab®. The same system has been used for measuring the same phenomena, but with only one camera and in water [4].

2 Experimental setup

The following measurement setup, shown in Fig. 1, is introduced by describing the wind tunnel, the heated cylinder, PIV/Schlieren methods and triggering, which was important for the connection between the velocity and temperature field of the flow behind the cylinder. We apply the trigger unit (TSI® trigger box) to synchronize the PIV laser, PIV camera and Schlieren camera.

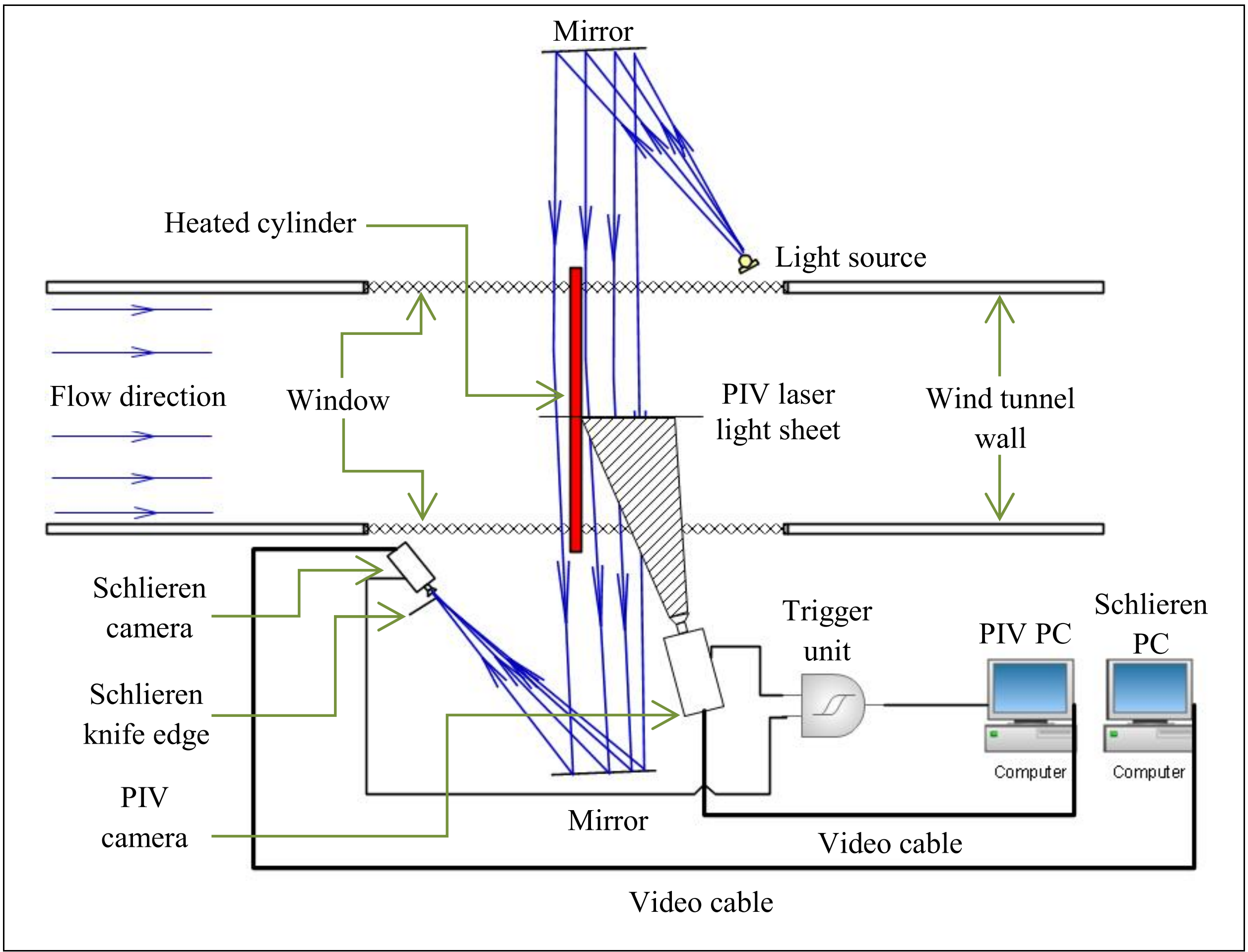


Figure 1. Schematic of experiment setup.

The flow behind a heated cylinder was investigated in an open wind tunnel. The cross-section of the measurement area was 500x500 mm.

The mean flow velocity was set to 0.3 m/s, since this was the minimum stable velocity of the wind tunnel in this configuration. The Reynolds number for the wind tunnel was Re=9,460, calculated from the mean flow velocity in the test section, the hydraulic diameter and the viscosity of the air at ambient temperature.

Two transparent windows were mounted on both sides of the measurement section, with a hole in the middle, used to mount the heated cylinder transversally to the main flow direction (see Fig. 1). The mean temperature of the cylinder was measured by a thermocouple and the power of the transformer was adjusted according to the desired value. The Reynolds number based on the mean flow velocity, the diameter of the cylinder and the kinematic viscosity of the air at the film temperature [3] of T_f=0.5·(298+573) K=435.2 K (ν=3.01·10^{-5} m²/s) was Re≈100. The predicted frequency of the vortex shedding was f_S = 4.85 Hz, calculated from the Strouhal number of St = 0.16.

The main objective of the measurements discussed here was to investigate the relation between the velocity and temperature field behind this heated cylinder in a low Reynolds number (cylinder reference area) flow. The system used for the present measurements was a regular 2D-PIV system and a Z-type Schlieren system consisting of the components listed in Table 1.

Table 1. Description of the PIV and Z-type Schlieren system

Component	Remarks	Manufacturer
PIV system		
Double frame CCD camera	PowerView™ Plus 4MP PIV camera with 12 bit resolution, recording freq.: 15 Hz	TSI
Objective	AF Nikkor 50 mm; f/1.8D; f-number: 4 and focus set to 500 mm	Nikon
Double pulse Nd-YAG laser	Power: 2x135 mJ at 532 nm, max. frequency: 15 Hz	Litron
Trigger box	Synchronization of PIV camera and laser timing and trigger signals of the Schlieren camera	TSI
PC with a frame grabber card and PIV software	For image data acquisition and for the processing of the acquired data	TSI
Z-type Schlieren system		
CCD camera	AVT Stingray F-033C CCD camera with 16bit resolution	Allied Vision Technologies
Objective	75 mm Focusable Double Gauss Lens; f-number: 4 and focus set to 2000 mm	TECHSPEC®
PC with a 1394b firewire card and software	AVT SmartView v1.13.1, for image data acquisition and for the processing of the acquired data	Allied Vision Technologies
Schlieren light source	Super Bright White LED, 530XW8C, 8000 mcd	-
Schlieren mirrors	Mirror thickness: 25% of the diameter; Optical quality of the mirror: λ/8; Offset angle: θ=3˚; Power of lens: f/10; Distance between the mirrors: 4500 mm.	ANCHOR Optics

The applied software for the acquisition and evaluation was commercial PIV software INSIGHT3G™ from TSI. The PIV and Z-type Schlieren measurements are only briefly discussed here, since there are numerous publications describing the principals of PIV (e.g., [5-6]). Two different cameras were used for PIV and Schlieren measurements. The PIV camera was calibrated with the help of a calibration plate to set the pix/mm factor and to eliminate possible distortion. The calibration plate was put in the test area and set to the measurement plane. The camera optics was focused on the calibration plate and the *f*-number was set to 4. For the PIV measurements, oil droplets of 3 μm diameter were added to the flow as tracer particles and the measurement plane was lit by a double pulse laser through the light sheet optics.

For the evaluation, first image dewarping was applied using a direct linear transformation, obtained previously during the calibration process. Then the velocity field was calculated from the dewarped and scaled images using a cross correlation with a 32x32 pixel interrogation area, with 50% overlap. Finally, range validation was applied to the vector field in order to eliminate possible error vectors. The resulting vector maps were then exported to ASCII files for later visualization using Matlab®.

With respect to the Schlieren measurements, the measurement area was lit by an LED light source. We apply a razor blade knife edge and use a 3D mini traverse system (see Fig. 2a) to determine the calibration curve. Finally, range validation was applied to the contrast field in order to eliminate possible error contrast values. The temperature was calculated by equations found in the literature [6-9] (see Section 2.1).

2.1 Sensitivity of the Schlieren system

The sensitivity of the Schlieren system is one of its basic characteristics. In the case of the Schlieren optics – at least those considered here – the output is a 2D image in x and y-coordinates (see Fig. 2b). More specifically, it is an array of picture elements characterized by amplitude or greyscale contrast variations [6-9].

Now consider the case of a Schlieren object in the measurement area that refracts a certain light ray through the angle ε having x-component ε_x. This causes a weak elemental source image to shift forward in the knife-edge plane by a distance $\Delta a = \varepsilon_x \cdot f_2$, where f_2 is the focal length of the first mirror. Substituting Δa for a, one obtains [6-9]:

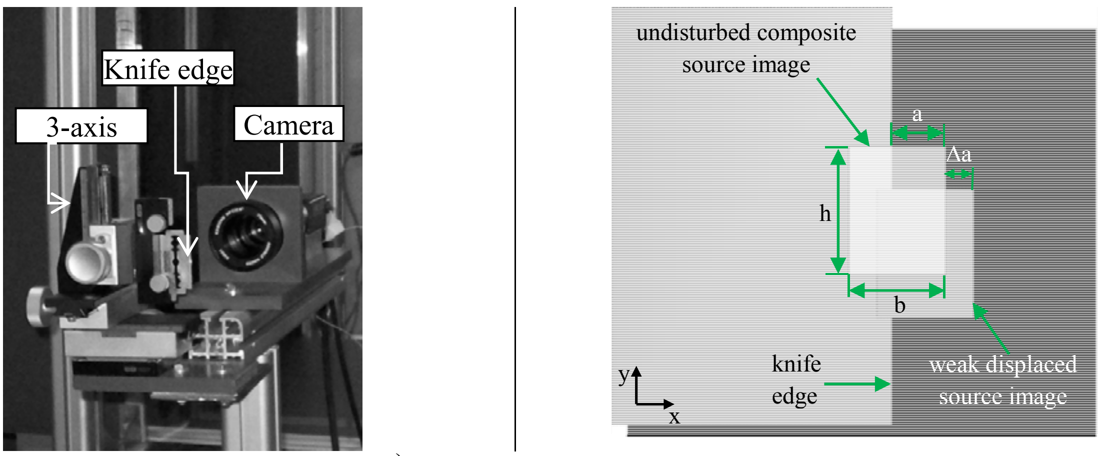
$$\Delta E = \frac{B \cdot h \cdot \varepsilon_x}{m^2 \cdot f_1}, \qquad (1)$$

which describes the incremental gain in illumination at the corresponding image point due to the refraction ε_x in the measurement area. In this case, B is the illuminance of the light source, f_1 is the focal length of the first mirror, and m is the magnification factor (the ratio between the image size and test area). The magnification factor in our case was 1.5.

The contrast in the Schlieren image refers to the ratio of differential illuminance ΔE at an image point to the general background level E.

$$C = \frac{\Delta E}{E} = \frac{f_2 \cdot \varepsilon_x}{a}. \qquad (2)$$

This image contrast C is the output of the Schlieren equipment [9]. The input is a pattern of irregular ray deflections ε, resulting from refractive-index gradients in the measurement area, in an otherwise regular beam. The sensitivity of any measurement system is basically an influence coefficient.



a) b)

Figure 2. Knife edge with 3-axis stage (a) and undisturbed and weak displaced source image (b).

The Schlieren sensitivity is the rate of change of the image contrast in respect to the refraction angle:

$$S = \frac{dC}{d\varepsilon} = \frac{f_2}{a}. \tag{3}$$

The temperature field can be calculated from the contrast changes (refractive-index changing) and using the Gladstone–Dale equation [7-9]. The Gladstone–Dale equation is very important to determine the refracting index that depends on the absolute temperature T and the pressure p (ρ is the density of the gas)

$$\frac{\varepsilon - 1}{\rho} = const. \tag{4}$$

Applying the ideal gas law $p/(\rho \cdot T) = const.$ to two states of the same medium yields

$$\frac{\rho}{\rho_0} = \frac{p}{p_0} \cdot \frac{T_0}{T}. \tag{5}$$

Substituting the Gladstone–Dale equation:

$$\frac{\varepsilon - 1}{\varepsilon_0 - 1} = \frac{p}{p_0} \cdot \frac{T_0}{T}. \tag{6}$$

Substituting the refractive index:

$$\varepsilon = \left(\frac{p}{p_0} \cdot \frac{T_0}{T} \right) \cdot (\varepsilon_0 - 1) + 1, \tag{7}$$

where ε_0, p_0 and ρ_0 are the refraction index, pressure and density at reference temperature T_0, respectively.
In the case of an isobar process $(p = p_0)$:

$$\varepsilon = \left(\frac{T_0}{T} \right) \cdot (\varepsilon_0 - 1) + 1. \tag{8}$$

Substituting the absolute temperature we obtain:

$$T = \frac{\varepsilon_0 - 1}{\varepsilon - 1} \cdot T_0. \tag{9}$$

Temperature field can be calculated from the refracting index changes by the Eq. (9).

2.2 Calibration curve

In flows with density variations, the beam is deviated and focused in an area covered by the knife-edge so that it is blocked. The result is a set of lighter and darker patches corresponding to positive and negative fluid density gradients in the direction normal to the knife-edge. The knife-edge can be translated laterally by a quantity Δx.
We can establish a relationship between the contrast level of the image and the transverse knife-edge position. The relationship between Δx and light intensity was determined by a 3-axis stage (see Fig. 3). More details about PIV and the Schlieren method can be found in [10].

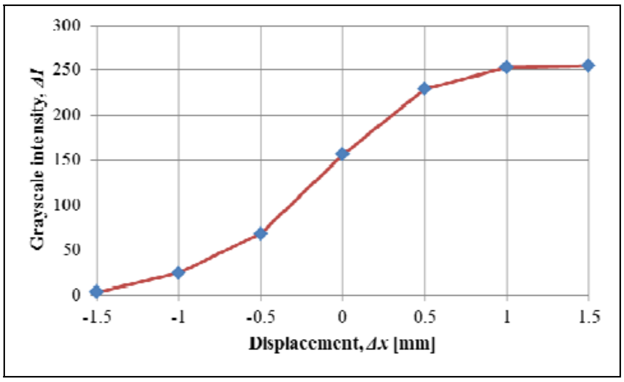


Figure 3. Calibration curve.

3 Measurement results

The raw PIV (laser lighting) and Z-type Schlieren (LED lighting) recorded data are shown in Fig. 3. Vortex shedding can be seen in Fig. 4 in the PIV image (left side). The diffraction caused by the air density change near the heated cylinder can be slightly seen in the Schlieren image (Fig. 4, right side). A dewarping process was applied to the PIV picture analysis. A masking process was applied to the Schlieren picture analysis for filtering the knife edge errors.
The resulting velocity field (PIV method) and temperature field (Schlieren method) are shown in Fig. 5, where the periodicity of the vortex and temperature detachment can be seen (the velocity vector field and temperature field).
The results of the temperature field visualized only the average value of the 3D flow (because of the principles of the Schlieren measurement technique). Both ends of the heated cylinder were outside the wind tunnel, so free convection (occurring outside the wind tunnel) can be seen in Fig. 5 and Fig. 6.

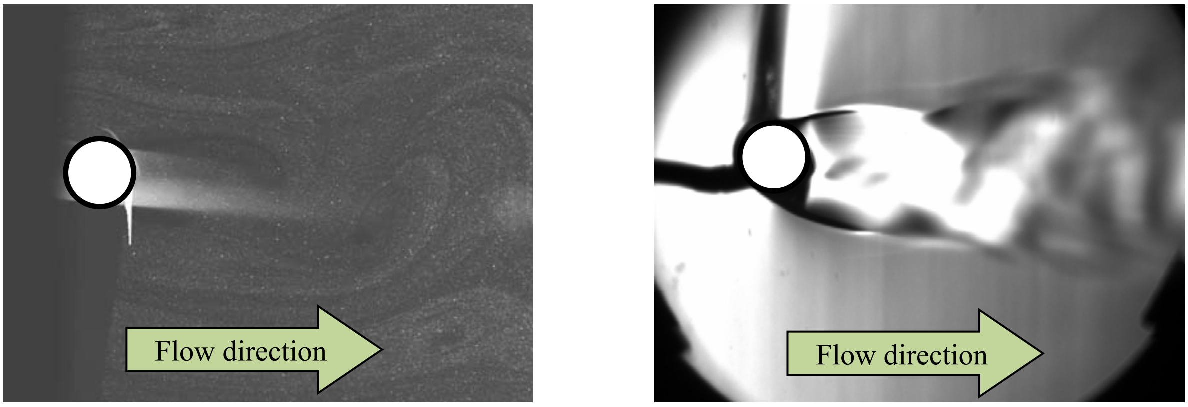


Figure 4. PIV (left) and Schlieren (right) raw images (heated cylinder surface temperature 300 ˚C; mean velocity 0.3 m/s).

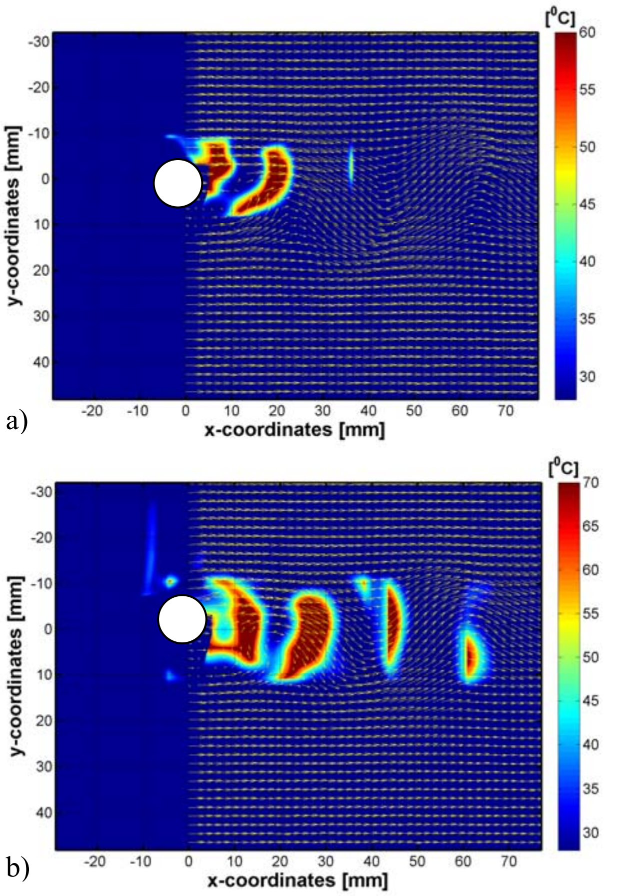


Figure 5. Temperature and vector field for a heated cylinder surface temperature of 100 ˚C (a)and 200 ˚C (b) with 0.3 m/s mean velocity).

Vertical temperature distribution over the heated cylinder can be seen in Fig. 5 and Fig. 6.
The relationship between the vortices and the heat transfer was visualized by the relevant measurement system (2D PIV and Z-type Schlieren system). The results show that the accuracy of the Schlieren system still requires some improvement.

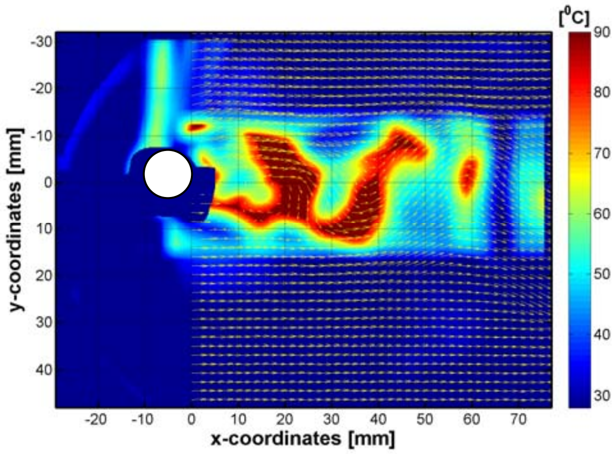


Figure 6. Temperature and vector field for a heated cylinder surface temperature of 300 ˚C with 0.3 m/s mean velocity.

The accuracy of the PIV system mainly depends on the following parameters: particle image diameter, particle image shift, particle image density and background noise [6]. Before being measured, the main parameters such as particle diameter, particle shift and particle density were optimized. A high-pass filter (cut off 537 *nm*) attached to the objective lens suppressed unwanted noise. In the post processing we apply the minimum correlation filter.
The accuracy of the Schlieren system depends mainly on the background light noise. The measurements were made in a dark room. Before performing the measurements, we measured the temperature in the wake of the cylinder at one point to validate the Schlieren post processing.
The PIV and Schlieren systems are suitable for determining the velocity and temperature field in the

wake of the heated cylinder. In the literature we found similar measurements [4] and the system was concluded to be suitable for analysis of those phenomena.

4 Conclusion

The measurement results presented in this work confirm that the Z-type Schlieren system is in principle suitable for the visualization and quantitative analysis of the temperature field in a wind tunnel. However, considerable improvement (such as a precision color filter) is still required in the existing system to carry out more accurate measurements. In order to analyze the images in a further step, the recording quality must be increased to obtain more meaningful images. These temperature field results will be useful for validation of our numerical simulation results (computed by our own code and by commercial software). The developed Matlab® script was successfully applied to the calculation of the temperature field from the measured deflection, resulting from the density variations in the flow. Thanks to the employed triggering mechanism, the temperature and velocity measurements could be reasonably synchronized and finally simultaneously presented. A further validation possibility should also be sought for checking the measured temperature values with the aim of detecting the differences in vortex shading due to the temperature of the cylinder.

Acknowledgements

The authors are grateful to NKTH-OTKA (68207) and to the Hungarian-German Intergovernmental S&T cooperation programs P-MÖB/386 for the financial support of this research.
The described work was carried out as part of the TÁMOP-4.2.1.B-10/2/KONV-2010-0001 project in the framework of the New Hungarian Development Plan. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

References

[1] Williamson, C.H.K.: *Vortex dynamics in the cylinder wake,* Annual Review of Fluid Mechanics, 28 (1996), 477-539.

[2] Wang, A.B., Trávníček, Z.: *On the linear heat transfer correlation of a heated circular cylinder in laminar crossflow using a new representative temperature concept*, International Journal of Heat and Mass Transfer, 44 (2001), 4635-4647.

[3] Baranyi, L., Szabó, Sz., Bolló, B., Bordás, R.: *Analysis of Flow Around a Heated Circular Cylinder,* Journal of Mechanical Science and Technology, 23 (2009), 1829-1834.

[4] Martínez-González, A., Guerrero-Viramontes, J.A., Moreno-Hernández, D.: *Temperature and velocity measurement fields of fluids using a Schlieren system,* Applied Optics, 51 (2012), 3519-3525.

[5] Hargather, M.J., Settles, G.S.: *A comparison of three quantitative Schlieren techniques,* Optics and Lasers in Engineering, 50 (2012), 8-17.

[6] Adrian, R.J.: *Particle-Imaging Techniques for Experimental Fluid Mechanics,* Annual Reviews in Fluid Mechanics, 23 (1991), 261-304.

[7] Toepler A.: *Observations by new optical method in fluid*. In: Meyer-Arendt, J.R., Thomson, B.J. (Eds.), *Selected Papers on Schlieren Optics,* WA: SPIE Optical Engineering Press Bellingham, 1992.

[8] Alvarez-Herrera, C., Moreno-Hernández, D., Barrientos-García, B.: *Temperature measurement of an axisymmetric flame by using a Schlieren system,* Journal of Optics A: Pure and Applied Optics, 10 (2008), 1-7.

[9] Settles, G. S.: *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media*, Springer-Verlag, Berlin, Heidelberg, 2001.

[10] Bencs, P., Szabó, Sz.: *Application of Z-type Schlieren technique for Flow Visualization around Heated Cylinder,* 14th International Symposium on Flow Visualization, Daegu, Korea, 2010, 1-7.