# ISFV 14

## The 14th International Symposium on Flow Visualization

**June 20 - 24, 2010** | EXCO, Daegu, Korea




_Organized by The Korean Society of Visualization

_Co-organized by Pusan National University
Brain Korea 21 Division of Mechanical Engineering for Emerging Technology, POSTECH

# INVESTIGATION OF THE VELOCITY (PIV) AND TEMPERATURE FIELD (BOS) OF A HEATED CYLINDER IN A LOW RE-NUMBER FLOW

Bencs, P.*, Szabó, Sz.*, Bordás, R.**, Thévenin, D.**, Zähringer, K.**, Wunderlich, B.**
* Department of Fluid and Heat Engineering
University of Miskolc, Hungary
** Laboratory of Fluid Dynamics and Technical Flows
University of Magdeburg "Otto von Guericke", Germany

**KEYWORDS**:
**Main subject(s):** *bluff body, heated cylinder, vortex structure, heat exchange,*
**Fluid:** *gas flow, low Re number,*
**Visualization method(s):** *PIV, BOS*
**Other keywords:** *experiment, forced convection, temperature field*

**ABSTRACT** : *During the following experiments a low Re number flow (Re < 200) was applied. The low Re number ensured that the vortex shedding was uniform along the axis of the cylinder. The experiments were carried out in a wind tunnel with an electrically heated cylinder of 10 mm diameter. The wake of the cylinder was investigated in a flow with 0.3 m/s mean velocity and at a cylinder mean temperature of 300 °C. The flow field was visualized by means of oil fog and the velocity field was determined by the Particle Image Velocimetry (PIV) method.*

*The main objective of this recent research was the determination of the temperature field. After the successful application of the Z-type Schlieren-technique, the Background Oriented Schlieren (BOS) method was applied as well. Numerous optical tests were carried out and the proper background pattern was selected. The recorded BOS-images were processed by a commercial PIV-software. The temperature field can be quantified by means of software based post-processing. Thus, it was proven that the BOS method can be applied for the described investigations. In the present work, optics was selected with a reduced optical distortion, enabling proper recordings of the flow behind the bluff body.*

## 1 Introduction

Bluff bodies placed in a flow often have different temperature compared to that of the surroundings, such as electrical transmission lines, cartridge heaters, pipes of heat exchangers, factory chimneys and so on. The structure of the flow developing around bluff bodies has been already examined for a long time [1, 2]. The evolving Kármán vortex street was and is examined by numerous researchers, both experimentally and numerically. Nevertheless the question arises, how this vortex street is modified by a heated cylindrical body. What is the influence of heating on the frequency of the detaching vortices, the structure of the vortices and the location of the detachment? We have already answered many of these questions with the help of numerical simulation and of measured velocity distributions using Particle Image Velocimetry (PIV) and the vorticity distribution obtained from this [3]. A further question is the heat loss caused by the vortex structure and the forced convection. To tackle this question, the Background Oriented Schlieren (BOS) method described below has been developed. At the same time, we have taken the first steps towards determining in real time the temperature and vorticity distributions, which we introduce in this paper.

The objective of this work was to carry out non-intrusive measurements of the temperature and flow fields by means of BOS and PIV respectively, using the experience from previous research [3-5]. The flow was examined behind a heated cylinder, mounted in a Göttingen-type (closed-loop) wind tunnel with suitable conditions. Future intention is to validate existing numerical calculations.

## 2 Experimental setup

In the following the measuring setup is introduced by describing the wind tunnel, the heated cylinder, the PIV/BOS methods and the triggering, which was important for the connection between the velocity and temperature field of the flow behind the cylinder.

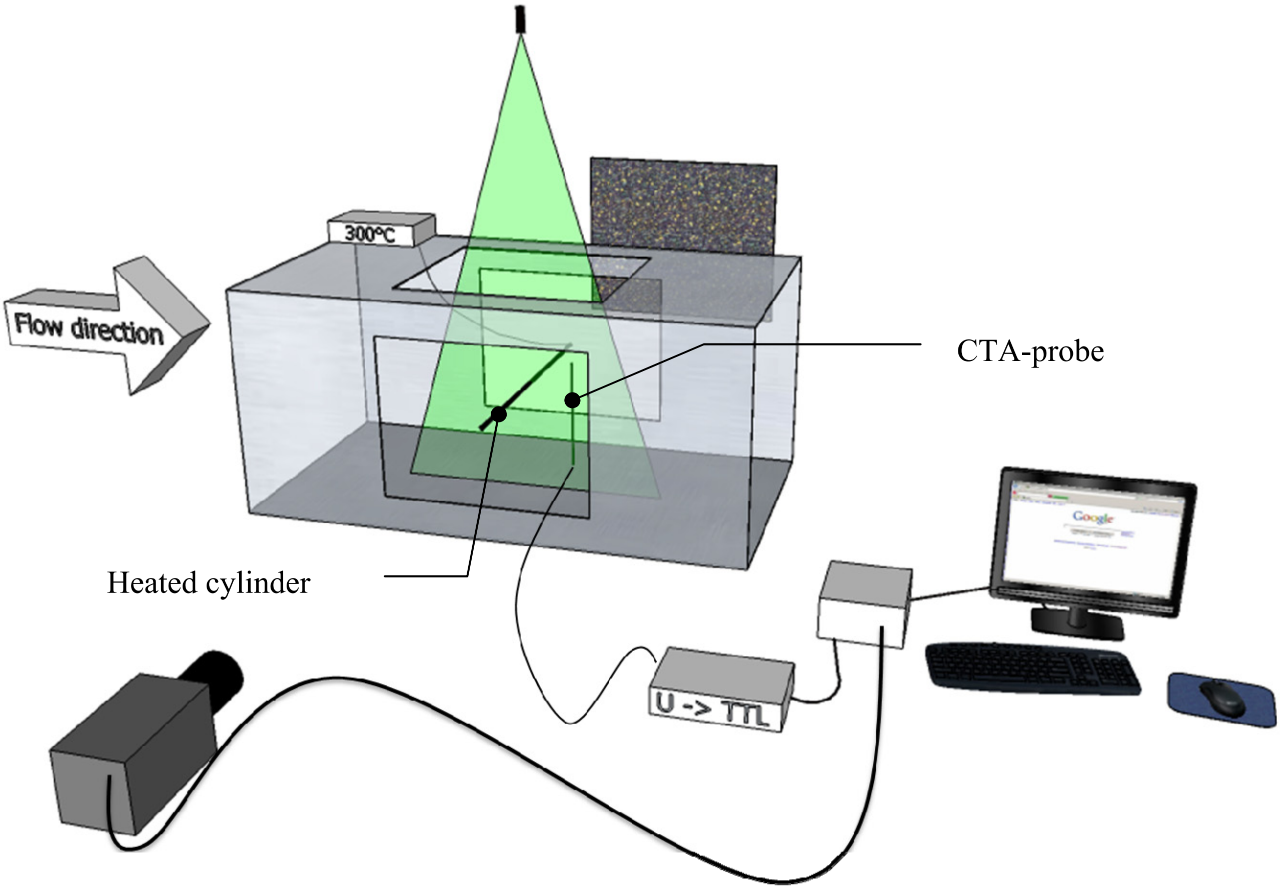


Fig. 1: Schematics of the experimental setup

### 2.1 Wind tunnel

The flow behind a heated cylinder was investigated in a closed-loop wind tunnel. The cross-section of the measurement area had the dimensions of 500x600 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. This led to a flow Reynolds number of Re=11,000, calculated from the mean flow velocity in the test section, the hydraulic diameter and the viscosity of the air at ambient temperature.

### 2.2 Heated cylinder

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 cylinder with a diameter of 10 mm was electrically heated by an adjustable transformer. 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 cylinder Reynolds number was Re=100, calculated with the mean flow velocity, the diameter of the cylinder and the viscosity of the air at the reference temperature [6] of $T_f = 0.5 \cdot (293+573)$ [K] ($\nu = 2.984 \cdot 10^{-5}$ m²/s). The predicted frequency of the vortex shedding was $f_S = 4.8$ Hz, calculated from a Strouhal number of St = 0.16 [6].
The main objective of the measurements discussed in this publication was to investigate the relation between the velocity and temperature field behind this heated cylinder in a low Re-number (cylinder reference) flow.

## 2.3 PIV/BOS system

The system used for the present measurements was a regular 2D-PIV system, consisting of the components listed in Table 1.

| Component | Remarks | Manufacturer |
|---|---|---|
| Double frame CCD camera | Flow Sense 2M/E with 8 bit resolution, recording freq.: 15 Hz | Dantec Dynamics |
| Objective | 105 mm AF Micro-Nikkor; *f*-number: 8 and focus set to ~3 m | Nikon |
| Double pulse Nd-YAG laser | Power: 2x300 mJ at 532 nm, max. frequency: 15 Hz | Litron |
| High-energy mirrors | for a wavelength of 532 nm | CVI Melles Griot |
| Laser sheet-optics | $f = -10$ | LaVision |
| Trigger box | Synchronization of camera and laser timing and for the trigger signals of the mini-CTA system | Dantec Dynamics |
| Mini-CTA system | Triggering the image recording according to the shedding vortices | Dantec Dynamics |
| PC with a frame grabber card and PIV software | For image data acquisition and for the processing of the acquired data | Dantec Dynamics |

Table 1: Description of the PIV/BOS system

The applied software for the acquisition and evaluation was a commercial PIV software (Dynamic Studio 3.0 from Dantec Dynamics), used both for the PIV and BOS measurements. The PIV measurements are only briefly discussed here, since there are numerous publications describing the principals of PIV (e.g., [7]). Camera alignment was the same for both PIV and BOS measurements. The camera was calibrated with the help of a calibration plate to set the pix/mm factor and to eliminate possible distortion. The camera optics was focused on the calibration plate and the *f*-number was set to 8.

### *2.3.1 PIV Measurements*

For the PIV measurements the back window was darkened, oil droplets of 3 µm diameter were added to the flow as tracer particles and the measurement plane was lit by the double pulse laser through the light sheet optics. For the evaluation, first an 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, without overlap. Finally, a range validation was applied for 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®.

### *2.3.2 BOS Measurements*

For the Schlieren measurements a background with white noise was generated and placed 1.5 m behind the plane of focus. The background was illuminated homogeneously with a halogen lamp, such that the same *f*-number could be applied as in case of the PIV measurements. The Schlieren recordings were carried out in single frame mode. The reference image (Fig. 2 left) was an average of 50 images without any flow or heating the cylinder (an image without density changes). The second image used for the BOS-correlation was the image with the temperature and thus density changes (Fig. 2 right).

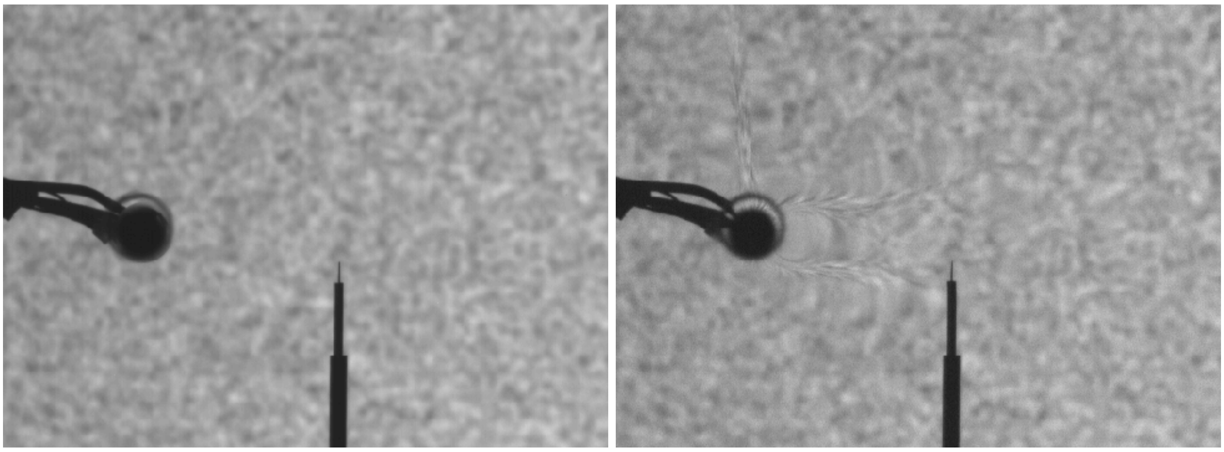

Fig. 2: The first (reference) and the second frame of a double frame BOS-image
(flow direction: from left to right)

The double frame images were created using a defined time between the frames (in this case $dt = 1$ ms), which was important for the calculation of the deflection from the exported velocity information. These images were then dewarped similar to those of PIV. Non-interesting areas (e.g. the cross section of the cylinder and the hole in the transparent windows) were masked out and finally a cross-correlation was carried out with an interrogation area of 32x32 pixels and an overlap of 75%. Finally, the vectors were smoothed by an average filter of 5x5 pixels. The results were also exported in an ASCII file for later post processing and visualization in Matlab®.

## 2.4 Mini-CTA system for triggering

To make sure that the temperature and velocity information were synchronized, a triggering was applied for the recordings. The synchronization was coupled to the vortex shedding behind the cylinder. To recognize the vortices, a mini-CTA probe was fixed behind the heated cylinder in the flow (see Fig. 1). The voltage output of the CTA-system was in correlation with the vortices (as both velocity and temperature changed in the flow). Then, a circuit with an adjustable threshold and TTL-signal output was switched into the system. In this manner, the input of the trigger-box could be applied to record the camera images as a vortex passed.

## 3 Results and discussion

The post processing was implemented in Matlab®. The previously exported ASCII files were imported, the temperature field was calculated, the velocity vectors were corrected and finally both fields are presented as contour plots with 2D-vectors.

### 3.1 Calculation of the temperature field

Since the software Dynamic Studio® exports the data with velocity units (m/s), these values should be multiplied by the time interval between the double frame images. Thus, from the velocity vectors the deflection could be obtained, which was important for the calculation of the density gradients. The angle of deflection $\varepsilon$ could be calculated using a simplified equation, valid for small angles of deflection [8]:

$$\varepsilon = \frac{d}{z_d}, \tag{1}$$

where $d$ was the measured deflection in [m] and $z_d$ the distance between the Schlieren object and the background image. Equation (2) defined the relation between the angle of deflection $\varepsilon$ and the density gradient $\Delta\rho$:

$$\varepsilon = Gw\Delta\rho, \tag{2}$$

where $G$ was the Gladstone-Dale constant (see Eq. 3) and $w$ = 10 mm is the width of the Schlieren object. Using Eq. (1) and Eq. (2), the density gradient could be calculated directly from the deflection. The Gladstone-Dale constant was found using the relation between the index of refraction and the density of the medium:

$$n = G\rho + 1. \tag{3}$$

Thus the density field could be calculated using the following equation:

$$\rho_n = \rho - \frac{d^2}{z_d Gw}. \tag{4}$$

Finally, the temperature field was calculated using the ideal gas law and presented as a contour plot.

### 3.2 Improvement of the velocity results

The results of the PIV measurements were acceptable except for the region, where the cylinder threw a shadow and the tracer particles were insufficiently illuminated (see Fig. 3). This region was then corrected in Matlab® and the velocity vectors were replaced by the interpolated ones from those obtained along the boundary of the shadow.

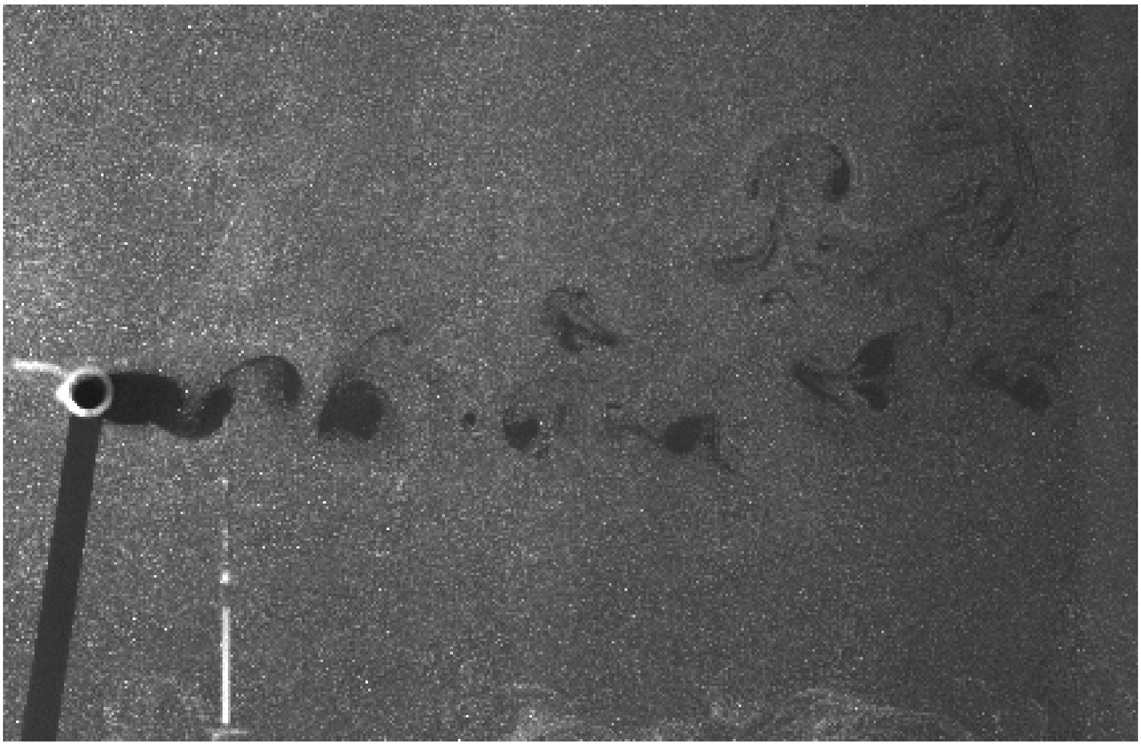

Fig. 3: PIV raw image. The shadow of the cylinder can be noticed.

### 3.3 Results and discussion

Two exemplary temperature and velocity images are presented in Fig. 4. It can be seen that the results for the temperature field (coulor plot) are appropriate. The high temperature regions can be recognized behind the cylinder in the detached vortex pockets; their temperature is within the expected range. The measured velocity ranges between 0.25 and 0.4 m/s and thus within the expected range around the mean velocity of the flow (0.3 m/s). It can also be seen that there is a relationship between the velocity and temperature distribution behind the heated cylinder. The vortex-street can be followed very well in both cases.

However, several improvements are still required. A proper method should be found to calibrate or validate the measured temperature field. The triggering mechanism should also be improved, since the time interval between two trigger signals was not always regular thus making it difficult to superimpose corresponding velocity and temperature fields.

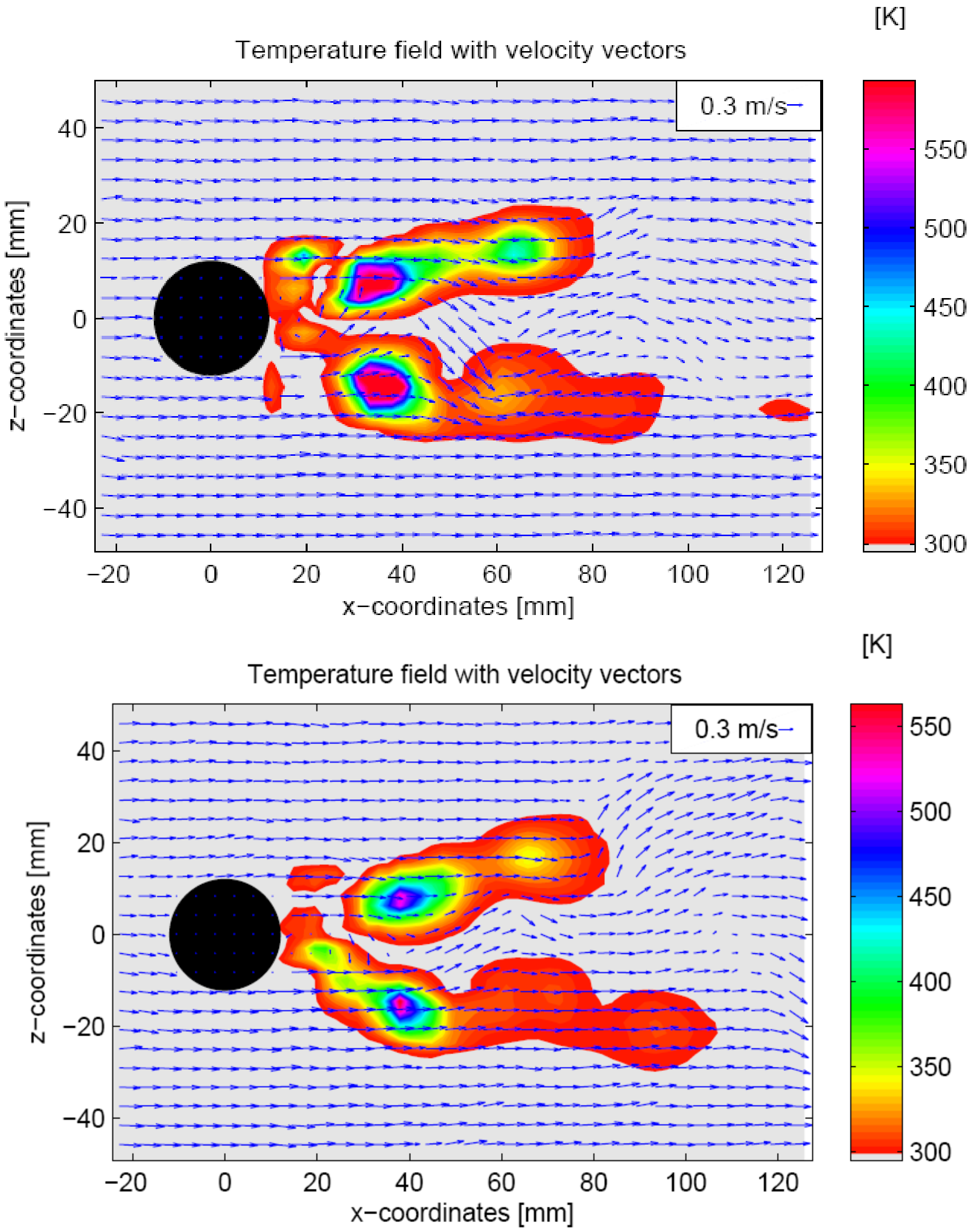


Fig. 4: Visualization of temperature and velocity field around the heated (573 K) cylinder

## 4 Conclusions

The measurement results presented in this work confirm that the BOS system is suitable to visualize and quantitatively describe the temperature field of the vortex street behind a heated cylinder in a wind tunnel. 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. Thank to the employed triggering mechanism, the temperature and velocity measurements could be reasonably synchronized and finally presented simultaneously. However, considerable improvements (especially concerning triggering and optics) are still required in the existing system to make more reliable and comparable measurements. A further validation possibility should also be found to check the measured temperature values in the aim to detect 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 help of M. Schulze and J. Hessenkemper is also appreciated during the measurements.

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