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INFLUENCE OF BACKGROUND PATTERN ON THE TEMPERATURE FIELD MEASURED BY BACKGROUND ORIENTED SCHLIEREN

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

ABSTRACT: Bluff bodies placed in a flow with a different temperature compared to that of the surroundings are of wide interest in practical engineering as well as in scientific applications. The objective of this work is to find the optimal dot density for the background pattern used in Background Oriented Schlieren (BOS) measurements. BOS is based on light deflection of a background pattern due to density gradients in the investigated flow field. The present contribution considers the effect of different background structures on the resulting temperature field. It is obvious that the background quality (dot pattern and density) have an influence on the results, when the temperature (density) gradients locally vary. The measurements are carried out in the wake of an electrically heated cylinder (with a diameter of 10 *mm* and with a maximum surface temperature of 300 *°C*) mounted in a wind tunnel with a closed test section. The flow is kept in the laminar region. Such a flow is mostly two-dimensional, i.e., the flow does not change considerably along the axis of the cylinder. The main innovation of the developed method is the associated visualization of the temperature field. BOS is now employed in order to obtain quantitative results. First synchronization tests have helped determining the proper background pattern and the delay process for BOS in the present configuration.

1 Introduction

Bluff bodies placed in a flow, such as electrical transmission lines, cartridge heaters, pipes of heat exchangers, factory chimneys and so on, often have a different temperature compared to that of the surroundings. The structure of the flow developing around bluff bodies has been investigated for a long time [1-7]. The Kármán vortex street was and is examined by numerous researchers, both experimentally and numerically. Nevertheless, the question arises as to how this vortex street is modified by a heated cylindrical bluff 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? Many of these questions have already been answered with the help of numerical simulations and of measured velocity and vorticity distributions using Particle Image Velocimetry (PIV) [1-7]. 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 is applied here. At the same time, first steps have been taken towards determining temperature and vortex distributions simultaneously, as discussed in this paper. Main objective and novelty of this work is the developed solution for simultaneous measurements with a single camera using the experience from previous projects [8,9].

Different background patterns were examined to obtain high quality BOS measurements of the temperature field. Forced convection was investigated behind a heated cylinder, mounted in a Göttingen-type (closed-loop) wind tunnel, with repeatable conditions. These results will be used to validate companion numerical calculations. This project is a fundamental research project, which is supported by Hungarian, German and European Union fundings.

2 Experimental setup

The experimental setup (Fig. 1) is mounted in a closed-loop wind tunnel. The cross section of the test area had the dimensions of 500x600 *mm*.

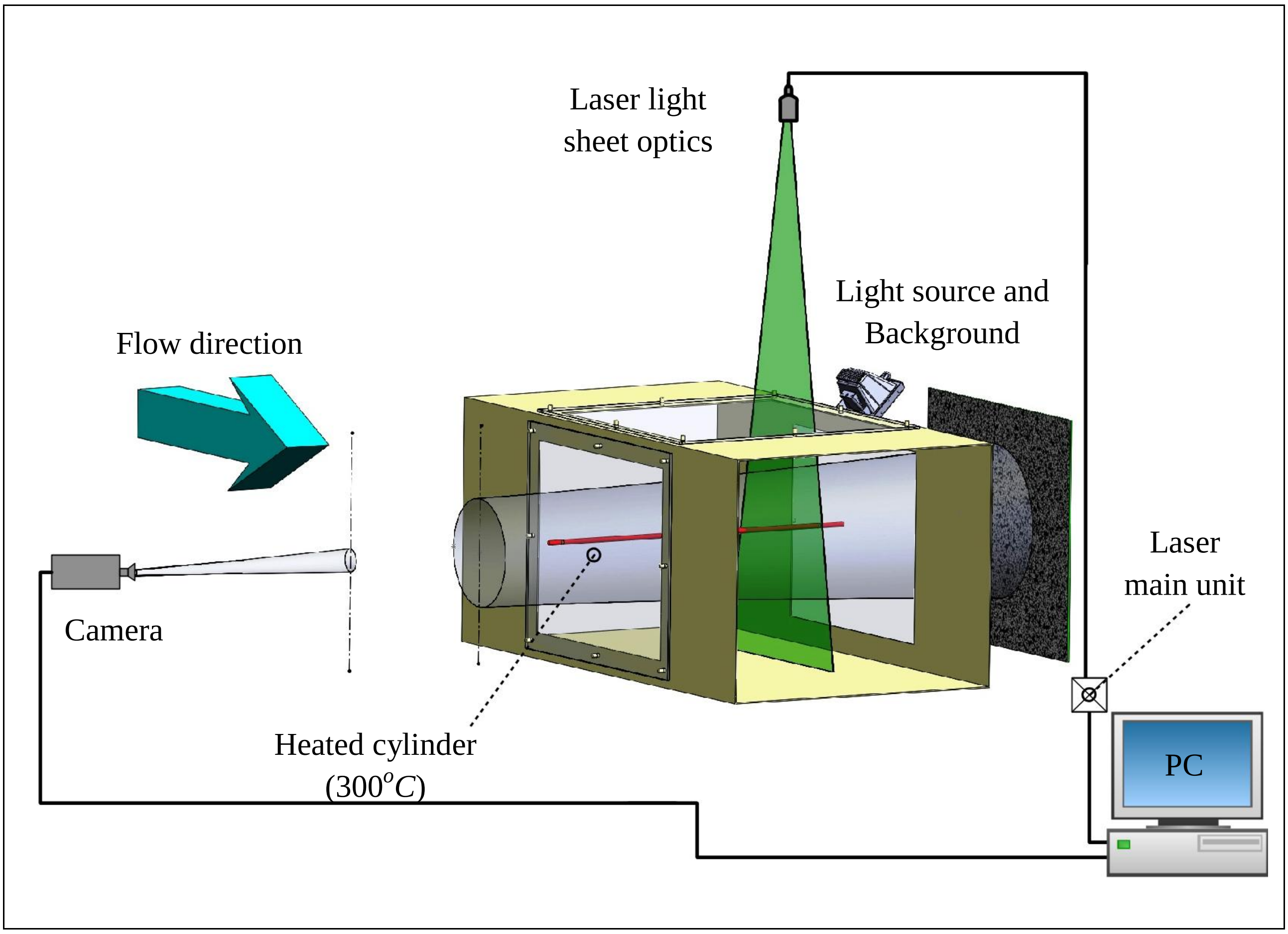


Fig. 1: Schematics of the experimental setup

For first tests, a low flow velocity is helpful. Hence, the mean airflow velocity was set to v=0.3 *m/s*, since this was the minimum stable velocity of the wind tunnel. This led to a wind tunnel Reynolds number of Re=11 000, calculated from the mean flow velocity in the test section, the hydraulic diameter of the wind tunnel and the viscosity of 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 perpendicular to the main flow direction (Fig. 1). The cylinder with a diameter of d=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 set to the required value. The main temperature of the cylinder was 300$^o C$ during all measurements. The cylinder Reynolds number was Re_{cyl}=200, calculated with the mean flow velocity, the diameter of the cylinder and the viscosity of air at ambient temperature.

2.1 BOS system

The system used for the present measurements was a planar, double frame camera system, consisting of the components listed in Table 1.

Component	Remarks	Manufacturer
Double frame CCD camera	FlowMaster3S ImagerIntense with 12 bit resolution, recording freq.: 10 *Hz*	LaVision
Objective	105 *mm* AF Micro-Nikkor; *f*-number: 11 and focus set to ~3 *m*	Nikon
PC with a frame grabber card and software	DaVis 7.2 for image data acquisition and PIVlab for processing of the acquired data	LaVision; W. Thielicke

Table 1: Description of the PIV/BOS system

The applied software for the acquisition and evaluation was a commercial PIV software (DaVis software ver. 7.2 from LaVision), used for the 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 11.

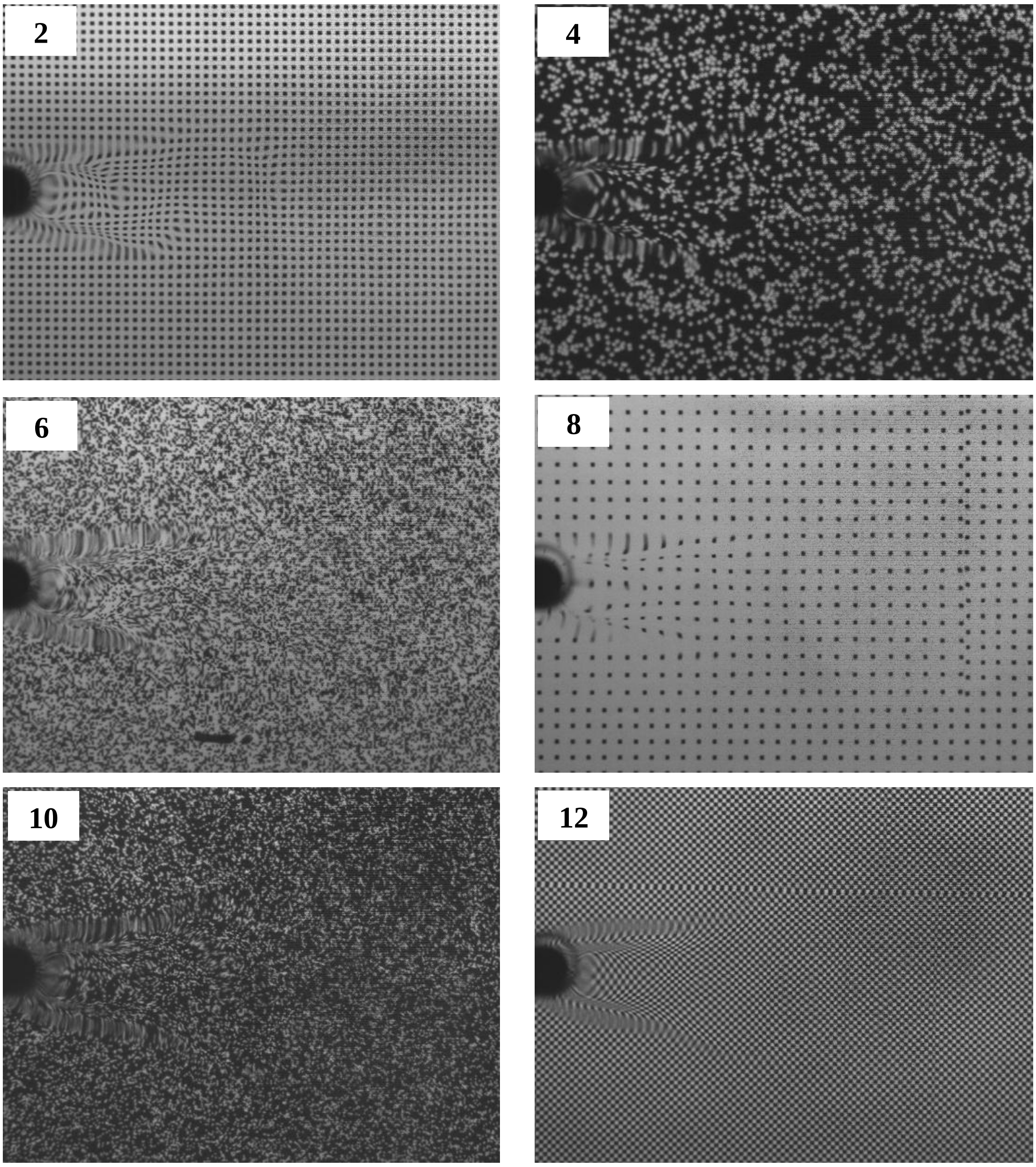
2.2 Background patterns

No.	Remarks	No.	Remarks
1.	Square Pattern[1]	15.	Triangular Pattern[1]
2.	Square Pattern[2]	16.	Triangular Pattern[2]
3.	Random Pattern (50000 1*mm*)[1]	17.	Triangular Pattern double size, 2 lamps[1]
4.	Random Pattern (50000 1*mm*)[2]	18.	Triangular Pattern double size[1]
5.	Random dot field Pattern[1]	19.	Triangular Pattern double size, 2 lamps[2]
6.	Random dot field Pattern[2]	20.	Triangular Pattern double size[2]
7.	Variable density Square Pattern[1]	21.	Triangular Pattern 2 double size, 2 lamps[1]
8.	Variable density Square Pattern[2]	22.	Triangular Pattern 2 double size[1]
9.	Random Pattern (50000 0.8*mm*)[1]	23.	Triangular Pattern 2 double size, 2 lamps[2]
10.	Random Pattern (50000 0.8*mm*)[2]	24.	Triangular Pattern 2, double size[2]
11.	Double triangular Pattern[1]	25.	Variable Background Pattern 2, 2 lamps[1]
12.	Double triangular Pattern[2]	26.	Variable Background Pattern 2[1]
13.	Variable Background Pattern[1]	27.	Variable Background Pattern 2, 2 lamps[2]
14.	Variable Background Pattern[2]	28.	Variable Background Pattern 2[2]

Table 2: Investigated background patterns

[1] Exposure time = 64 *ms*
[2] Exposure time = 102 *ms*

To improve the quality of non-intrusive measurements concerning the temperature field, different background patterns were tested during BOS measurements. These different background patterns are listed in Table 2. Following pictures (Fig. 2) illustrate those background patterns. Here and in all further images, the flow is always from left to right. All backgrounds were produced by an in-house script developed running under Matlab® software. The retained backgrounds build on top of published results as well as on our own previous experience [8,9].



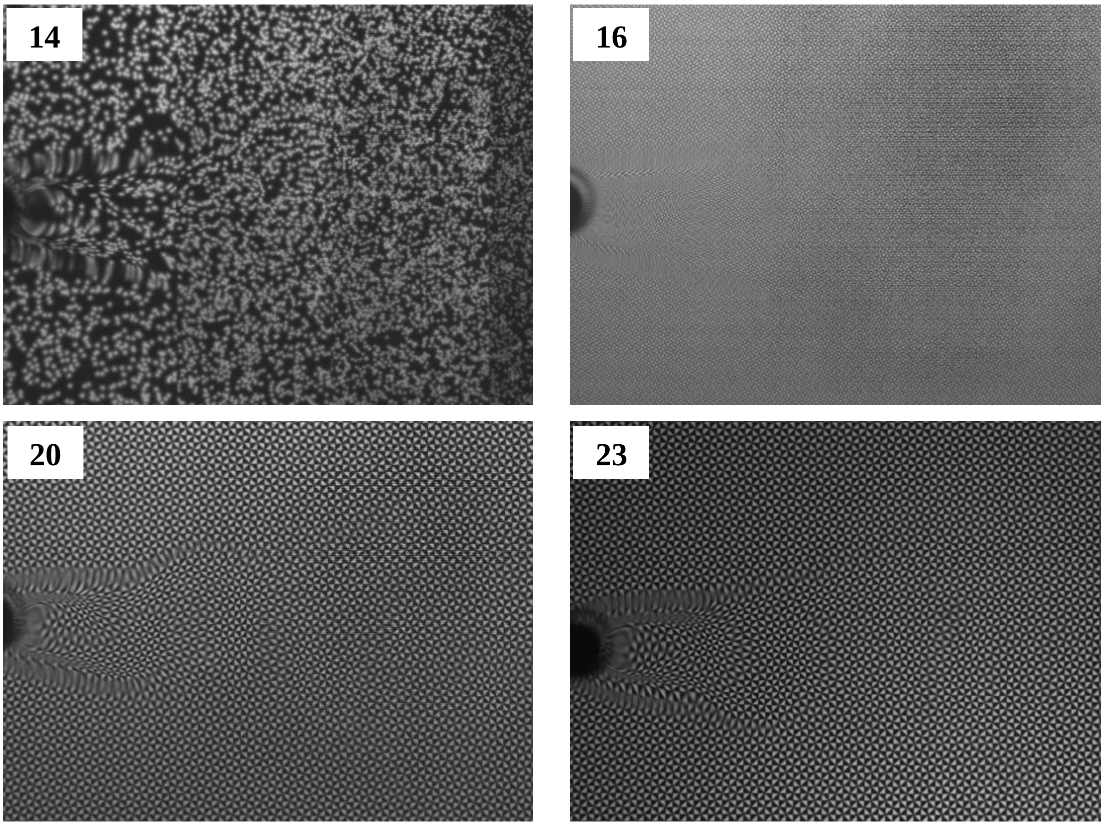


Fig. 2: Different background patterns during operation

For all BOS measurements the background was placed 0.28 *m* behind the plane of focus and was illuminated homogeneously with a halogen lamp, such that the same *f*-number could be applied as in for the PIV measurements. The Schlieren recordings were carried out in single frame mode. The reference image (Fig. 3 left) was without any flow or without heating the cylinder (i.e., an image without density changes). The second image used for the BOS-correlation was the image with heat exchange and thus density changes (Fig. 3 right).

For image analysis, the open source Matlab® code PIVlab 1.31 was always used (command line version). The same settings were applied to all BOS pictures. The Region Of Interest was determined in the software and the interrogation area also was set in the software code.

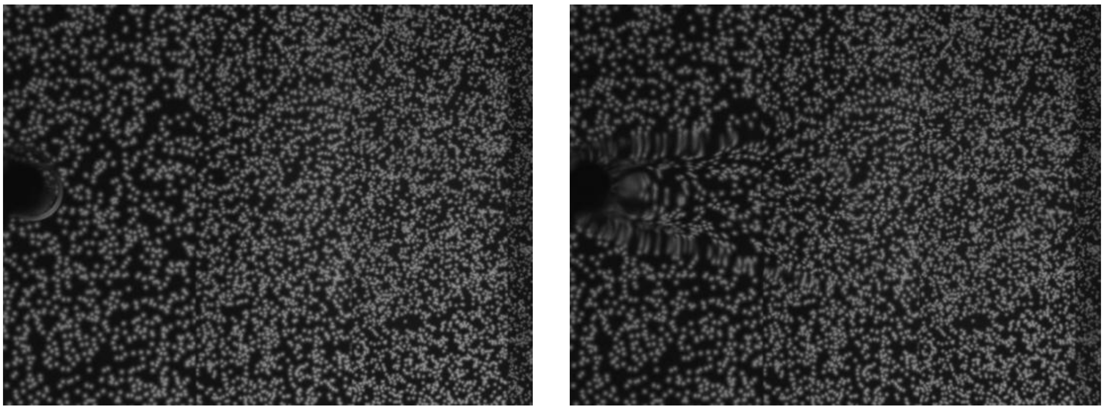


Fig. 3: First (reference, left) and second frame (with heat exchange, right) of a double frame BOS-image (background #27).

Non-interesting areas (e.g. the cross section of the cylinder and the hole in the transparent windows) were masked out and then a cross-correlation was carried out with an interrogation area of 32x32 *pixels* and an overlap of 50%. Finally, the vectors were validated. The results were exported in a MAT file for later post processing and visualization in Matlab®.

3 Results and discussion

The full post processing was implemented as Matlab® script. The previously exported MAT files were imported and the temperature field was calculated. 101 pictures were made with each type of background pattern and were analyzed by the Matlab® code.

3.1 Error vectors in cross-correlation process

Erroneous vectors were determined before the vector validation process in the PIVlab software.

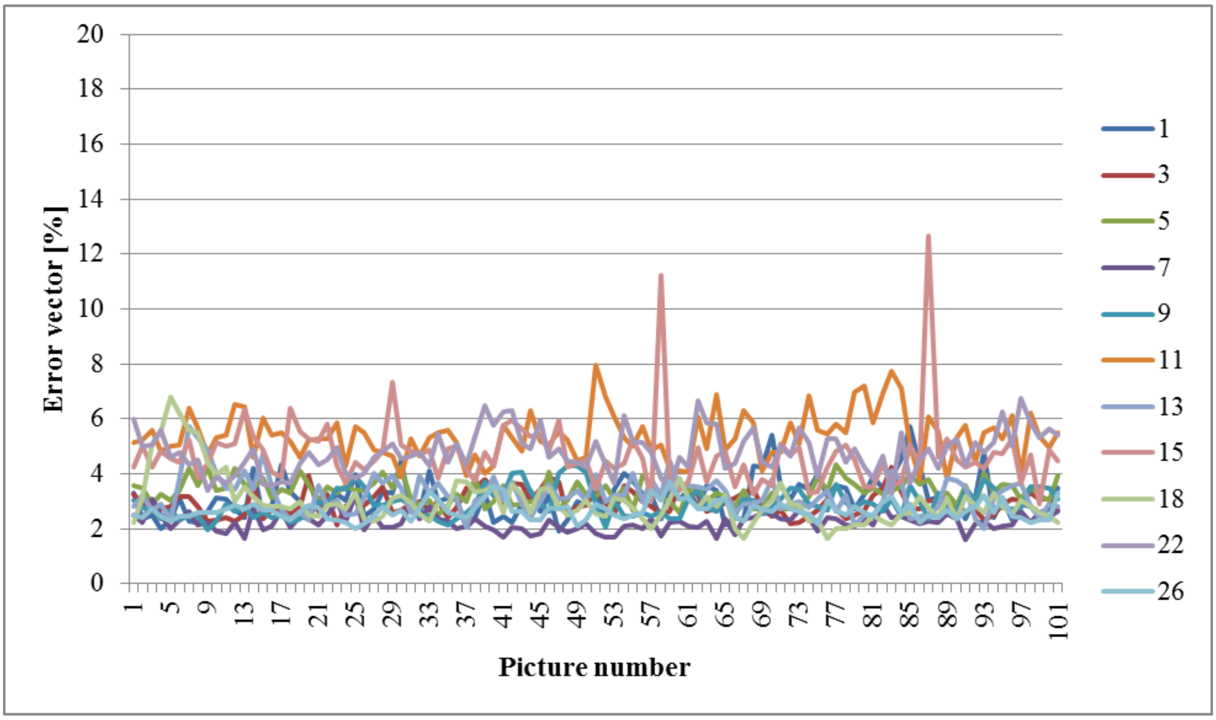


Fig. 4: Error vectors in case of exposure time 64 *ms* for selected backgrounds

An erroneous vector is a vector outside the valid region, which is manually defined due to the physically plausible temperature range: larger or equal to ambient temperature and smaller or equal to the surface temperature of the heated cylinder.

Figures 4 and 5 show that the number of erroneous vectors divided by the total number of vectors found during the cross-correlation process are less than 10% (for both cases: Exposure time 64 *ms* and 102 *ms*). Even if the cross-correlation process appeared to work reasonably well, the percentage of erroneous vectors varies noticeably as a function of the background and from image to image. In order to identify the best background patterns, further processing was carried out.

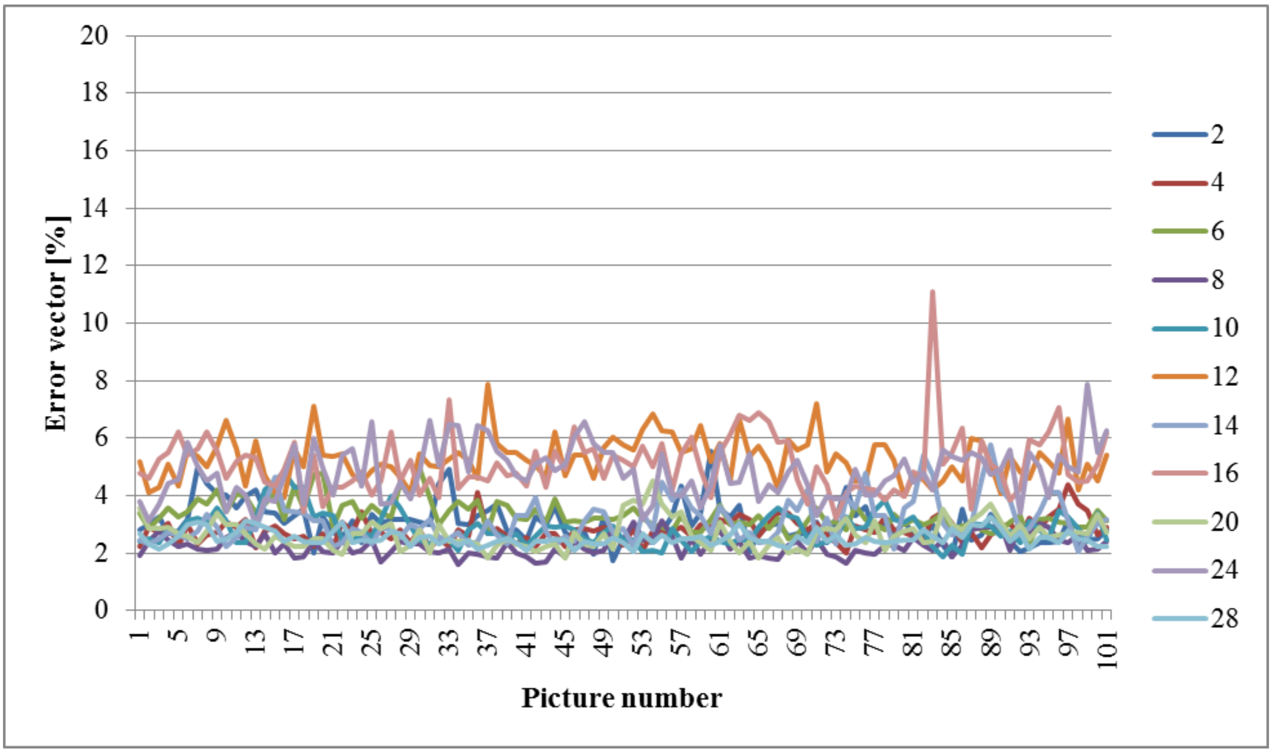


Fig. 5: Error vectors in case of exposure time 102 *ms* for selected backgrounds

3.2 Efficiency of background patterns

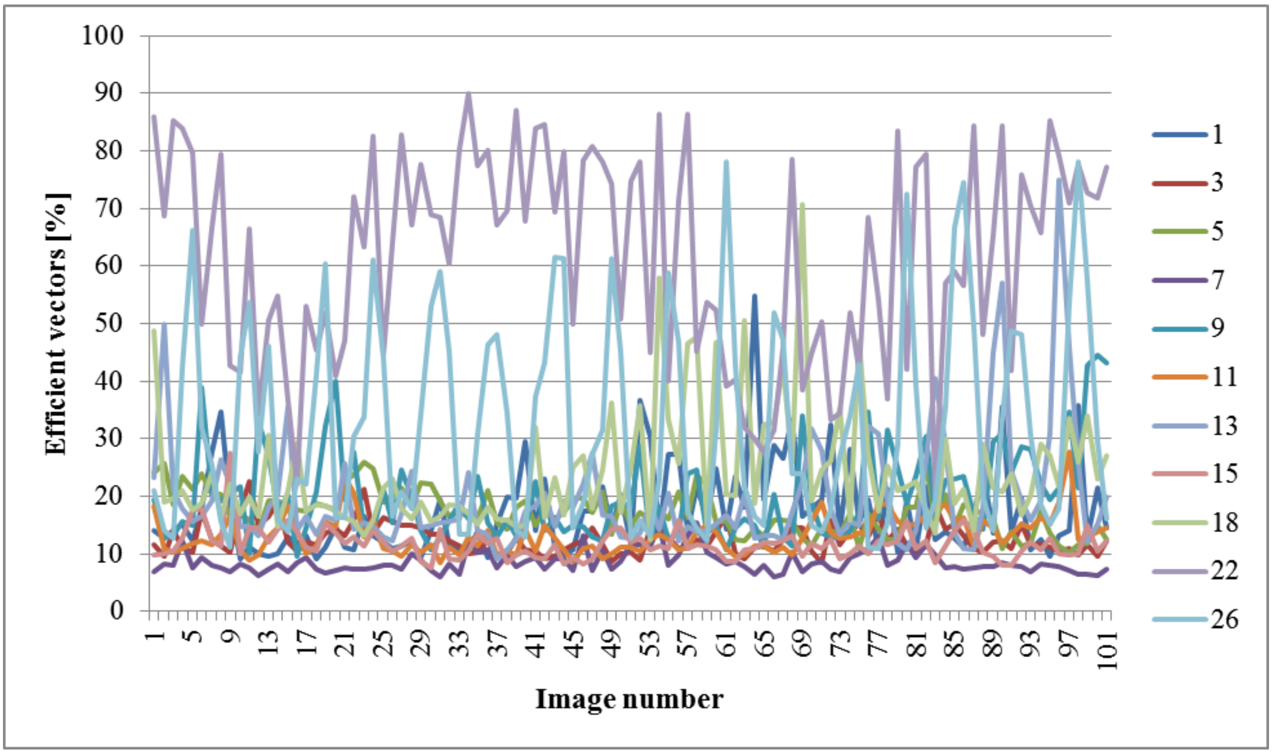


Fig. 6: Efficient vectors in case of exposure time 64 *ms* for selected backgrounds

Efficiency has been calculated analogous to the percentage of the erroneous vectors, but the range considered valid now does not take into account the ambient temperature. With other words, efficiency quantifies the number of vectors with a noticeable temperature difference compared to the ambient temperature.

Figure 6 shows, that efficiency of background patterns #22 and #26 is maximum, leading possibly to the best results for the employed BOS system. The results shown in Fig. 6 were similar in the second case, when setting the exposure time to 102 *ms* (not shown).

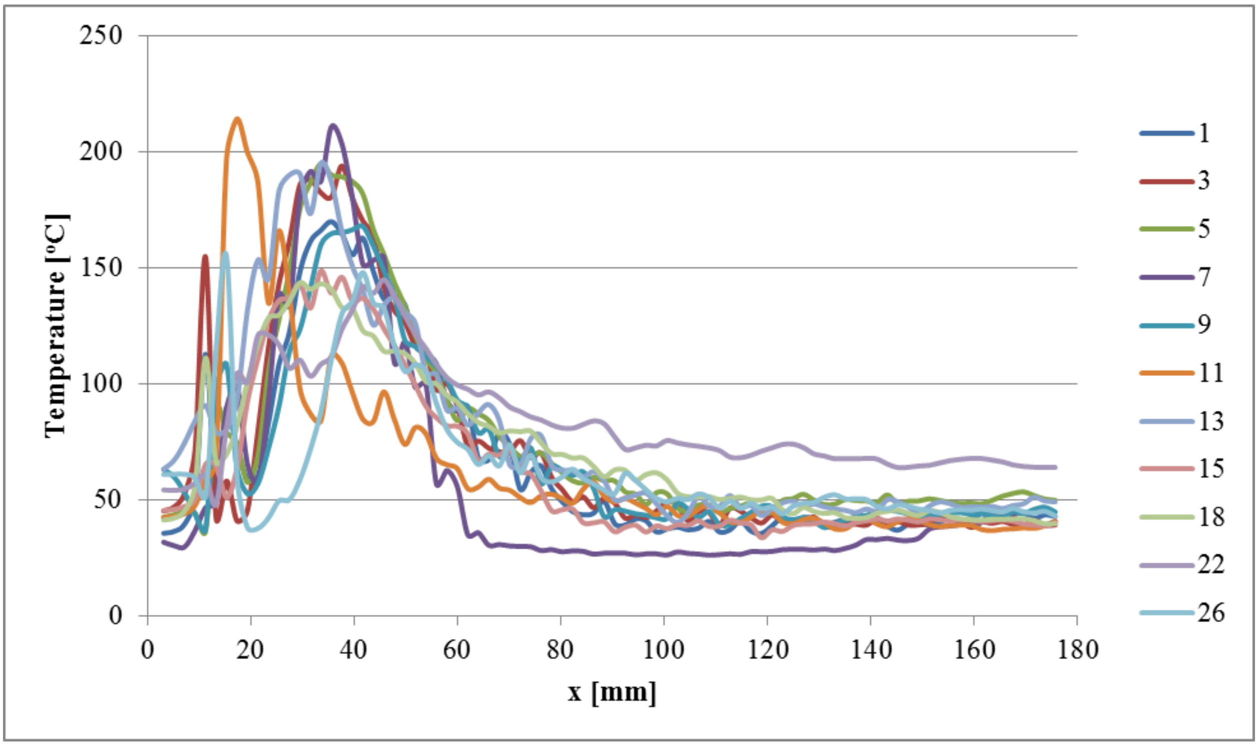


Fig. 7: Average temperature distribution along the centerline downstream of the cylinder

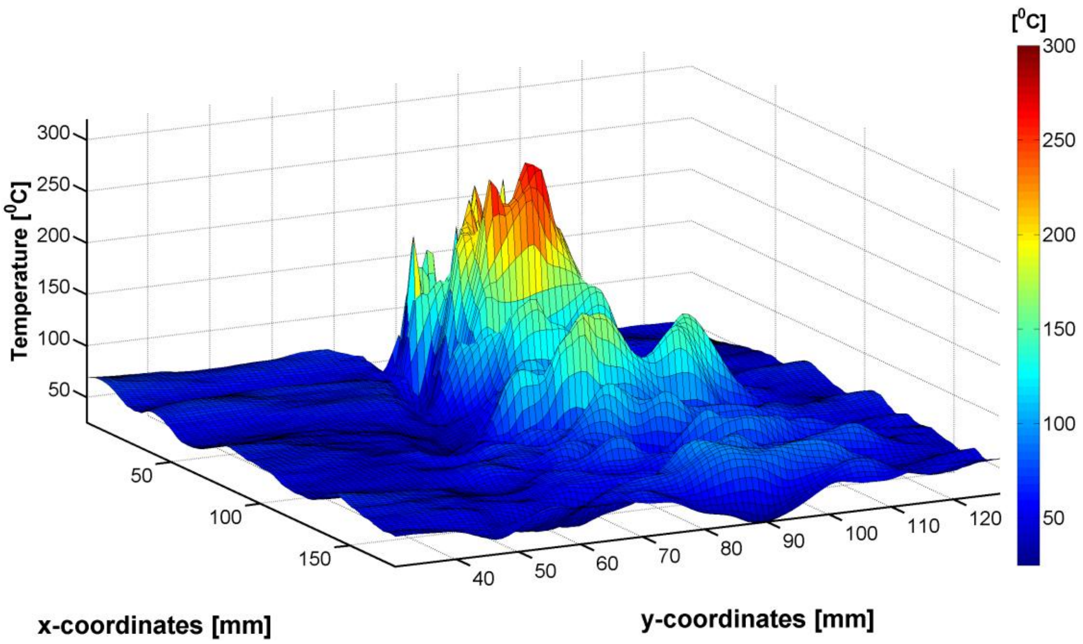


Fig. 8: Average temperature distribution behind the cylinder (background #26)

Figure 7 shows the average temperature distribution obtained from all 101 images for each background pattern, obtained when the exposure time was 64 *ms* (similar results were obtained with an exposure time of 102 *ms*). Even if pattern #22 has been identified by the efficiency criterion as one of the most suitable backgrounds, it is clear from Figure 7 that this pattern delivers unrealistic high temperature values. Therefore, the most suitable pattern according to both criteria is clearly the pattern #26. Figure 8 shows the average temperature distribution in space using the best background pattern (#26).

4 Conclusions

The measurement results presented in this work confirm the impact of the employed background pattern to quantitatively measure the temperature field of the vortex street behind a heated cylinder in a wind tunnel. The developed Matlab® script was successfully applied to the analysis of the temperature field and the most suitable pattern for the present conditions has been identified (#26). In order to quantify more precisely measurement errors and accuracy, a further validation possibility should be identified in order to check the measured temperature values. Afterwards, it will become possible detect the differences in vortex shedding due to the temperature of the cylinder.

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