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Chapter 1
Examples of Application

In this chapter a number of applications of the PIV technique will be described, contributed by leading PIV experts from different research establishments and universities worldwide. A complete list of authors and their affiliation is given in the acknowledgement at the beginning of this book.

Primarily, the objective of presenting these applications is to show how the PIV technique has spread out to the most different research areas. However, it is of even higher importance to gain the reader access to a wide variety of ideas for PIV measurements by presenting many different applications in fundamental or industrial research. For each experiment the most important parameters of the object under investigation, of the illumination and recording setup, etc. will be given. These data together with the hints and tricks briefly described and the references to further, more detailed, literature may be useful for the reader when trying to solve problems of his own application.

1.1 Combined PIT / PIV of Air Flows Using Thermochromic Liquid Crystals

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Thermal convective air flows are abundant in technical applications such as heat exchangers or indoor climatisation and of great interest in fundamental studies as well. Since such flows are driven by temperature gradients, simultaneous acquisition of the instantaneous velocity and temperature fields are highly desirable. In this context, our study aims at the dynamics of thermal plumes as well as their influence on the local and global heat transfer in thermal convection. Hereto, measurements of mixed convection of air in a
Table 1.1 PIV recording parameters for turbulent thermal convection using thermochromic liquid crystals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow geometry</td>
<td>turbulent mixed convection in a cuboidal sample with rather low out-of-plane component</td>
</tr>
<tr>
<td>Maximum in-plane velocity</td>
<td>$U_{\text{max}} \approx 0.15 , \text{m/s}$</td>
</tr>
<tr>
<td>Field of view</td>
<td>$250 \times 150 , \text{mm}^2 (W \times H)$</td>
</tr>
<tr>
<td>Interrogation volume</td>
<td>$5.0 \times 5.0 \times 8.0 , \text{mm}^3 (W \times H \times D)$</td>
</tr>
<tr>
<td>Dynamic spatial range</td>
<td>DSR $\approx 30 : 1$</td>
</tr>
<tr>
<td>Dynamic velocity range</td>
<td>DVR $\approx 100 : 1$</td>
</tr>
<tr>
<td>Dynamic temperature range</td>
<td>DTR $\approx 20 : 1$</td>
</tr>
<tr>
<td>Observation distance</td>
<td>$z_0 \approx 1300 , \text{mm}$</td>
</tr>
<tr>
<td>Recording method</td>
<td>dual frame/single exposure</td>
</tr>
<tr>
<td>Recording medium</td>
<td>Pixelfly qe @ 1280 $\times$ 1024 pixels for PIV</td>
</tr>
<tr>
<td></td>
<td>Pixelfly colour @ 1280 $\times$ 1024 pixels for PIT</td>
</tr>
<tr>
<td>Recording lens</td>
<td>$f = 50 , \text{mm}$ $f_p = 1.4$</td>
</tr>
<tr>
<td>Illumination</td>
<td>60 white LEDs (OSRAM Platinum Dragon)</td>
</tr>
<tr>
<td>Pulse delay</td>
<td>$\Delta t = 8 \sim 16 , \text{ms}$</td>
</tr>
<tr>
<td>Seeding material</td>
<td>thermochromic liquid crystals (TLCs)</td>
</tr>
</tbody>
</table>

cuboidal sample with aspect ratio $1 \times 1 \times 5 \, (W \times H \times L)$ were performed (see figure 1.1).

For simultaneous measurement of temperature and velocity fields, mainly two different approaches are followed: Since many decades, PIV is combined with Particle Image Thermography (PIT) for flow measurements in liquids using thermochromic liquid crystals (TLCs) as tracer particles (“TLC-PIV”) [3]. This approach allows for very precise measurements of small temperature differences at moderate temperatures. For a survey on this technique, the reader is referred to the recent review given by Dabiri [2]. A rather new approach comprises thermographic phosphor particles as tracer particles [1]. These are useable for larger temperatures ranges, however, providing an accuracy of the order of 1 K only. For our study of mixed convection of air, we needed a very high temperature precision, and hence, adopted the TLC-PIV technique from liquids.

![Fig. 1.1 Sketch of the mixed convection sample.](image)
Under illumination with white light, TLCs reveal the special behaviour to appear in different colours, depending on their temperature. More specifically, different wavelengths are reflected preferentially as a function of temperature. Further, the wavelength of the reflected light depends on the size of the particles and the viewing angle. Hence, for each experimental setup, a colour-temperature calibration has to be conducted. First experiments using TLCs to visualize the temperature field have been conducted by Hiller et al. [3]. Nowadays, the technique is well established for investigations in liquids. However, its high effort, in specific for the calibration of the TLCs, makes this technique still challenging to use.

The usage of the TLCs for combined PIV / PIT in air flows is mainly restricted by the size of the TLC particles. On the one hand, the particles must be as small as possible in order to ensure good tracking of the fluid motion. On the other hand they must be large enough in order to provide a good colour play. Estimations result in suitable particle diameters for air flows of the order of 10 \( \mu \text{m} \) [5]. This is about one order of magnitude smaller as compared to TLC particles commonly used in liquids. Accordingly, particle generation, illumination and image filtering processes state a challenge when using TLCs as tracer particles for PIT in air flows.

We realized the particle generation using a solvent and atomization processes. The thermal and mechanical response times as well as details of the particle generation are described in Schmeling et al. [5]. Therein, the newly developed high intensity white light source based on LEDs is described as well. The light source provides a homogeneous lightsheet with a thickness of 9 mm over a distance of 500 mm, see figure 1.2(a). While the hue value of the colour image is determined by the temperature of the TLCs [2], image filtering to increase the signal-to-noise ratio is conducted using the saturation and the value component. Therefore, the image is sliced into interrogation windows, in which only those pixels are taken into account, that have the \( n \)-highest V values (HSV colourspace). The hue values of these pixels are used to calculate an average hue value for the interrogation window. More details on the image filtering routine can be found in [5]. The hue-temperature calibration is usually performed at constant temperature conditions. However, in our system with continuous air exchange, such uniform and stable conditions for the temperature can not be achieved. Therefore, a dynamic calibration is applied to correlate temperature and hue values. It is based on the simultaneous recording of the temperature using a precisely calibrated, fast-reacting tiny glassbed thermistor and the hue component of the colour image in its surrounding, see figure 1.2(b). A correlation between hue signal and the recorded temperature returns the calibration function. A detailed error propagation allows to estimate an absolute and relative error of 0.19 and 0.06 K, respectively. The latter results in a dynamic range of 20 based on the investigated temperature range.

Dewarping of the b/w and the colour image (see e.g. figure 1.3(a)), which has to be recorded in backward reflection to improve the colour play of the
Fig. 1.2 Intensity (photo voltage) and width of the lightsheet (fwhm) as a function of the distance from the front lens (left), time series of hue (TLCs) and temperature (calibration thermistor) (right).

Fig. 1.3 Raw colour particle image, blue particles correspond to warm, whereas red ones to cold regions (colour image @dc(dc-tlc-piv-raw-colour-image)) (a), from top to bottom: horizontal and vertical pixel displacement as well as horizontal and vertical sub pixel displacement statistics (b), interrogation windows of frame 1 and 2 as well as correlation plane (bottom) (c).

TLCs, as well as the superposition of the two images were conducted using well-known stereo-PIV algorithms. Standard 2C-2D PIV algorithms were used to calculate the velocity field, see figure 1.3(b) and 1.3(c) for details.

Figure 1.4 shows an evaluated temperature and velocity field. It represents the vertical cross section through a hot thermal plume, which was formed in the bottom thermal boundary layer and rises through the sample. Since the plume transports heat from the warm to the cold plate of the convection sample, it is of great scientific and industrial interest to get a deeper understanding of the plume dynamics. The presented figure shows the stem of the plume, where the region of warmest fluid correlates with upward motion. The top part of the plume is defined by its two side swirls. This mushroom-like shape is also name giving for this type of thermal plume. To our best knowledge the results presented in [5], are the first experimental measurements representing a thermal plume with such high accuracy in air. A colour version of this figure as well as the time evolution, recorded at a frequency
Fig. 1.4 Instantaneous temperature and velocity field, recorded at $Pr = 0.71$, $Ra = 9.0 \times 10^7$ and $Re = 0$, that is, no external pressure gradient was applied (colour image @dc(dc-tlc-piv-result-image) and video @dc(dc-tlc-piv-result-video)). Every other vector is shown in each direction.

of 4 Hz, can be found online. A further application of this measurement technique can be found in [6], wherein a the behaviour of line-plumes in a horizontal layer close to the bottom boundary layer of this convection sample was investigated.

As an outlook we want to emphasize recent results of Schiepel et al. [4], who combined PIT using TLCs with tomographic PIV to capture all three velocity components and the temperature in a three dimensional measurement domain.

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