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Accepted Version

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Wu, Q., Zhu, C.-a., Liu, L., Liu, J. and Luo, Z. ORCID: <https://orcid.org/0000-0002-2082-3958> (2019) Two-dimensional flow visualization and velocity measurement in natural convection near indoor heated surfaces using a thermal image velocimetry method. *Applied Thermal Engineering*, 146. pp. 556-568. ISSN 1359-4311 doi: <https://doi.org/10.1016/j.applthermaleng.2018.10.023> Available at <https://centaur.reading.ac.uk/79752/>

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To link to this article DOI: <http://dx.doi.org/10.1016/j.applthermaleng.2018.10.023>

Publisher: Elsevier

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1 Two-dimensional flow visualization and velocity measurement
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9

10 **Abstract:** Indoor velocity measurement techniques are categorized into point-wise and global-
11 wise measurement techniques. Currently, measurements are either intrusive or restricted to the
12 measurement area. This study presents a thermal image velocimetry (TIV)-based flow measurement
13 method that is suitable for visualizing indoor two-dimensional velocity fields near indoor heated
14 surfaces. The proposed technique uses only an infrared camera for mapping the surface temperature
15 fluctuations. Image processing steps that are used to recover the velocity distribution include the
16 decomposition of the video files into individual frames, the application of filtering to remove
17 background noise, cross-calculation to estimate the velocity, and a final velocity correction based
18 on the continuity equation. To investigate the feasibility of this method, natural convection was
19 studied close to a heated vertical surface in a rectangular cavity. Thermal image velocimetry and
20 particle image velocimetry (PIV) were used to visualize the flow field above a heating unit. The
21 results indicate that the airflow field can be visualized by TIV, and the results measured by TIV are
22 shown to be similar to those for the surface of 6 mm away from the heated surface measured by
23 PIV. A linear correlation is established between TIV and PIV.

24 **Keywords:** Thermal image velocimetry; Heated surface; Particle image velocimetry; Indoor airflow.
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28 **Nomenclature:**

29 **Abbreviations**

TIV thermal image velocimetry

PIV particle image velocimetry

30 **Symbols**

x horizontal position (m)

y vertical position (m)

t_1 the time of the first image (s)

t_2 the time of the second image (s)

u velocity-x component (m/s)

v velocity-y component (m/s)

V velocity (m/s)

val the value describing the uniformity degree of the grids

r the ratio of the vectors that are different from neighboring vectors or outside the physically possible velocity range

N the number of the vectors in the entire flow field

n the query value to find the critical grid when the val values of all the grids are arranged in ascending order

val_n the val value of the critical grid

u_n the horizontal velocity of the critical grid for velocity correction (m/s)

v_n the vertical velocity of the critical grid for velocity correction (m/s)

v_{max} the maximum velocity along a horizontal line near the warm vertical surface (m/s)

H the distance from the lower level of the heated vertical surface (m)

T_o target surface temperature (T or °C)

T_u atmospheric temperature (T or °C)

T_a ambient air temperature (T or °C)

K sampling size (pairs)

$z_{\alpha/2}$ coefficient determined by the confidence interval

a' root mean square velocity (m/s)

A time-averaged velocity (m/s)

$S(A)$ the random sampling error of the time-averaged velocity (%)

E_{bi} the black body radiation intensity (W/ m²)

E_{λ} the radiant intensity detected by thermal infrared camera (W/ m²)

PIV6 PIV measurement results of the surface of 6mm away from the heated surface

PIV12 PIV measurement results of the surface of 12mm away from the heated surface

31 **Greek letters**

α horizontal displacement of the thermal spot (m)

β vertical displacement of the thermal spot (m)

$\Delta\theta$ the temperature difference between the wall and the adjacent air (T or °C)

ε_{λ} target surface emissivity

τ_{at} atmospheric spectral transmittance

32 **Subscripts**

i the horizontal sequence numbers of the nine grids consisting -1,0,1

j the vertical sequence numbers of the nine grids consisting -1,0,1

33 1. Introduction

34 Accurate quantification of airflow fields is of great significance in evaluating and creating
35 healthy indoor environments [1]. The currently conducted research on airflow fields can be
36 implemented using experiments and numerical simulations. Typically, numerical simulation relies
37 on accurate boundary conditions and experimental validation [1]. By contrast, experiments can
38 provide primary raw data of the actual airflow field and, therefore, is more reliable and fundamental.
39 Traditionally, experimental methods can be classified into two primary categories: point-wise and
40 global-wise measurements [1]. The point-wise technique obtains velocity information at pre-
41 determined representative points by arrangement of velocity measurement probes. Hot-wire
42 anemometer, hot-sphere anemometer, ultrasonic anemometer, and laser Doppler velocimetry are
43 common types of point-wise measurement techniques. Typically, point-wise measuring systems are
44 relatively precise and easy to operate. In addition, anemometers have fast response times and are
45 sufficient for turbulent measurements. Therefore, this method is widely used in numerous indoor
46 airflow measurement systems [2]-[5]. Global-wise measurement, such as particle image velocimetry
47 (PIV), particle tracking velocimetry, and particle streak velocimetry, can estimate the two-
48 dimensional or three-dimensional velocity vector distributions of an entire domain, and are applied
49 in numerous types of indoor airflow measurement systems [6]-[9]. Of these techniques, PIV is
50 thought to be the most extensively used optical velocimetry method for indoor airflow
51 measurements given its mature development level, an abundance of experimental literature, and the
52 availability of commercial systems [10]. Compared to point-wise measurements, the ability to obtain
53 detailed flow pattern makes PIV more advantageous for measuring extensive airflow fields.

54 The airflow measurement close to a heated surface is an important aspect for indoor airflow
55 measurements. Dominated by buoyancy originating close to a heated surface, the airflow is
56 significantly complex, and a thorough understanding of its characteristics is of great significance
57 for studies on room thermal comfort and energy efficiency [11]. The rising airflow induced by

58 buoyancy generated close to the heated wall contributes to the air circulation in an entire room, and
59 can alleviate the heat loss and the thermal discomfort induced by the infiltration of cold air. To date,
60 there have been limited experimental studies [11]-[14] investigating the airflow field close to heated
61 surfaces. This discrepancy can be attributed to the complexities of the building environment and the
62 limitations of measurement technologies. The abovementioned measurement technologies have
63 rarely been successfully applied in actual measurements close to heated surfaces. The primary
64 reasons for this regarding point-wise measurements can be summarized as follows: a) because of
65 the complexity of airflow near the heated surface, it is difficult to predetermine representative points
66 indicative of the characteristics of the entire airflow field, b) the bulk of the point-wise probes are
67 relatively bulky and the arrangement of probe arrays would disturb the flow field and significantly
68 influence the accuracy of the results, and c) for probes that are electrically heated, such as hot-film
69 anemometers, additional thermal buoyancy is experienced around them, and this would introduce
70 considerable errors into the results [1]. For global-wise measurements, there are also practical
71 difficulties in the application of measurements close to heated surfaces. Specifically, a) tracer
72 particles accumulate readily on an actual surface that has a certain degree of roughness, causing the
73 particle concentration to be uneven in space, ultimately affecting the measurement, and b) because
74 of the limitations of the optical path and camera resolution, it is rarely applied in full-scale
75 measurements and the area is typically smaller than 1 m² [15].

76 Infrared thermal imaging technology is a powerful method for measuring surface temperatures
77 and has been used for years in a variety of fields, including geography, military, medicine, and
78 aviation [16]-[19]. Compared to standard techniques, such as thermocouples, the thermal camera
79 can obtain data from the entire surface temperature field without accessing the target surface. Based

80 on this property, an infrared camera can be used to estimate the temperature and compute the heat
81 flux of complex flows [20] [21] [22]. Because of the high-spatial resolution and the ability to sample
82 the spatial and temporal changes of surface temperatures, infrared thermography has significant
83 potential in climatological studies. A. Christen et al. [23] and R. Voot et al. [24] observed significant
84 high-frequency fluctuations on the street canyon using infrared thermography and found that the
85 fluctuations were controlled by near-surface winds. They confirmed that there was a link between
86 surface temperature fluctuations and adjacent turbulent air movements. Based on the resolution of
87 surface temperature fluctuations caused by coherent heat exchanging between land surfaces and the
88 atmosphere using thermal imagery, additional studies have been conducted [25]-[30]. However,
89 these studies cannot provide the velocity field directly and merely infer the turbulent state according
90 to the temperature fluctuations. In current research study, thermal infrared velocimetry (TIV) based
91 on time-sequential infrared thermography [31] was used for outdoor airflow analysis. Based on this
92 theory, Y. Fan et al. [32] and A. Tiddens et al. [33] investigated the flow fields close to outdoor
93 walls and the river flow respectively. In spite of the considerable potential of thermography, its
94 utilization in flow visualization is still at an early stage of development. In current studies, only
95 qualitative vector fields can be provided, and studies of the indoor airflow measurement using TIV
96 are limited.

97 In order to analyze the application of TIV in measuring indoor two-dimensional flow fields
98 close to indoor heated surfaces, a scaled experimental cavity was set up and the natural convection
99 velocity field near the heated surface was studied. The aims of this study are as follows: (a) propose
100 a TIV-based method suitable for indoor airflow measurements near the heated surfaces, (b) visualize
101 the near-wall airflow field by TIV and PIV, and (c) compare the data obtained from these two

102 methods, analyzing the feasibility of the TIV in the measurement of the near-wall airflow fields.

103 2. TIV-based velocity measurement method near heated surfaces

104 2.1 Theory background of TIV

105 The infrared detectors detect the infrared radiant energy of the target surface, and the radiant
106 energy is then converted to electrical signals in the signal processing system and processed into the
107 thermal image [34]. In the actual measurement, numerous factors, such as target surface emissivity,
108 target surface reflectivity, background radiation, atmospheric attenuation, measurement distance,
109 and ambient air temperature, affect the measurement accuracy [35]. The radiation received by the
110 thermal camera primarily includes the target radiation, ambient reflection, and atmospheric radiation,
111 that are described below.

$$E_{\lambda} = \tau_{a\lambda}\varepsilon_{\lambda}E_{b\lambda}(T_o) + \tau_{a\lambda}(1-\varepsilon_{\lambda})E_{b\lambda}(T_u) + (1-\tau_{a\lambda})E_{b\lambda}(T_a) \quad (1)$$

112 where E_{λ} is the radiation intensity detected by the thermal infrared camera and $E_{b\lambda}$ is the black
113 body radiation intensity, and T_o, T_u, T_a are the target surface temperature, atmospheric temperature,
114 and ambient air temperature, respectively, ε_{λ} is the target surface emissivity, $\tau_{a\lambda}$ is the
115 atmospheric spectral transmittance.

116 The energy detected by the thermal camera depends on both the surface emissivity coefficient
117 and the environmental conditions. In Eq. (1), the term $(1-\tau_{a\lambda})E_{b\lambda}(T_a)$ is the emission from the
118 atmosphere and $\tau_{a\lambda}$ can be assumed to be equal to 1 when the camera is positioned close to the
119 target surface in indoor measurements. Correspondingly, $\tau_{a\lambda}(1-\varepsilon_{\lambda})E_{b\lambda}(T_u)$ is the reflected
120 emission from the surrounding surfaces and $\tau_{a\lambda}\varepsilon_{\lambda}E_{b\lambda}(T_o)$ is the emission from the measured
121 surface captured by the camera. From Eq. (1), it can be concluded that the surface emissivity for a
122 wavelength detectable by the thermal camera should be sufficiently great to decrease the
123 background noise signals. In addition, when the target surface temperature is close to the
124 background temperature, the noise would significantly influence the accuracy of the measurement.
125 Therefore, the temperature difference between the surface and adjacent air should be adequate.
126 Regarding the airflow near the heated surface, a relatively great temperature difference can be

127 guaranteed between the heated surface and the adjacent air. In addition, the condition of the wall is
128 also conducive to TIV. The surface of a wall is relatively rough with a small albedo and high
129 emissivity. The significant surface emissivity increases the radiation detectable by the thermal
130 infrared camera and decreases the interference of ambient surfaces.

131 The link between the surface temperature and energy balance is introduced to study the
132 relationship between temperature and velocity [31]. Energy transfer comprises four parts: heat
133 storage, heat conduction, turbulent heat exchange, and radiation energy transfer. These four parts
134 have a joint effect on the surface temperature and adjacent air temperature. For indoor environments,
135 the turbulent heat exchange plays the leading role in the interaction between the wall surface and
136 air. Driven by buoyancy, convection flow is formed near the heated surface and influences the
137 turbulent heat transfer. Because of the development of turbulent structures, the heat transfer between
138 the wall surface and adjacent air is promoted or suppressed. The trace of turbulent structures will
139 leave a “footprint” on the surface temperature distribution, and this “footprint” changes with the
140 velocity near the heated surface [31]. Based on the temporal variation of the near wall temperature
141 distribution measured by infrared camera, a cross-correlation analysis similar to PIV is performed
142 to calculate the flow velocity. In the next section, the processing steps of TIV are introduced in
143 detail.

144 **2.2 Data processing for TIV**

145 Similar to the data processing of PIV, TIV measures the two-dimensional velocity by
146 evaluating the displacement of thermal spots between two temporally continuous images. The
147 technical approach used in this study comprises four steps, as shown in Fig. 1.

148 **Fig. 1.** Technical approach

149 2.2.1 Step 1: Preparing thermal images

150 Data collection involves the acquisition of a temperature fluctuation video of the target object
151 by means of an infrared camera. The ResearchIR software is provided by FILR for research and
152 science cameras and can be used for camera control and high-speed data recording. In this step, we
153 use the ResearchIR software to specify the frame rate and the duration of each image time series.
154 First, the raw .ats video files are obtained by the infrared camera. These files are then imported into

155 MATLAB and are parsed into image stacks comprising individual frames.

156 2.2.2 Step 2: Pre-processing

157 During the experiment, there is a need to accentuate fluctuations of the surface temperature
158 compared to the background. In the case of TIV technology, the local heterogeneities of the surface
159 also influence the surface temperature pattern [31]. The image enhancement aims at reducing the
160 influence of background noise [36]. A filter serves as a frequency selection tool and allows specific
161 frequency signals to pass and blocks other frequency signals. Proper filtering is critical in the process
162 of image enhancement. As the storage of digital images is discrete, the discrete Fourier transform is
163 commonly used [37]. Typically, through the use of the fast Fourier transform the spatial domain f
164 (x, y) is converted to a frequency domain, and the frequency domain is then multiplied by the filter
165 transfer function. The filtered results are then obtained by the inverse fast Fourier transform.
166 Through optimization in numerous preliminary experiments, the Gaussian high-pass filter is used
167 in this study.

168 2.2.3 Step 3: Image processing

169 Similar to PIV, TIV estimates the velocity according to cross-correlation calculation [38]. Fig.
170 2. shows the data processing procedure for TIV measurement.

171 **Fig. 2.** The data processing for TIV measurement

172 The images are divided into small calculation sections that are similar to the interrogation
173 windows in the PIV algorithm. As shown in Fig. 3, the thermal spot is located in one position (x, y)
174 in the first image at time t_1 and in $(x + \alpha, y + \beta)$ at time t_2 for the second image. The cross-
175 correlation calculation is executed within the calculation section to identify the point with maximum
176 correlation. The calculation section is of 64×64 image pixels, 50% overlapped. Through the
177 identification of the maximum correlated point, the displacement of the thermal spot is identified.
178 The x -component of velocity (u) and the y -component of velocity (v) are calculated according to the
179 displacement of the point divided by the time increment between the two images. The calculation
180 section is shifted subsequently in the image to evaluate the entire flow field.

181 2.2.4 Step 4: Data correction

182 The image processing step is simply a mathematical method and the physical property of the
 183 flow field is not considered. The output from step 3 that is based on the cross-correlation method
 184 comprises a number of vectors that cannot satisfy the fundamental law of fluid dynamics. They are
 185 either appreciably different from neighboring vectors or outside the physically possible velocity
 186 range [39]. In this process, *val* is defined as the value describing the uniformity degree of the grids
 187 and the raw vectors can be validated by analyzing the *val* of each grid that is calculated using the
 188 eight closest neighboring vectors, as shown as Fig. 3. The location where *val* is sufficiently small
 189 indicates that the vector in this grid reaches a degree of uniformity. The *val* is defined according to
 190 the continuity equation [40]. For incompressible fluid, the two-dimensional fluid continuity
 191 equation is:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

192

193 **Fig. 3.** The sketch for velocity grid in the step of data correction

194 In the two-dimensional vector field, the correct velocity vector should follow the continuity
 195 equation. The two-dimensional fluid continuity equation at the grid position (0, 0) can be described:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = \sum_{i,j} [(u_{i,j} - u_{0,0}) \text{sgn}(i) + (v_{i,j} - v_{0,0}) \text{sgn}(j)] = 0 \quad (3)$$

$$\text{sgn}(\delta) = \begin{cases} 1, & \delta \geq 0 \\ -1, & \delta < 0 \end{cases} \quad (4)$$

196 where $u_{0,0}$ and $v_{0,0}$ are the horizontal and vertical velocities at the grid position (0, 0) respectively;
 197 $u_{i,j}$ and $v_{i,j}$ indicate the horizontal and vertical velocities of the eight grid positions around grid
 198 location (0, 0). According to Eq. (3), the following inequalities can be derived, as shown as Eq. (5)
 199 and Eq. (6). The *val* at the grid location (0, 0) in the two-dimensional velocity vector field can be
 200 calculated based on Eq. (7).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \leq \sum_{i,j} |u_{i,j}| + \sum_{i,j} |v_{i,j}| \quad (5)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \leq \sum_{i,j} |u_{i,j} - u_{0,0}| + \sum_{i,j} |v_{i,j} - v_{0,0}| \quad (6)$$

$$val = \frac{\sum_{i,j} |u_{i,j} - u_{0,0}| + \sum_{i,j} |v_{i,j} - v_{0,0}|}{\sum_{i,j} |u_{i,j}| + \sum_{i,j} |v_{i,j}|} \quad (7)$$

201 In this way, the *val* of each grid point in the two-dimensional velocity vector field can be
 202 calculated and then they are arranged in ascending order. Two parameters r and N , that are the
 203 percentage of the vectors that are different from neighboring vectors or outside the physically
 204 possible velocity range and the number of vectors in the entire flow field, respectively, should be
 205 defined in the described algorithm. In this study, r was set to 6%, and N was multiplied by r to
 206 specify the value of the query values n . According to n , the corresponding *val_n* in the ascending
 207 array can be identified, and the corresponding grid location and the x and y -components of the
 208 velocities u_n and v_n can be obtained. By comparison with u_n (v_n), the velocities in the entire velocity
 209 field that are smaller than the critical values u_n and v_n are corrected using Eq. (8). In this case, by
 210 using the abovementioned algorithm, the entire flow field is corrected based on the physical
 211 properties of the fluid.

$$u_{0,0} = \frac{\sum_{i,j} u_{i,j}}{8} \quad v_{0,0} = \frac{\sum_{i,j} v_{i,j}}{8} \quad (8)$$

212 3. Scaled model experiment

213 3.1 Experimental cavity

214 Experiments were conducted in a closed rectangular cavity with internal dimensions $1200 \times$
 215 $500 \times 1400 \text{ mm}^3$, as shown in Fig. 4. The walls were made of 8-mm-thick Plexi-glass with a surface
 216 emissivity of 0.90. The cavity was built in an air-conditioned room with the room temperature set
 217 to $20 \text{ }^\circ\text{C}$. An electric heating unit with dimensions $500 \times 200 \text{ mm}^2$ was mounted on the bottom of
 218 one of the vertical walls. A 5-mm-thick foam sheet with a thermal conductivity of $0.2 \text{ W}/(\text{m}\cdot\text{K})$ was
 219 placed between the heating unit and the heated vertical wall. The foam sheet was used as an
 220 insulation material to reduce the heat loss through the rear of the heated vertical wall. In order to
 221 maintain the surface temperature, the heating unit was controlled by an electronic thermostat. In this
 222 study, the surface temperature of the heating unit was determined to be 50°C .

223 **Fig. 4.** Experimental setup: 1. Tracer particle inlet 2. Heating unit 3. CCD camera 4. Laser 5. Infrared
 224 camera 6. Visualized surface

225 3.2 Measurement system and domain composition

226 3.2.1 PIV measurement system and domain composition

227 The PIV system comprised a 15-Hz Nano L PIV, 135 mJ, 532 nm, double-pulsed Nd:YAG
228 laser used as a light source, in association with a double-frame, high sensitivity CCD camera
229 PIVCAM13-8 with a resolution of 2048×2048 pixels. An AF Nikko 50 mm f/1.8D objective lens
230 was mounted on the CCD camera. The thickness of the laser light sheet at the measurement plane
231 was approximately 1–2 mm. In order to capture the actual airflow motion, tracer particles with
232 proper intensity and size are required. A VZ09 - 0751 smoke generator was used, and was connected
233 to the plenum located on the bottom of the cavity. The tracer particles were released into the cavity
234 from the inlet.

235 If the CCD camera is positioned on the same side as the infrared camera, the pixels occupied
236 by the particles are significantly decreased, even though the shooting area increases. In addition, the
237 tracer particles suspended in the cavity significantly influence the quality of the measurement. As a
238 result, the CCD camera was positioned on the opposite side. Because of the existence of the heating
239 unit and the air plenum in the upper part of the heated vertical wall, the visualized area for PIV was
240 $500 \times 1000 \text{ mm}^2$, as shown in Fig. 5. By adjusting the position of the CCD camera in the preliminary
241 experiment, the dimensions of the image obtained by the CCD camera were determined to be 280
242 mm \times 280 mm. The regions were set to have horizontal and vertical overlaps of 60 mm and 30 mm,
243 respectively, with the neighboring domains shown in Fig. 5(a). For each domain measurement, 300
244 PIV image pairs were collected at a recording frequency of 7 Hz. The velocity vector maps were
245 prepared by determining the cross-correlation for 64×64 pixel interrogation areas and 50% overlaps
246 in both the x and y directions for all PIV image pairs. For each domain, the instantaneous velocities
247 for 300 image pairs and an average velocity field were obtained. The statistical data associated with
248 eight regions were exported to MATLAB for connecting the eight flow fields.

249 **Fig. 5.** Schematic of measurement domains **a.** PIV **b.** TIV

250

251 3.2.2 TIV system and domain composition

252 A FLIR-T1040 infrared camera was used to track the flow of the surface near the heated wall.

253 The camera has a resolution of 1024×768 pixels and is sensitive in a range $7.5\text{--}14 \mu\text{m}$, thereby
 254 being suitable for indoor temperature measurements. In addition, it is able to resolve subtle
 255 differences in indoor temperature (noise-equivalent temperature difference $< 25 \text{ mK}$). A telephoto
 256 lens with a focal length of 25 mm was mounted on the camera to provide a data field of view of 28°
 257 $\times 21^\circ$. As the wavelength of the PIV laser is 532 nm and the sensitive wavelength range of the
 258 infrared camera is $7.5\text{--}14 \mu\text{m}$, the PIV and TIV measurements were performed separately. As shown
 259 in Fig. 4, there are three shooting positions located 250 mm , 600 mm , and 950 mm from the bottom
 260 of the cavity and three .ats video files were recorded from the three shooting positions. Based on the
 261 horizontal distance between the shooting positions and the visualized surfaces, the imaged area for
 262 one time is $598 \times 445 \text{ mm}^2$. The entire area that was investigated was decomposed into three
 263 domains with an overlap of 68 mm , as shown in Fig.5 (b). The sampling frequency was 10 Hz and
 264 the fluctuations of the temperature field were captured by the thermal infrared camera. Four hundred
 265 instantaneous velocities at a frame rate of 10 Hz were extracted to calculate the average velocity.
 266 Finally, the flow field measured by TIV was mirrored to compare with the PIV results.

267 4. Results

268 4.1 The flow characteristics of heat plume

269 Fig. 6 shows the changing tendency of the heat plume in consecutive moments. It indicates that
 270 the primary energy transmission direction is upward. A hot plume is first generated over the heating
 271 unit and a significant velocity gradient is generated adjacent to the heating unit. The heated air
 272 moves upward, and the space left by the rising hot plume is supplemented by cold air in the upper
 273 part of the cavity. The two airflow structures mix and momentum and energy are exchanged. The
 274 velocity gradient changes at a relatively lower rate and the entire flow field tends to be more uniform.

275 **Fig. 6.** Instantaneous velocity measured by TIV, with **a** to **d** representing four consecutive moments.

276 According to a relevant investigation by [11], the air velocity induced by the convection near
 277 a warm or cold vertical surface can be manipulated as follows:

$$v_{\max} = 0.1\sqrt{\Delta\theta H} \quad (9)$$

278 where v_{\max} is the maximum velocity along a horizontal line near the warm vertical surface, $\Delta\theta$ is

279 the temperature difference between the wall and the adjacent air, and H is the distance from the
280 lower level of the heated vertical surface. As debated by [11], Eq. (9) can provide an estimation of
281 the maximum velocity adjacent to the heated surface, but not above it. It is also assumed that this
282 equation is suitable for the region above the heating surface, that is not at a great distance from the
283 upper edge of the heating surface. In this study, the temperature difference between the heated
284 surface and air is approximately 30 °C according to the temperature difference of the heating unit
285 and the room temperature. At a height of 200 mm, that is 400 mm above the bottom of the heating
286 unit, the maximum velocity is 0.28m/s, as estimated by Eq. (9). The result obtained by TIV is
287 0.26m/s, that is similar to the result of Eq. (9).

288 **4.2 Mean flow fields measured by TIV and PIV**

289 The surfaces at 6 mm and 12 mm away from the heated vertical surface were visualized using
290 PIV technology. In the next sections, the PIV results of surfaces at 6 mm and 12 mm away from the
291 heated surface are referred to as PIV6 and PIV12, respectively. The instantaneous flow fields are
292 averaged, and the averaged velocity contour and vectors measured by PIV and TIV of the region
293 over the heating unit are shown in Fig. 7 and Fig. 8, respectively. All measurements were conducted
294 under steady-state conditions attained after a sufficiently long period. The infrared camera was used
295 to monitor the temperature variations of the near wall surface over the heating unit and the steady-
296 state was deemed to be reached when the temperature remained approximately constant. From a
297 visual inspection of Fig. 7 (a) and (c), and Fig. 8 (a), the spatial variability of the velocity appears
298 to comprise three patterns from the bottom to the top: (1) a high velocity region, (2) a moderate
299 velocity region, and (3) a low velocity and lagging region. Pattern 1 is attributed to the intense
300 energy and momentum exchange between the air and the heating unit. It is clear that the air adjacent
301 to the heating unit is heated and this causes the velocity to increase significantly. Over this region
302 is pattern 2, where, the airflow part rises in the original direction, and the other part could move to
303 the inner regions of the cavity because of an insufficient driving force. The transition point between
304 patterns 1 and 2 appears at a vertical height of 200 mm for the surface that is 6 mm away from the
305 heated surface, and at 400 mm for the surface that is 12 mm away from the heated surface, as shown
306 as Fig. 7 (a) and (c). In pattern 3, the velocity decreases to a minimum and vortices appear in the

307 corners close to the sidewalls, as shown as Fig. 8 (b) and Fig. 7 (b) and (d). The primary air motion
308 is upward, and the flow direction changes close to the top of the wall.

309 Overall, the TIV results are in good agreement with the PIV6 results shown in Fig. 7 (a) and
310 Fig. 8 (a). However, there is still **some differences** in the upper and lower regions. In the middle of
311 the lower region located at $y = 0\text{--}200$ mm, the velocity evaluated by TIV is smaller than the PIV
312 results. In this region, there exists greater heat and momentum transfer compared to the other regions.
313 In the lower region, the TIV measurement is more susceptible to the influence of shadows on the
314 glass target surface and thus affect the tracking of temperature fluctuations. Consequently, the
315 measured temperature fluctuations are smaller in the middle region and the evaluated velocity is
316 accordingly smaller. With regard to the upper regions located at $y = 800\text{--}1000$ mm, the velocity
317 measured by TIV is also smaller than that of PIV. As stated above, for the application of the TIV
318 method, a relatively significant temperature difference is required. In the upper region of the
319 measurement domain, the temperature difference is smaller, and this influences the quality of the
320 results. The velocity evaluated by TIV is relatively smaller than the PIV results for this reason.

321 **Fig. 7.** Velocity distributions near the heated surface evaluated by PIV: **a (b), c (d)** velocity contour
322 (velocity vector) of the planes 6 mm and 12 mm away from the heated surface.

323 **Fig. 8.** Velocity distributions near the heated surface evaluated by TIV: **a** velocity contour, **b** velocity
324 vector.

325 The histogram of the y -component of the velocity (v) at (200, 200) obtained by TIV and PIV6
326 is plotted in Fig. 9. Note that the x -component of the velocity is extremely small in magnitude and
327 is not plotted. The overall shapes of the distributions are similar. It is noteworthy that both
328 frequencies are approximately normally distributed. The measured y -component of the velocity (v)
329 is characterized by a relative broad spectrum with a maximum of 0.19 m/s for both PIV6 and TIV.
330 There is a good agreement between PIV6 and PIV, therefore, the statistical values can be taken as
331 reliable. It is interesting to notice that 0.19 m/s is a critical value. In the interval of 0.1–0.19 m/s, the
332 measured frequency of PIV6 is greater than that of TIV. However, the rule is modified in the interval
333 of 0.20–0.30 m/s. From Fig. 9, it can be deduced that the TIV measurements could be appreciably
334 greater than those of PIV6 and there appeared to be a correlation between them.

335 **Fig.9.** Histogram of y -component of the velocity (v) evaluated by TIV and PIV6.

336 4.3 Analysis of velocity in representative lines

337 A further comparison and analysis of the results of TIV and PIV is performed. Three vertical
338 lines at locations $x = 125$ mm, 250 mm, and 375 mm, as shown in Fig. 10(d), were chosen as
339 representative lines, and the y -components of the velocities of these lines are analyzed. The three
340 lines are referred to as Lines 1, 2, and 3. The y -component of the velocity (v) along the three vertical
341 lines at different locations along the x -axis are shown in Fig. 10. Overall, the y -components of the
342 velocities exhibited a distinct trend, that is marked by an increase toward a maximum value close to
343 $y = 0$ –200 mm, and by a subsequent decrease to a minimum value at the top of the cavity. Variations
344 were observed in the y -component of the velocity close to $y = 200$ mm. In this region, the heat
345 gradient is developed and warm fluid adjacent to the heating unit is transmitted upward, and is then
346 replaced by the upward cold air. This is a region that is adjacent to the heated surface, and where a
347 velocity y -component peak exists. In addition to the decreasing buoyancy, the change in the flow
348 direction could also elicit a sudden decrease close to $y = 200$ mm. Movement toward the inner parts
349 of the cavity could exist, and the increase in the velocity normal to the heated surface influences the
350 variation of the y -component of the velocity. The thermal plume generated by the heating unit rises
351 in the y -direction and is likely to separate from the surface that is 6 mm away from the heated surface
352 close to $y = 100$ mm, and spread to the interior of the cavity where a circulation is formed. Similarly,
353 the departing location on the surface 12 mm away from the heated surface could be $y = 200$ mm.
354 This is in good agreement with previous studies in [41][42].

355 **Fig.10.** y -component of the velocity (v) measured by TIV and PIV in **a** Line1, **b** Line2, **c** Line3 and **d**
356 the representative lines.

357
358 With the exception of minor differences, the results of PIV6 and TIV for the three lines are
359 similar in terms of the general trends exhibited. For heights within the range 0–200 mm, the
360 differences between TIV and PIV6 are relatively greater, specifically at the corresponding locations
361 of Line 2. In Line 2, the TIV results within the range $y = 0$ –200 mm are specifically affected by the
362 abovementioned shadows. Compared to other locations, the temperature fluctuation gradient is
363 significant, and the shadows interfere with the acquisition of temperature fluctuation data. Overall,
364 the TIV result are similar to those of the PIV6.

365 The airflow in Line 2 is close to free flow, but the airflow in Lines 1 and 3 is unavoidably

366 disturbed by the sidewalls. Similarly, the flow in the location of $y = 0-200$ mm is also perturbed by
367 the heating unit, resulting in the actual flow in Lines 1 and 3 differing from that in Line 2. Overall,
368 the distributions of the vertical velocity profiles in Line 1 and Line 3 are similar. However, the
369 vertical profiles in Line 1 are not similar to Line 3, although all the geometric boundary conditions
370 are similar. For actual flow, the boundary conditions on both sides cannot be fully controlled and
371 kept consistent. In fact, the flow that should theoretically be symmetrical is asymmetrical, with a
372 number of inconsistencies. Some studies [12][43] have shown that the asymmetric flow exists under
373 symmetrical boundary conditions. The TIV and PIV measurements has indicated that the results of
374 TIV and PIV6 are apparently closer within the range $y = 200-1000$ mm. There appears to be a linear
375 relationship between the results of TIV and PIV in the range $y = 0-200$ mm. A linear fit is applied
376 for Line 1 within the range, as shown as Table 1, and the results yield good linear relationships with
377 high R-square values. In addition, it can be concluded that the results of TIV and PIV6 are almost
378 identical.

379 **Table 1.** Linear fit equations of TIV, PIV6 and PIV12 in line 1

380 The x -component of the velocity (u) in Line1 is plotted in Fig. 11. Unlike the y -component (v),
381 the x -component of the velocity (u) in the vertical direction is significantly smaller in magnitude
382 and is close to zero. No significant pattern exists for the x -component of the velocity.

383 **Fig.11.** x -component of the velocity in line 1

384

385 In order to further investigate the relationship between the PIV6 and TIV, scatter plots and
386 linear fit plots of the y -components of the velocities evaluated by TIV and PIV6 in the three lines
387 are shown in Fig. 12 and Fig. 13. These values are positively correlated with high R-square values
388 and fit well on the line $y=ax$ with high correlation coefficients, thereby indicating that there is a
389 linear relation between TIV and PIV6.

390 **Fig.12.** Relationship between y -component of the velocity (v) measured by TIV and PIV6.

391

392 **Fig.13.** Relationship between velocity (V) measured by TIV and PIV6.

393 **4.4 Uncertainty analysis of PIV**

394 The uncertainty analysis of PIV can be discussed from two aspects: the system error and the
395 statistical error [44]. The system errors are caused primarily by tracing particle' following

396 performance, image deformation, and random particle displacement in the image analysis [44]. The
 397 motions of the tracer particles suspended in the air are affected by numerous factors, including air
 398 velocity, tracer particle density, and gravity. The tracer particle following performance is defined
 399 according to the ratio of the tracer particle velocity with the fluid velocity. In this study, the
 400 amplitude ratio of the tracer particles and the air is used to evaluate the following performance. The
 401 detailed calculation method can be referred to [12][45]. In addition, the amplitude ratio is 0.99 and
 402 the error contributed by following performance can be neglected. Typically, the error caused by
 403 image deformation is close to 0.3% [44]. As stated in [46], the random displacement error during
 404 the experiment was approximately 0.07 pixels, that will produce a relative error up to 4% for the
 405 corresponding mainstream region (>0.1 m/s). In conclusion, the maximum system error is
 406 approximately 4.3%.

407 The statistical error of PIV is caused primarily by random sampling errors. The PIV random
 408 sampling error can be evaluated according to the central limit theorem, assuming that the random
 409 sampling errors are normally distributed [47][48]. In this case, the random sampling error of the
 410 time-averaged velocity can be estimated:

$$S(A) = \frac{1}{\sqrt{k}} \cdot z_{\alpha/2} \cdot \frac{a'}{A} \quad (10)$$

411 where $S(A)$ is the random sampling error of the time-averaged velocity, k is the sampling size, $\frac{a'}{A}$
 412 is the ratio of the root mean square velocity and the time-averaged velocity. $z_{\alpha/2}$ is a coefficient
 413 determined by the confidence interval. When the confidence interval is 95%, the value of $z_{\alpha/2}$ is
 414 1.96. Fig.14 shows the random sampling errors when the time-averaged velocity is 0.1 m/s. The
 415 random sampling errors would increase with decreasing time-averaged velocity. In this regard, when
 416 the time-averaged velocity is smaller than 0.1 m/s, the random sampling errors would be greater,
 417 and vice versa. However, it is not reasonable to evaluate the errors of the entire measurement regions
 418 with the errors of regions with small velocities. It is necessary to choose a modest velocity to
 419 calculate the error. As can be seen from Fig.7.(a), in the bulk of regions, the velocities are greater
 420 than 0.1 m/s, and only a small percentage of the regions have insignificant velocities and are
 421 approximately stationary. Therefore, the random sampling error is calculated when the time-

422 averaged velocity is 0.1 m/s. According to Fig.14, it is possible to obtain a relatively high accuracy
423 with 300 images pairs. In this case, the random sampling error is 6.1%. Therefore, the uncertainty
424 of the PIV measurement is approximately 10.4 %.

425 **Fig. 14.** Random sampling error of the time-averaged velocity

426 **5. Discussion**

427 Considering the investigation in this study, a number of limitations and error sources that could
428 influence the velocity measurement via the use of thermal image series should be carefully
429 monitored in the measurements.

430 Quantifying the uncertainty related to the field of view of the camera is critical. The camera
431 needs to be positioned to ensure that the field of view encompasses the target measurement domain
432 and avoids inclusion of other surfaces as much as possible. In addition, the camera lens should be
433 perpendicular to the measured surface as even a slight tilt could cause image distortions. In addition,
434 the camera performance is critical for acquiring high-quality thermal images and it should be
435 accurately calibrated prior to the measurements.

436 The background noise could provide meaningless information, adding work to the acquiring of
437 thermal spot displacements. Shadows from other surfaces on the transparent target surface and the
438 surface local heterogeneities could obscure the thermal features and interfere with the acquisition of
439 the time-series thermal images. In addition, longwave reflections from adjacent surfaces will
440 increase the measurement error, specifically when radiation energy emitted by the target surface is
441 very small. According to the Stefan-Boltzmann law, the radiation emitted by the target object
442 depends primarily on the surface emissivity and the temperature. Typically, the surface temperature
443 is fixed for the selected measurement object. The surface emissivity should be sufficient to increase
444 the radiation energy measured by the thermal infrared camera.

445 The abovementioned preprocessing of the captured images can decrease the influence of the
446 local surface heterogeneities and low surface emissivity. Additional experiments were conducted to
447 analyze the influence of local heterogeneities, surface emissivity, and the pre-processing of the
448 captured images on the measurement accuracy. The area of the electric heating unit was 500 mm ×
449 400 mm and it was installed in the same location as in the previous experiment. The surface

450 temperature of the heating unit was maintained at 40 °C. The experiments were conducted under
451 three working conditions. Case 1 was used as the control group and has no change with the wall
452 surface. The surface emissivity input to the thermal infrared camera is 0.90, that is the emissivity of
453 the Plexi-glass. In Case 2, the wall surface was pasted with four pieces of black tape to add surface
454 heterogeneities, as shown in Fig.15 (b). In Case 3, the wall surface was pasted with silver tape to
455 alter the surface emissivity, and the surface emissivity was 0.83, as shown in Fig.15 (c). Except for
456 the target surface differences, the other boundary conditions remained the same. A region with
457 dimensions of 500 mm × 445 mm above the heating unit was measured by TIV. The velocity profiles
458 in the red line in Fig.15 are discussed. Fig. 16 shows the velocity profiles of the three cases and the gray
459 shaded areas in Fig.16 (a) are the areas where the black tape was pasted. It can be concluded that the
460 existence of local heterogeneities and low emissivity, in Fig.16 (a) and (b) respectively, do influence the
461 accuracy of the velocity measurements. However, through pre-processing of the captured images, the
462 deviation can be improved to some extent.

463 **Fig. 15.** Schematic diagram of wall surfaces of the three conditions: **a** Case1, the unaltered surface and
464 surface emissivity is 0.90, **b** Case 2, the surface with pieces of black tape and surface emissivity is
465 0.90, **c** Case 3, the whole surface with silver tape and surface emissivity is 0.83.

466 **Fig. 16.** Velocity profiles of the additional experiment to show the influence of local heterogeneities,
467 surface emissivity and the pre-processing of the captured images on the measurement accuracy

468 6. Conclusion and outlook

469 This study proposed a method for measuring the two-dimensional distribution of airflow near
470 a heated surface by tracking surface temperature images. The near wall airflow under natural
471 convection near the heated surface in the cavity was investigated by TIV and PIV. By comparing
472 the PIV results, the feasibility of TIV in the measurement of indoor airflow field near heated surfaces
473 under natural convection was discussed. The primary conclusions obtained from this study are as
474 follows.

475 (1) A velocity visualization method referred to as thermal image velocimetry is proposed. This
476 method obtains the velocity field by acquiring the temperature fluctuations near the heated
477 surface, and the algorithm is similar to the algorithm used for PIV. In this method, the only

478 instrument is a thermal camera that is portable and easy to operate compared to the PIV method.
479 It is noteworthy that this method can obtain the velocity field without access to the flow field.
480 Thermal image velocimetry has an advantage over the traditional measurement techniques and
481 has good application prospects in predicting the airflow field, such as the microclimate near the
482 terminal heating units in buildings.

483 (2) Based on the analysis of the time sequence of thermal images, the basic characteristics of the
484 flow field near the heated surface were evaluated. The spatial variability of the velocity
485 appeared to comprise three patterns in the vertical direction: (1) a high velocity region, (2) a
486 moderate velocity, and (3) a low velocity and relatively lagging region. The fluid velocity
487 increased in the vicinity of the heating unit and attained a maximum value in the range $y = 0$ –
488 200. The velocities of the three vertical lines exhibited linear relationships with high *R*-square
489 values at locations within the range 200–1000 mm ($y = 200$ –1000 mm).

490 (3) The summarized results indicated that the indoor velocity field near a heated surface can be
491 accurately evaluated using thermal image time series. Comparison of the velocities indicated
492 that the velocity fields obtained by thermal image velocimetry and the one measured by particle
493 image velocimetry at the surface that was 6 mm away from the heated surface was similar.
494 Specifically, it was observed that there was good agreement between the PIV measurements
495 and the velocity deduced from the thermal images. In the representative lines, they were
496 positively correlated with high *R*-square values. There was a linear relationship between TIV
497 and PIV6.

498 Although the initial investigations yielded encouraging results, additional studies could be
499 conducted to improve the reliability of TIV in indoor air velocity measurements. In this study, the
500 wavelength of the PIV laser was inconsistent with the sensitive wavelength of the infrared camera.
501 If both measurements were conducted at the same time, the laser of PIV would inevitably affect the
502 acquisition of surface temperature fluctuations in TIV measurement. In result, the two
503 measurements were performed separately. Although the boundary conditions maintained good
504 consistency, the turbulent nature of the flow makes the velocity of the air variable locally and
505 temporally. Future studies can carried out using TIV in conjunction with another reliable velocity
506 measurement method for synchronous measurement. From the experimental comparison in this

507 study, it could be seen that in the prediction of the flow field near the heating surface, the TIV and
508 PIV results exhibited a high degree of consistency. This indicates that the TIV method has the
509 potential for independently measuring indoor airflow fields. Specifically. When it comes to actual
510 full-scale airflow measurements near the actual heating terminal units, as mentioned above, PIV
511 could be unsuitable. However, as an alternative experimental method, TIV requires only a thermal
512 infrared camera and, therefore, has greater operability. Regarding the application of TIV in the
513 velocity measurement of actual full-scale room, further studies are required.

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Figures

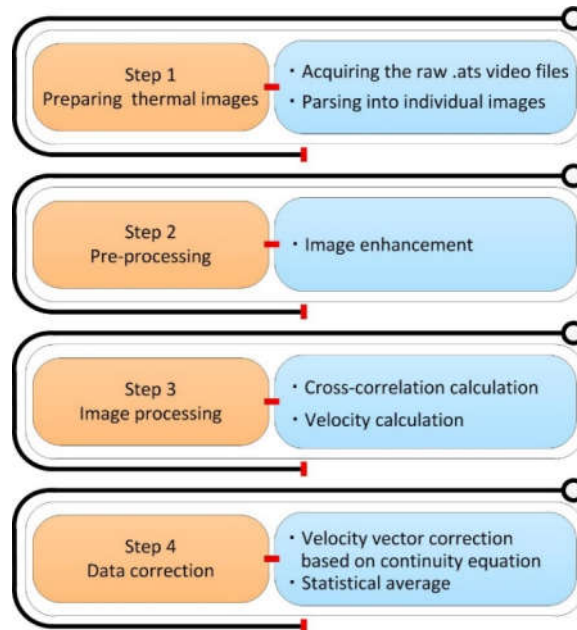


Fig. 1. Technical approach

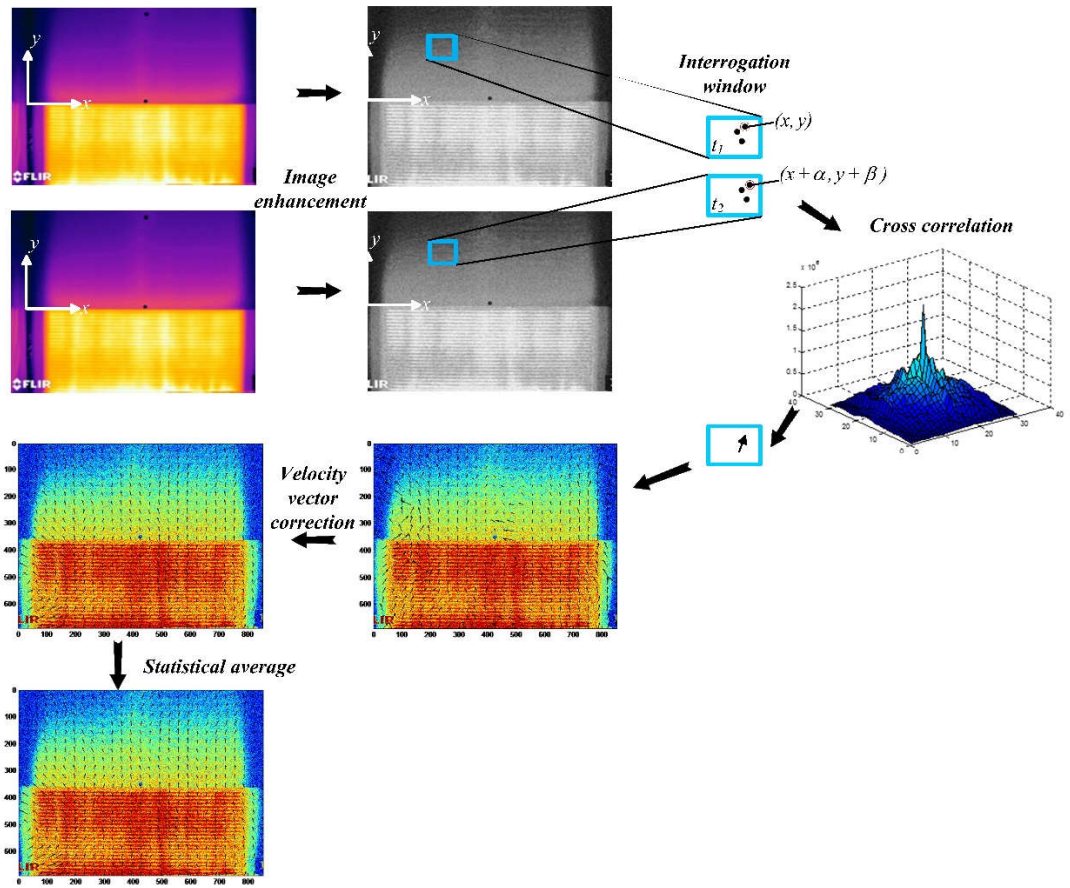


Fig. 2. The data processing for TIV measurement

$(-1,1)$	$(0,1)$	$(1,1)$
$(-1,0)$	$(0,0)$	$(1,0)$
$(-1,-1)$	$(0,-1)$	$(1,-1)$

Fig. 3. The sketch for velocity grid in the step of data correction

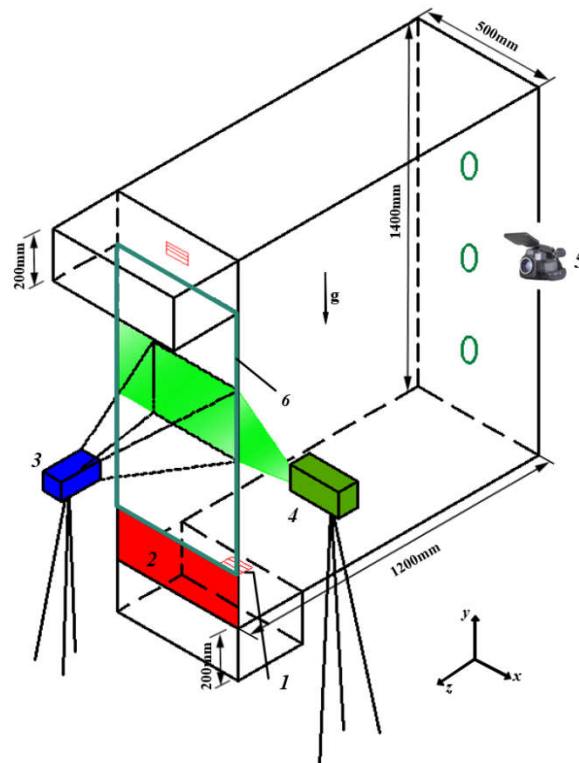


Fig. 4. Experimental setup: 1. Tracer particle inlet 2. Heating unit 3. CCD camera 4. Laser 5. Infrared camera 6. Visualized surface

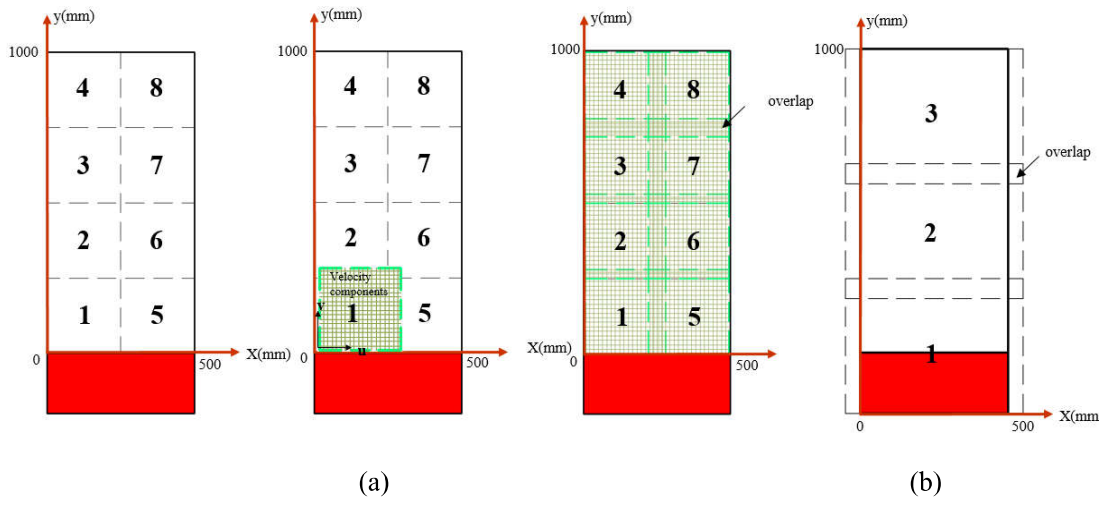


Fig. 5. Schematic of measurement domains **a.** PIV **b.** TIV

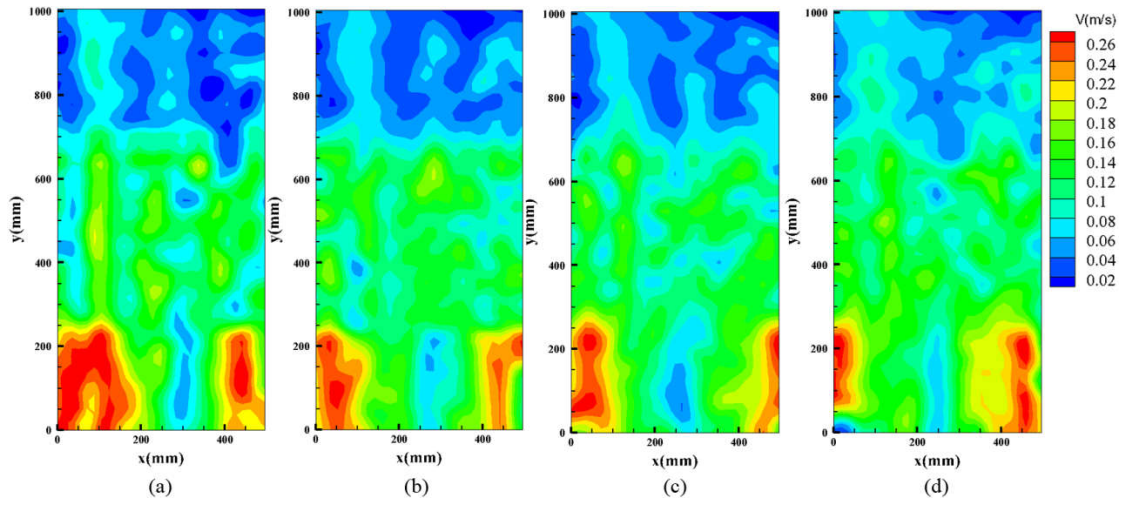


Fig. 6. Instantaneous velocity measured by TIV, with (a) to (d) representing four consecutive moments.

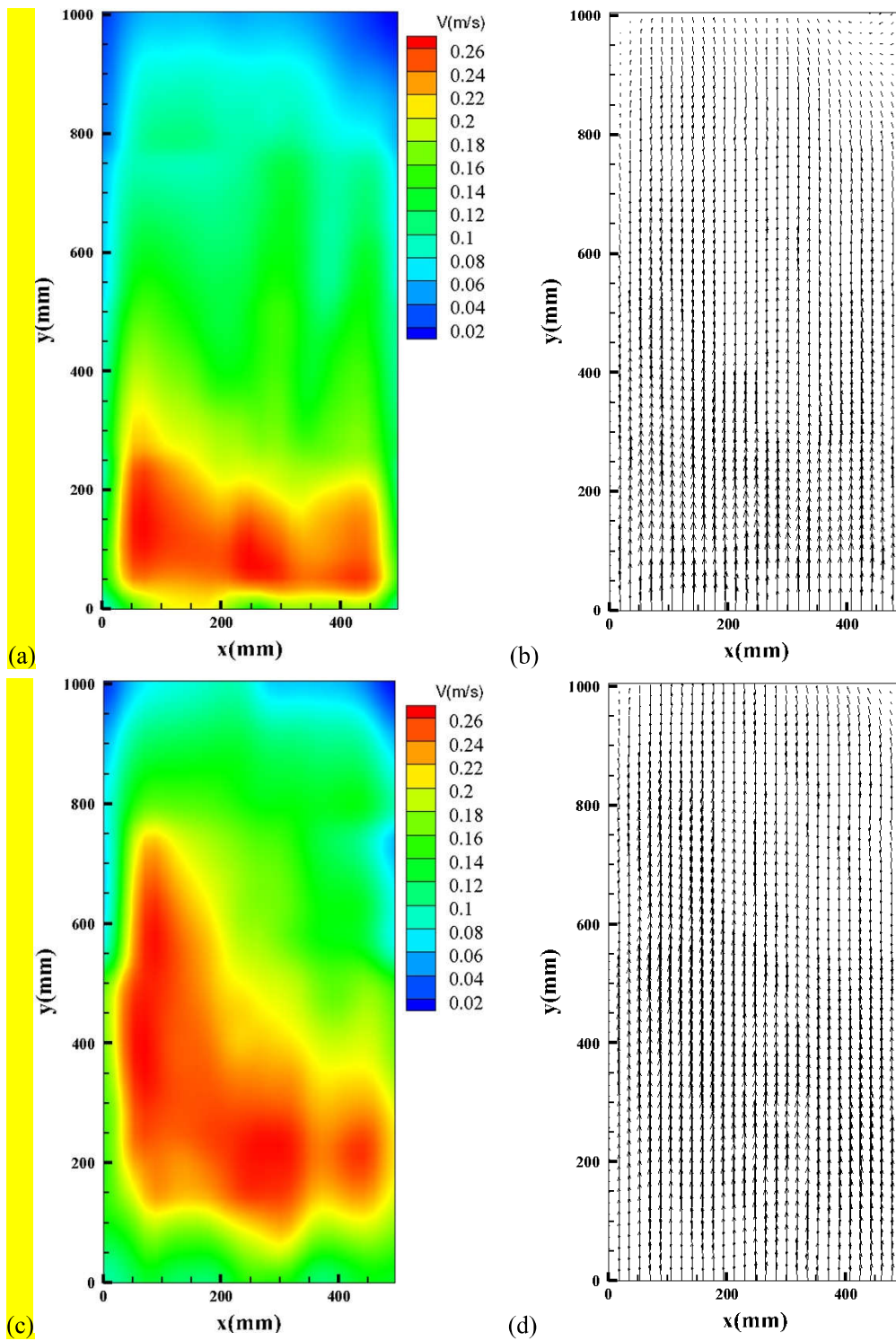


Fig. 7. Velocity distributions near the heated surface evaluated by PIV: a (b), c (d) velocity contour (velocity vector) of the planes 6 mm and 12 mm away from the heated surface.

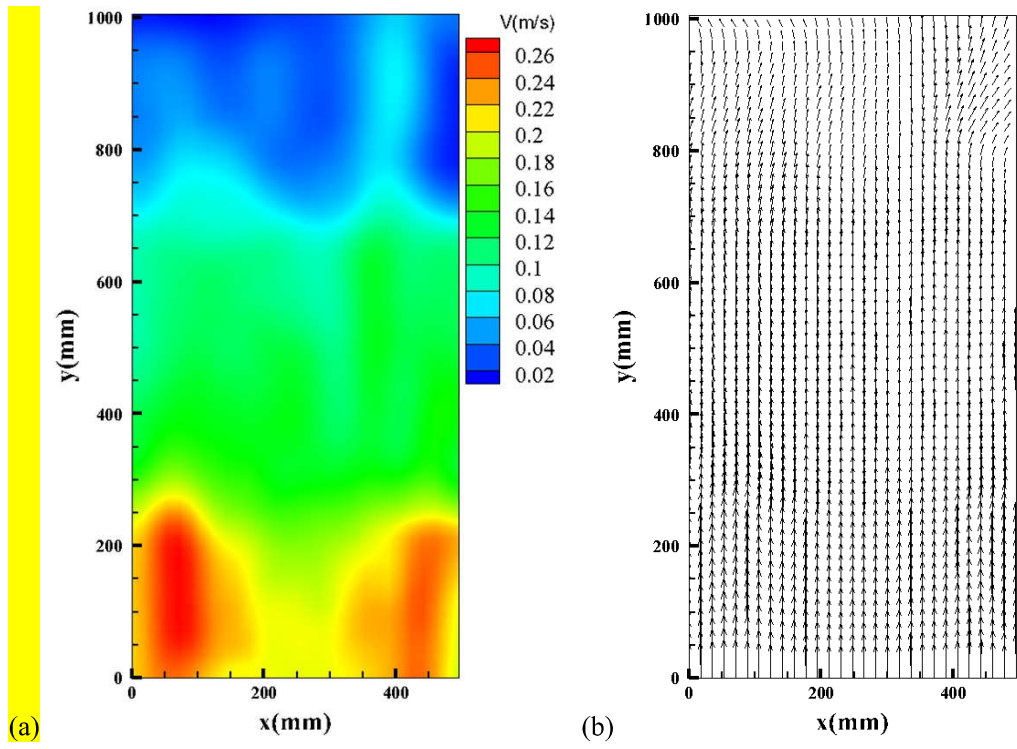


Fig. 8. Velocity distributions near the heated surface evaluated by TIV: **a** velocity contour, **b** velocity vector.

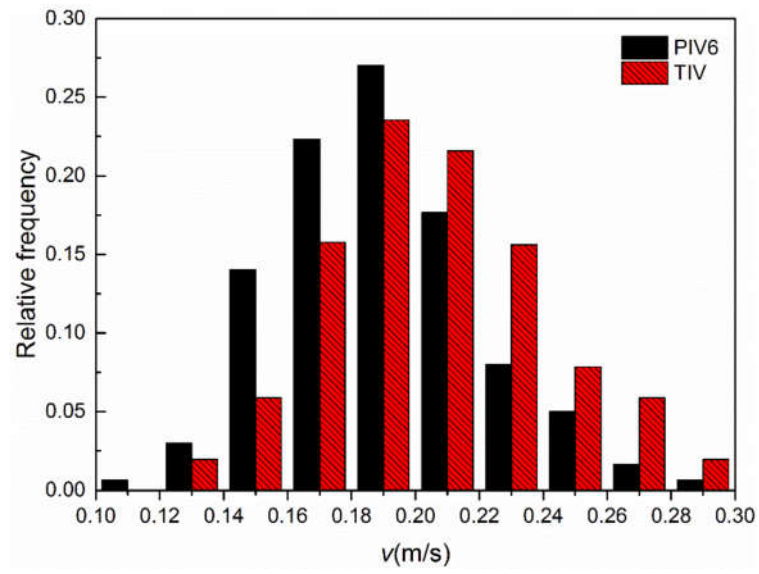


Fig. 9. Histogram of y -component of the velocity (v) evaluated by TIV and PIV6.

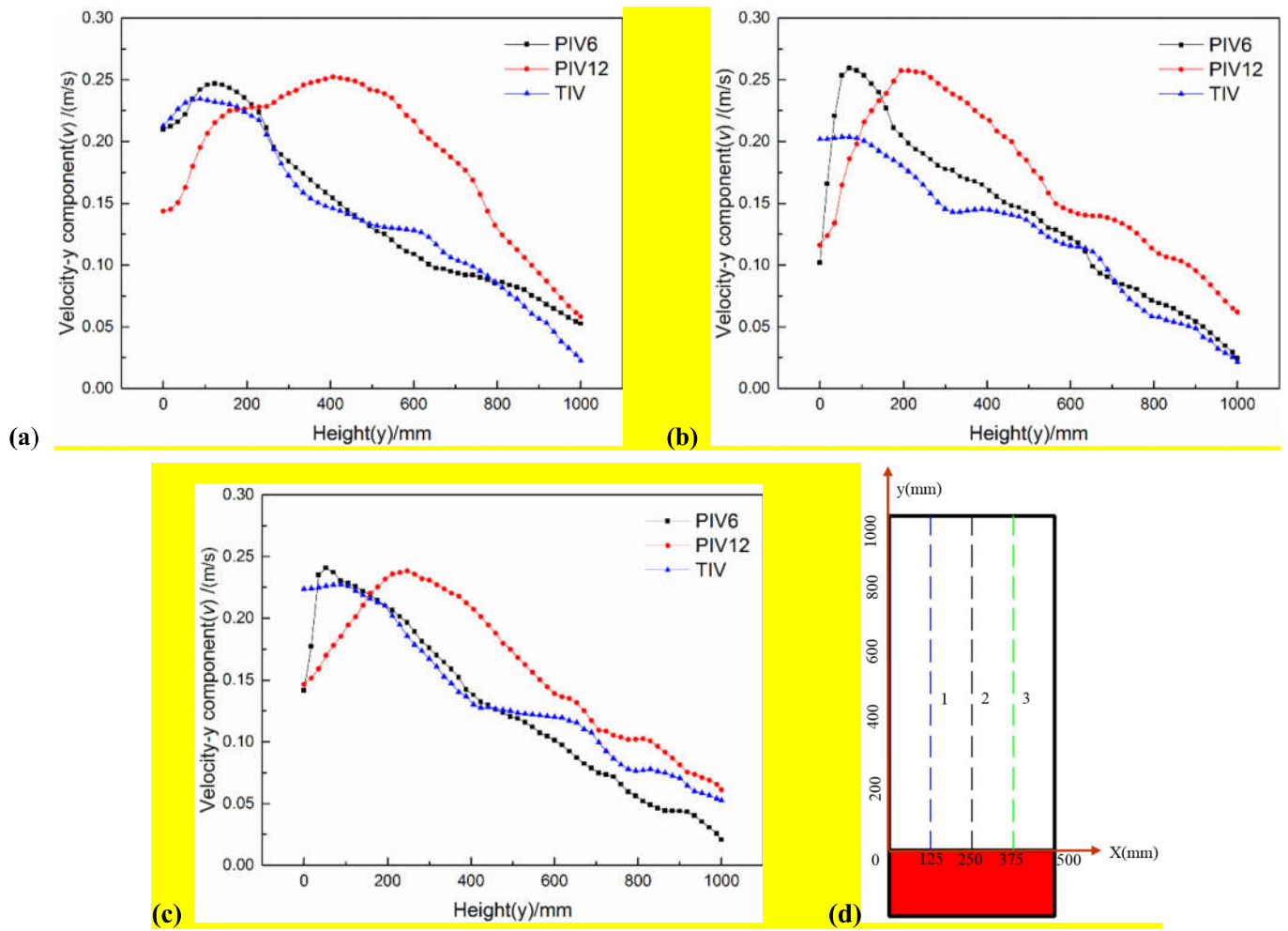


Fig. 10. y -component of the velocity (v) measured by TIV and PIV in **a** Line1, **b** Line2, **c** Line3 and **d** the representative lines.

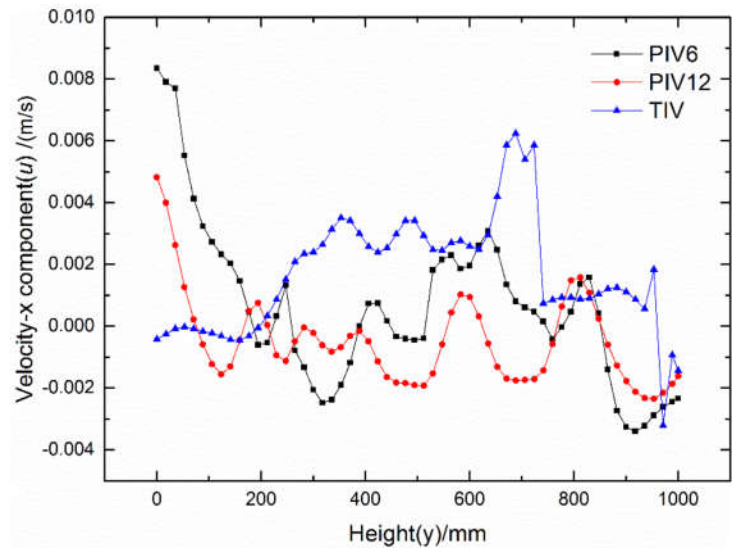


Fig. 11. x -component of the velocity in line 1

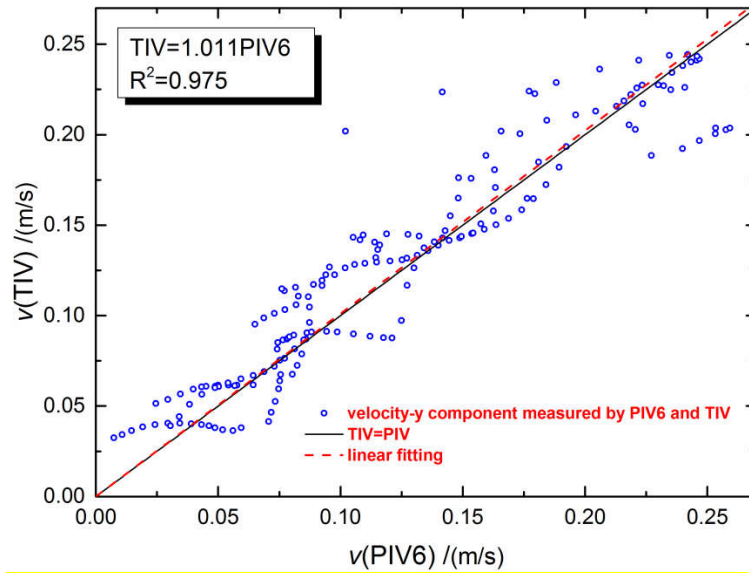


Fig. 12. Relationship between y -component of the velocity (v) measured by TIV and PIV6.

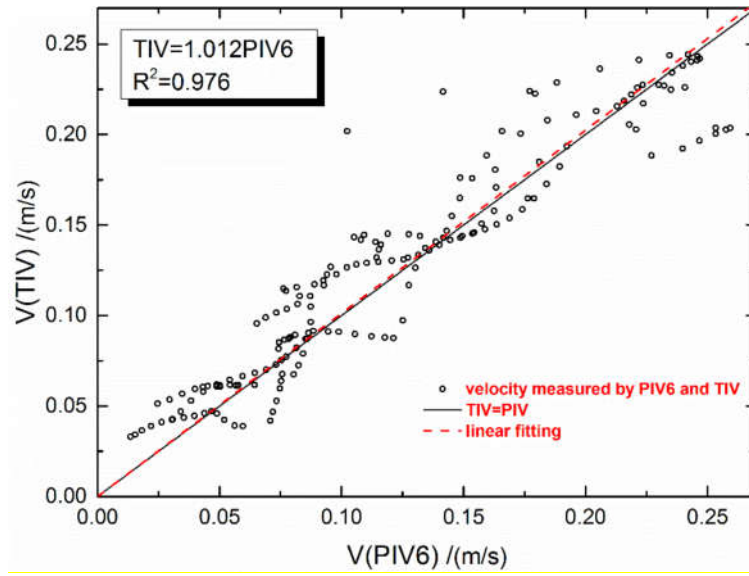


Fig. 13. Relationship between velocity (V) measured by TIV and PIV6.

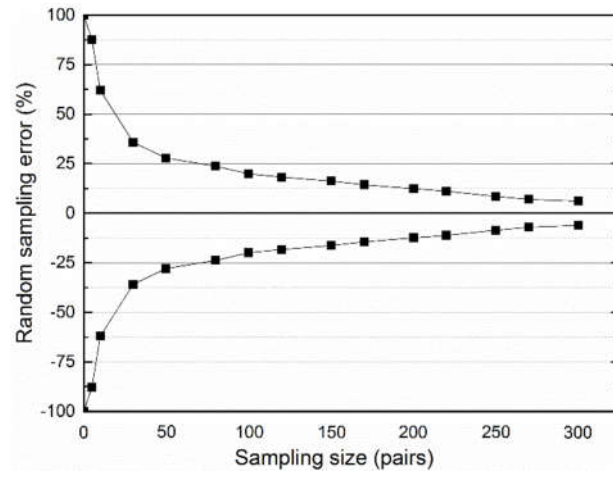
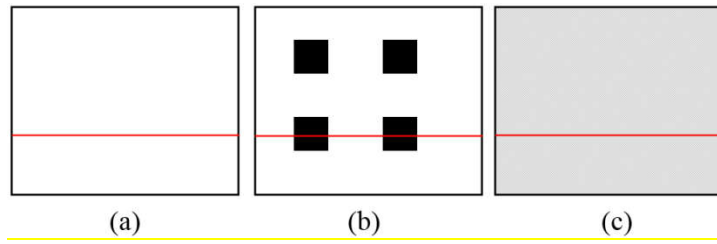


Fig. 14. Random sampling error of the time averaged velocity



514 **Fig. 15.** Schematic diagram of wall surfaces of the three conditions: **a** Case1, the unaltered surface and
515 surface emissivity is 0.90, **b** Case 2, the surface with pieces of black tape and surface emissivity is
516 0.90, **c** Case 3, the whole surface with silver tape and surface emissivity is 0.83.

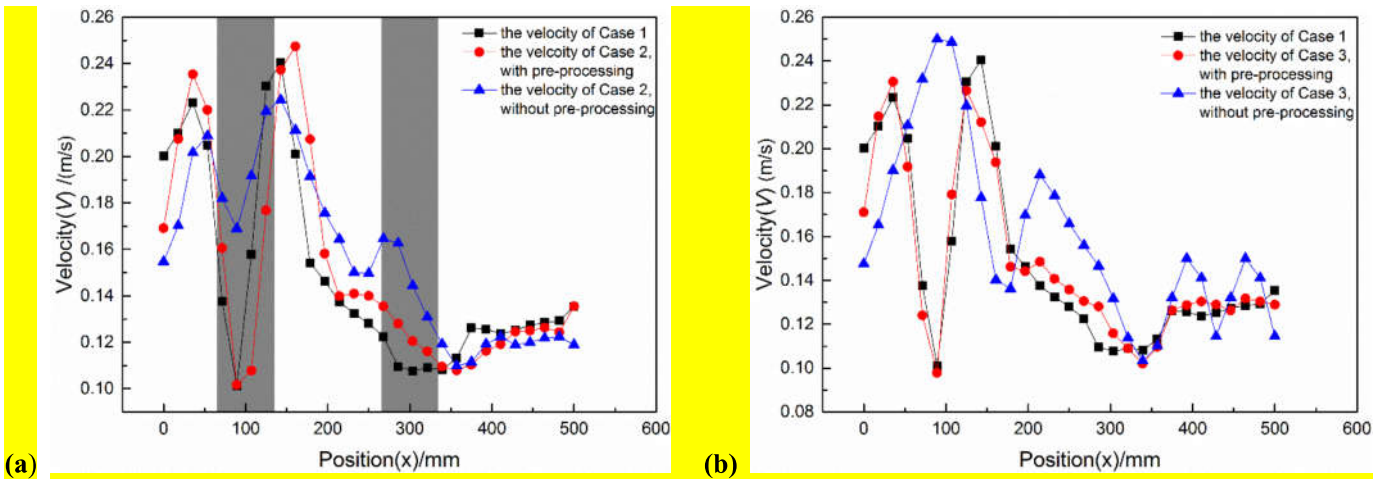


Fig. 16. Velocity profiles of the additional experiment to show the influence of local heterogeneities, surface emissivity and the pre-processing of the captured images on the measurement accuracy

Table

Table 1. Linear fit equations of TIV, PIV6 and PIV12 in line 1

Measurement	Linear regression equations	R^2
TIV	$v = 0.218 - 1.89(y / 10000)$	0.962
PIV6	$v = 0.246 - 2.169(y / 10000)$	0.995
PIV12	$v = 0.311 - 2.495(y / 10000)$	0.981