

## Research Paper

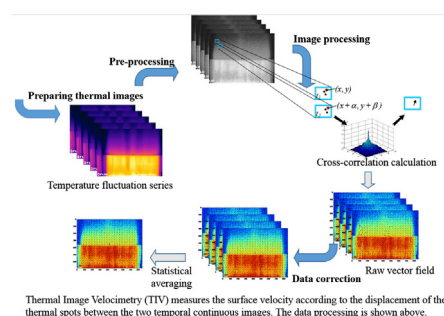
## Two-dimensional flow visualization and velocity measurement in natural convection near indoor heated surfaces using a thermal image velocimetry method

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## HIGHLIGHTS

- A thermal image velocimetry based method suitable for indoor airflow measurement is proposed.
- Visualization of the airflow near the heated surface based on sequences of thermal images and particle image velocimetry.
- A linear correlation between the results of thermal image velocimetry and particle image velocimetry is found.
- The flow field investigated by thermal image velocimetry is close to the surface of 6 mm away from the heated surface.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

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## ABSTRACT

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

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**Nomenclature****Abbreviations**

|     |                            |
|-----|----------------------------|
| TIV | thermal image velocimetry  |
| PIV | particle image velocimetry |

**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 (%)                   |
| $E_{b\lambda}$ | the black body radiation intensity (W/ m <sup>2</sup> )                       |
| $E_\lambda$    | the radiant intensity detected by thermal infrared camera (W/m <sup>2</sup> ) |
| PIV6           | PIV measurement results of the surface of 6 mm away from the heated surface   |
| PIV12          | PIV measurement results of the surface of 12 mm away from the heated surface  |

**Greek letters**

|                       |  |
|-----------------------|--|
| $\alpha$              | horizontal displacement of the thermal spot (m)                            |
| $\beta$               | vertical displacement of the thermal spot (m)                              |
| $\Delta\theta$        | the temperature difference between the wall and the adjacent air (T or °C) |
| $\varepsilon_\lambda$ | target surface emissivity  |
| $\tau_{a\lambda}$     | atmospheric spectral transmittance   |

**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   |

**1. Introduction**

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

The airflow measurement close to a heated surface is an important

aspect for indoor airflow measurements. Dominated by buoyancy originating close to a heated surface, the airflow is significantly complex, and a thorough understanding of its characteristics is of great significance for studies on room thermal comfort and energy efficiency [11]. The rising airflow induced by buoyancy generated close to the heated wall contributes to the air circulation in an entire room, and can alleviate the heat loss and the thermal discomfort induced by the infiltration of cold air. To date, there have been limited experimental studies [11–14] investigating the airflow field close to heated surfaces. This discrepancy can be attributed to the complexities of the building environment and the limitations of measurement technologies. The abovementioned measurement technologies have rarely been successfully applied in actual measurements close to heated surfaces. The primary reasons for this regarding point-wise measurements can be summarized as follows: a) because of the complexity of airflow near the heated surface, it is difficult to predetermine representative points indicative of the characteristics of the entire airflow field, b) the bulk of the point-wise probes are relatively bulky and the arrangement of probe arrays would disturb the flow field and significantly influence the accuracy of the results, and c) for probes that are electrically heated, such as hot-film anemometers, additional thermal buoyancy is experienced around them, and this would introduce considerable errors into the results [1]. For global-wise measurements, there are also practical difficulties in the application of measurements close to heated surfaces. Specifically, (a) tracer particles accumulate readily on an actual surface that has a certain degree of roughness, causing the particle concentration to be uneven in space, ultimately affecting the measurement, and (b) because of the limitations of the optical path and camera resolution, it is rarely applied in full-scale measurements and the area for PIV measurement is typically smaller than 1 m<sup>2</sup> [15].

Infrared thermal imaging technology is a powerful method for

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