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Numerical and experimental comparison of 3D Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV) accuracy for indoor airflow study

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A B S T R A C T

Experimental measurement still plays an important role in indoor airflow study. To obtain three-dimensional and high-quality experimental data in building's indoor airflow study, Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV) have been increasingly used. The accuracy and precision of measurement technologies is always a crucial issue. This paper first numerically compares the measuring performance of 3D PTV and typical 2D PIV algorithms on three laminar macro scale flows of known displacement, as a function of the particle tracking density defined as the ratio of mean particle spacing to mean particle displacement. Then, 3D PTV and 2D PIV results are compared using an experimental low-turbulence indoor airflow generated by a low-speed tailpipe. Results suggest that when the tracking density is smaller than two, 3D PTV generally cannot yield reliable measurement results. As the tracking density increases, 3D PTV has a better ability to measure larger displacement than PIV.

1. Introduction

Although Computational Fluids Dynamics (CFD) technology has been increasingly applied in recent years [1], experimental measurement still plays an important role to better understand the characteristics of indoor airflow. Besides, a reliable CFD simulation usually needs to be validated by abundant experimental data. For achieving high-quality experimental data, many experimental measurements are done using different modern measurement methods for indoor airflow. However, it is not an easy task to conduct perfect measurements when the airflow is unsteady and turbulent, and it is usually more difficult to measure the airflow in a three dimensional (3D) space.

Sun and Zhang [2] summarized main modern measurement methods for airflow. In general, these methods can be divided into point–wise techniques, such as Hotwire Anemometry (HWA), Ultrasonic Anemometry (UA) as well as Laser Dropper Anemometry (LDA), and global-wise techniques, including Particle Tracking Velocimetry (PTV), Particle Streak Velocimetry (PSV) and Particle Image Velocmetry (PIV). Compared to the point–wise techniques, because of the utilization of particle tracers and visualization technology, the global-wise techniques are non-intrusive for the measuring volumes, and have the ability to measure the airflow velocity fields of the whole domain directly, without displacing the measurement sensors on multiple points. Therefore, the local airflow is not be disturbed by the measurement tools, which can lead to a better understanding of the airflow characteristics.

Although PIV and PTV techniques are regarded as global-wise measurement techniques, they are actually based on different measurement principles. PIV technique, as an Eulerian measurement method, yields fluid velocity $\vec{v}$ as a function of position x and time T, as described in Eq. (1). Generally, $\vec{v}$ can be a one-, two- or three-dimensional vector, based on the PIV technique used.

$$\vec{v} = \frac{d\vec{x}}{dT} \tag{1}$$

In the PTV technique, as a Lagrangian measurement method, the fluid velocity $\vec{v}$ is obtained through tracking the motion of each individual point, as a result of Eq. (2).

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Nomenclature

$\boldsymbol{a}$	Coefficient determined by polynomial curve fitting in a least square sense in equation (5)
$\boldsymbol{b}$	Coefficient determined by polynomial curve fitting in a least square sense in equation (5)
$\boldsymbol{c}$	Coefficient determined by polynomial curve fitting in a least square sense in equation (5)
d_m	Measured particle displacement
d_r	Imposed particle displacement
$\bar{f}_{u,v}$	The mean of $f(x,y)$ in the region under the template
$f(x,y)$	Research window
$F_{i,j}$	Fundamental matrix linking camera i and j
N_p	The number of particles
N	The number of samples
R_i	3 × 1 rotation matrix transferring camera i 3D reference frame to calibration target 3D reference frame
R_j	3 × 1 rotation matrix transferring camera j 3D reference frame to calibration target 3D reference frame
s	Stereo pair matching threshold
$\bar{t}$	The mean of the template (interrogation window)
t	Frame number
T	Time
T_i	3 × 1 rotation matrix transferring camera i 3D reference frame to calibration target 3D reference frame
T_j	3 × 1 rotation matrix transferring camera i 3D reference frame to calibration target 3D reference frame
$[u]_x$	Cross-product
$\vec{\boldsymbol{v}}$	Fluid velocity vector
v_x	Fluid(particle) velocity on x-direction
v_y	Fluid(particle) velocity on y-direction
$\boldsymbol{x}_{pre}$	Estimated particle position
$\vec{\boldsymbol{x}}$	Fluid (particle) position
x	Real world's coordinates on x-direction
x_{cam}	Pixel coordinates on x-direction
x_i	Normalized pixel coordinates on x-direction
X	Size of volume on x-direction
X_{sch}	Schematic coordinates on x-direction
y	Real world's coordinates on y-direction
y_{cam}	Pixel coordinates on y-direction
y_i	Normalized pixel coordinates on x-direction
Y	Size of volume on y-direction
Y_{sch}	Schematic coordinates on y-direction
z	Real world's coordinates on y-direction
Z	Size of volume on z-direction
ξ	Tracking density
λ	Coefficient in equation (3)
$\gamma(u,v)$	Result of normalized cross-correlation
β	Bias
δ	RMS total error
σ	Random error

$$\vec{\boldsymbol{v}}(x(T),T) = \frac{d\vec{\boldsymbol{x}}}{dT} \quad (2)$$

Besides, Lagrangian measurement methods can yield individual point trajectories. More details on measurement principles of global-wise techniques can be found in scientific literature e.g. Refs. [3,4].

Abundant research has been done on PIV algorithms and on PIV accuracy evaluation during the past 25 years e.g. Refs. [5–8]. Some commercial PIV measurement systems and some open-source PIV algorithms have also been developed and are now available. Typical PIV technology as well as its application in airflow study has been reviewed by Cao et al. [9], and the review indicates that PIV technology is becoming a powerful measurement method in airflow study. However, PIV technology is still limited to large scale two-dimensional measurement or small-centimetric-scale three-dimensional measurement. This limitation comes from its need for laser illumination, which is very difficult to generate and control in safe experimental conditions in large three-dimensional space. Due to the availability and the easy and safe operation of ordinary halogen-like continuous light sources, 3D PTV technology can be applied in large scale three-dimensional measurement, but the complexity of tracking algorithms still limits its development to a certain extent. Nevertheless, it is more and more applied in indoor airflow measurement [10].

Whatever the measurement methods, the accuracy and precision respectively defined as the proximity of measurement results to the true value and the reproducibility of the measurement results, are always a crucial issue. However, it is not trivial to assess the accuracy and precision of PIV and PTV techniques. Regarding PIV technique, its accuracy and precision is always affected by a large range of parameters, such as particle image concentration, particle image size, background lighting, the positions of the camera, the ability of tracer particles to follow the flow, etc. [8,11]. Similarly, these parameters also have influence on the accuracy and precision of the PTV technique. Substantial research has been devoted to investigate the effects of these parameters on the accuracy and precision of PTV and PIV techniques e.g. Refs. [12–14]. Kim et al. [15] compared the experimental measurement results of Tomo-PIV and 3D PTV for micro-fluidic flows. Such a comparison is still lacking in large scale air volumes. Besides, in these previous researches, the effect of 'tracking density', an indicator of tracking difficulty introduced by Malik et al. [16], is seldom considered. Generally, bigger tracking density means easier particle tracking.

In traditional PIV, seeding density is usually chosen high [17], without any reference to the spacing-displacement ratio. On the contrary, in 3D PTV, the tracking density is generally chosen based on the ability of the tracking algorithm to tackle strong seeding density, on the size of the measuring volume and on the ability of the particle generator to produce numerous particles. Biwole et al. [18] tested their 3D PTV algorithm using a tracking density ranging from 2.1 to 8.1, while Barker et al. [19] and Lobutova et al. [20] used tracking density of the order of 25 for 3D PTV in volumes over three cubic meters.

This paper firstly investigates the effect of small tracking densities (from 1 to 5) on the accuracy and precision of macro scale 2D PIV and 3D PTV measurement using numerical methods. Then, typical 2D PIV and 3D PTV are used to conduct a comparative measurement on low turbulence airflow in real experimental conditions. The paper solely compares the ability of PIV and PTV to measure instantaneous velocity fields. The ability of PTV to provide trajectories is not taken into account since PIV is an Eulerian measurement method.