Energy and Buildings 69 (2014) 367–380

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Review

Particle image velocimetry measurement of indoor airflow field: A review of the technologies and applications

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ARTICLE INFO

Article history:
Received 8 September 2013
Accepted 1 November 2013

Keywords:
Indoor environment
Airflow
Particle image velocimetry (PIV)
Measuring technique

ABSTRACT

Quantifying the airflow field in building room or vehicle cabin is crucial for creating a thermal comfortable and healthy indoor environment. Airflow field measurement can provide quantitative information of indoor air distribution and local air velocity around occupants or passengers, which has strong relationship with the ventilation effectiveness, the pollutant transportation and the energy conservation in a building or a vehicle. Specifically, PIV has gradually became the most popular and promising technique for airflow field measurement in indoor environment during the last decade. This paper firstly gave an overview of the typical PIV technologies used in indoor environment and the state-of-the-art applications of PIV in measuring the indoor airflow fields. The overview shows that the quantitative and detailed turbulent flow information obtained by PIV is critical for analyzing turbulent properties and validating numerical simulations. Specifically, the authors focused on the pros and cons of PIV measurement and gave the typical parameters of PIV used in indoor airflow field measurements. Generally, the researchers should pay more attention to the selection of appropriate PIV system parameters according to their specific research needs. The accuracy of PIV measurement and the limitations of measurement systems using PIV were also discussed.

Contents

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http://dx.doi.org/10.1016/j.enbuild.2013.11.012

1. Introduction

Ventilation concepts, including natural ventilation and mechanical ventilation, have been widely used and discussed in indoor environment quality studies [1–4]. The performance of ventilation system can be assessed in terms of airflow pattern, the distribution of contaminant concentration, air velocity, air temperature, global ventilation effectiveness, air distribution effectiveness, etc. [4]. Among the various studies dealing with the performances and applications of ventilation systems, the indoor airflow patterns and airflow field are some of the most widely concerned issues. It is because that the air motion responsible for transporting both heat and pollutants is one of the main factors controlling indoor environment quality, which helps to create a thermally comfortable and safe built environment as well as to provide adequate ventilation for reducing gaseous and particulate concentrations of contaminant. Moreover, indoor air distribution designs in HVAC also have a strong influence on building energy consumptions. For a space heating and cooling system, the type of air distribution system plays a decisive role in the energy performance. A reasonable approach to indoor air distribution, such as the under floor air distribution (UFAD), can save a great amount of energy due to the higher supply air temperature and lower ventilation rate. A previous study [5] showed that the potential energy benefit of UFAD is significant compared to the conventional ceiling air distribution system. Therefore, quantifying the airflow field in a room is crucial for creating both a thermal comfortable, healthy and energy-saving indoor environment.

Experimental measurements and numerical simulations are the two main methods available for the indoor airflow field studies. Airflow field measurement can provide reliable quantitative information of indoor air distribution or local air velocity around occupant [6–8]. However, experimental measurement is usually difficult and time-consuming. Numerical simulation can provide both global and detailed airflow quantities under various cases at relatively low cost, which is very helpful for the design and assessment of indoor ventilation system. However, conducting numerical simulation always relies on accurate measurements as the boundary conditions [9–11]. The simulated results also cannot be completely trusted unless being validated by corresponding high quality experimental data [12–15]. Therefore, experimental measurement is still the necessary and fundamental step of indoor airflow study.

Nevertheless, the airflow field in indoor environment is normally characterized by high turbulent level and unsteady flow due to the relatively low air velocities from diffusers, thermal plumes of heat sources and unsteady perturbation of occupants' behavior. Therefore, it is not easy to conduct accurate airflow field measurement in indoor environment. Sun and Zhang [16] summarized various kinds of modern indoor air motion measurement techniques. In general, the velocimetry can be divided into point-wise and global-wise. The point-wise techniques include Pitot tube and rotating-vane anemometry, which are based on pressure differential principles; hotwire anemometry, hot-film anemometry and hot-sphere anemometry, on heat transfer principles; ultrasonic anemometry (UA), on acoustics principles; and laser Doppler velocimetry (LDV), on Doppler shift principles. The global-wise techniques mainly include particle tracking velocimetry (PTV), particle streak velocimetry (PSV) and particle image velocimetry (PIV), which are based on optical principles. The traditional point-wise anemometry can only obtain the velocity information at the point of the probe sensor. Generally, it is very difficult to conduct accurate and detailed measurement of the global turbulent airflow field in indoor environment with point-wise velocimetry. Meanwhile, most of the point-wise velocimetry, such as thermal anemometry and ultrasonic anemometry, are thought to have perturbations on the local airflow. Even using the non-intrusive point-wise techniques (e.g. LDV), it is still excessively difficult and time-consuming to conduct the global airflow field measurement point by point.

For this reason, optical velocimetry have gradually become the alternative tools for measuring indoor airflow distributions. Optical velocimetry can obtain the velocities and related statistical information in a global domain without disturbing the airflow, which makes the whole instantaneous and mean velocity field measurement possible. PIV is the most robust and widely used optical velocimetry for flow field studies [17,18]. Specifically, PIV has begun to be used in indoor airflow field measurements during the last decade. The main reasons for the popularity of PIV measurements are well-developed technologies, rich experimental experiences and commercially available systems. Though the setups of PTV and PSV are similar to PIV and have been applied in some indoor air motion measurements [19–23], they are still developing and not commercially available in the market at present, due to the complex algorithms and special experimental settings involved. It is not convenient for common researchers in HVAC&R field to use PTV or PSV to conduct the indoor airflow field measurements. Therefore, PIV is supposed to be the most appropriate and promising technique for airflow field measurement in indoor environment.

This study focuses on providing an overview of the typical PIV technologies used in indoor environment and the state-of-the-art applications of PIV in measuring the indoor airflow fields. The key technologies used in typical PIV systems and the pros and cons of PIV measurement in indoor environment will be reviewed during the last decade. The accuracy of PIV measurement and the limits of measurement systems using PIV will be discussed.

2. PIV technologies for indoor applications

The term 'Particle Image Velocimetry' (PIV) first appeared in the literature in 1980s [18]. The significant scientific and technical progress achieved in the last 30 years in lasers, image recording and evaluation techniques, and computer techniques led to the further development of PIV technique. Presently, PIV has become a powerful tool for studying flow field in indoor environment. The measurement principle and major developments of PIV have been reviewed in many excellent papers [24–28] and in a comprehensive book by Raffel et al. [17]. Therefore, in this section, we just introduce the PIV technologies focusing on the applications in indoor environment.

PIV is a technique to achieve quantitative measurement of instantaneous turbulent velocity fields as an extension of qualitative flow visualization. PIV tracks the tracer particles seeded in the air to obtain the whole velocity field of the given measurement area. A typical PIV system consists of a multi-pulsed laser system, one or more digital cameras synchronized with the lasers, and a computer to control the system and analysis the data. A 2D–2C PIV system only uses one camera while a 2D–3C PIV system uses two cameras. As for volumetric PIV system, such as tomographic PIV system, more than three cameras will be used. Due to the complicated experimental setup and much more expensive price of a volumetric PIV system, the most common used PIV in indoor airflow measurements is still 2D–2C PIV. The basic setup of a 2D–2C PIV system is shown in Fig. 1 [29]. The key technologies applied in a typical 2D-PIV system will be briefly discussed hereinafter.

2.1. Illumination system

For the indoor airflow field measurements, the most widely used illumination system is a double-pulsed Nd:Yag lasers system with an articulated delivery arm to generate a green light sheet of 532 nm