Building and Environment 115 (2017) 251–268

Contents lists available at ScienceDirect

Building and Environment

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

Numerical investigation and accuracy verification of indoor environment for an impinging jet ventilated room using computational fluid dynamics

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ARTICLE INFO

Article history:
Received 24 September 2016
Received in revised form
19 January 2017
Accepted 19 January 2017
Available online 31 January 2017

Keywords:
CFD
Full-scale test
Impinging jet
Thermal stratification

ABSTRACT

The impinging jet ventilation (IJV) system has been proposed as an air distribution strategy to provide a better thermal environment with a medium supply momentum than displacement ventilation (DV) system. However, no simplified prediction method that is practically applicable has been established to date. The ultimate goal of this study is to establish a calculation model to predict the vertical temperature profile in an IJV system. The authors aim to propose a one-dimensional model, where the room is divided into several control volumes. To perform this, the turbulent thermal diffusion between control volumes needs to be well understood. Therefore, a knowledge about the effect of each design factor such as the supply air velocity on the turbulent thermal diffusivity needs to be acquired through a parametric study. Computational Fluid Dynamics (CFD) is effective for this purpose. As a first step, the accuracy of CFD simulations is verified by conducting a full-scale experiment. The velocity profiles inside the impinging jet and the indoor temperatures are measured and compared with the CFD results. It is shown that the shear-stress transport k-ω model has a sufficient accuracy to analyse the target room, and an appropriate grid layout is established as well. The convection-radiation coupling CFD prediction where the external temperature is used as a boundary condition is adopted as the best method for the numerical study in this research. Finally, a parametric study on the supply air velocity is performed based on this setting and its effect on the thermal stratification is presented.

1. Introduction

The air distribution system inside a room is of great importance because it has a significant impact on the indoor environment, which is one of the main concerns in the design of an air-conditioning system of buildings. In addition to providing thermal comfort of the inhabitants, the energy efficiency of such distribution systems needs to be carefully considered as well. In this perspective, designing an efficient air distribution system for occupied spaces has attracted many theoretical and practical interests. The displacement ventilation (DV) system is regarded as one of such energy-efficient air distribution systems because of its thermal stratification and high ventilation effectiveness owing to the flow that is governed by buoyancy. The DV system began to be generally applied in the early 1980s, especially in the Nordic countries [1,2]. Many academic research regarding its performance in terms of indoor airflow, indoor air quality, and thermal environments have been reported afterward, and many findings have been published to date. For instance, the mechanism of the DV air distribution is well described by Etheridge and Sandberg [3], Nielsen [4], Skistad [5], Yuan [6], and Mundt [7]. Given the practical applications of the displacement technique for the air-conditioning system design, the indoor environment needs to be predicted in advance. This led to several prediction models of the vertical temperature profile, many of which were proposed in the 1990s [7–10]. The performance of the DV system has been investigated by a number of researchers for practical use [11–15]. Several models to predict the indoor pollutant concentration profile have been

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http://dx.doi.org/10.1016/j.buildenv.2017.01.022
0360-1323/

proposed as well [16,17]. While the DV system has a strength because of its high ventilation effectiveness and thermal stratification, it could cause a decrease of performance in some occupied zones owing to its low-momentum air supply. For instance, Melikov [18] evaluated the risk of local discomfort due to draft and vertical temperature difference. In addition, the DV system has a disadvantage in that it is difficult to apply as a heating system.

The impinging jet ventilation (IJV) system, which is a new air distribution system that overcomes the aforementioned obstacles and provides a better indoor environment within an occupied zone, has been attracting increasing attention during the last decade. In an IJV system, the air is supplied downwards onto the floor and spreads over a room as a thin layer with its momentum decreasing gradually. It is generally known that the IJV system can combine both advantages of the mixing and displacement ventilation due to a medium momentum supply [19]. Namely, the system can provide the supply airflow more evenly than DV system, which leads to a clean air zone in the lower part of the room. If compared with the DV system, the air reaches a longer distance owing to higher momentum. Consequently, the IJV system is less likely to generate an undesirable horizontal distribution of temperature and contaminant concentration while maintaining the same strength of the DV system such as the thermal stratification and high ventilation efficiency. Moreover, the IJV system has a possibility to be applied as heating system as well.

Focusing on the advantages of the IJV, some research papers have been published in recent years. For instance, Karimipanah and Awbi [20] compared the ventilation performance between a wall-mounted DV and IJV system by means of actual measurement and CFD. Although these studies were performed under specific conditions and further studies are still required, they concluded that the IJV system had a better balance and velocity distribution and age of air than the DV system for their case. Varodompun and Navvab [21,22] have shown the vertical profiles of velocity and temperature of the wall impinging jet by means of both a full-scale experiment and CFD simulation. They demonstrated the performance of the IJV system in a classroom and showed the ventilation indices as a practical case study. Varodompun [23] also examined the performance of IJV regarding the terminal configuration, HVAC operation, space volumes and so on. He showed that the supply air velocity is one of the important variable to determine the characteristics of the jet flow. Chen, Moshfegh, and Cehlin [24–26] studied as well the IJV system mainly by using CFD. They started from an analysis of the fundamental behaviour of the isothermal impinging jet and validated CFD results by comparing with actual measurement, and showed the temperature and velocity fields inside a small office room. In their research, the draught discomfort was finally evaluated by changing several calculation conditions as design factors, e.g. the supply airflow rate, height of the IJV diffuser, and supply air temperature. Ye [27] analysed the heating energy consumption in both the mixing ventilation and IJV systems, and showed that the total heating energy usage in IJV system was less than that in mixing ventilation. Zuo [28] evaluated the potential risk of particle resuspension from the floor in IJV system by means of experiment.

When applying the IJV system to a practical air-conditioning system design, the thermal stratification inside a room becomes a major concern to designers because it significantly affects the thermal comfort and energy efficiency. The vertical temperature profile is determined roughly by correlation between the momentum and buoyancy of the supply airflow and thermal plume. This is a fundamental difference from the conventional mixing ventilation and leads to difficulty in designing the IJV system. As mentioned above, several prediction models have been proposed for the DV system. As for the IJV, however, there is no general and simplified model available at present.

The ultimate goal of this study is to establish a new prediction model for the vertical temperature profile in an impinging jet ventilated room. The authors aim to propose a one-dimensional model where the room is divided into several control volumes in the vertical direction, and the advective/diffusive heat flux between control volumes is considered. In order to predict a rational temperature profile in such a prediction model, the effect of turbulent diffusion is relatively important as it is affected by a number of design factors such as the supply air velocity, and temperature difference. Therefore, the characteristics of the turbulent thermal diffusivity need to be clarified first by a parametric study. To perform this, the CFD prediction is an effective approach. As a first step of this research, the authors aim to verify the accuracy of the CFD results especially on the macroscopic temperature profile in vertical direction, which is the target of the simplified prediction model.

In this study, both a full-scale laboratory measurement and CFD analysis are performed. By using several RANS turbulence models, the accuracy of the CFD simulation of an impinging jet ventilated room is studied under a non-isothermal condition as a validation study. Then, as a parametric study to understand the fundamental performance of the IJV system, CFD analyses at varying supply velocities are conducted, and the effect of supply velocity on the vertical temperature profile is presented.

2. Full-scale experiment

2.1. Full-scale test room

A full-scale experiment of the IJV system was conducted in a test room depicted in Fig. 1. The test room was located inside the main laboratory of which floor plan had a dimension of 32 m × 10 m × 5.0 m (length × width × height). The air temperature in the main laboratory was 27.0 °C when the experiment was conducted. The test room had a dimension of 9000 mm × 5000 mm × 2700 mm (length × width × height), and it was provided with a plenum space above the suspended ceiling and a crawling space under the floor. The walls and the roof over the plenum space were insulated by 50 mm-thick rigid polyurethane foam as shown in Fig. 1. In order to reduce the effects of heat transfer due to convection and radiation, sheets of 8.0 mm thick polyethylene insulation were additionally installed on the internal surface of the vertical walls of the room. For simplicity and to facilitate the understanding of the effect of supply airflow characteristics on the room temperature distribution, the insulation sheets were provided with an aluminium-metallised film on the surface, which could decrease the internal radiative heat transfer. In the test room, an IJV supply terminal shown in Fig. 2 was installed with its bottom end 600 mm above the floor. The cross-section of the IJV terminal was a semicircular configuration with a diameter of 300 mm. The supplied airflow rate and temperature were regulated at 600 m^3/h and 20 °C, respectively. Consequently, the average velocity over the supply area of the terminal was 4.17 m/s.

As an internal heat load, a heating box, which has a relatively large heat generation rate, was installed on the floor at the centre of the room. It is noted that an air-conditioning system forming a thermal stratification like the IJV system is advantageous especially in a building with a high heat load such as industrial buildings. In this study, the authors intended to analyse a room where a relatively strong plume is generated. The heating box, as shown in Fig. 3, had a cubic configuration of 800 mm, and was made of 3.0 mm thick stainless steel plates. Three heating elements of coiled resistance wire were installed inside the box, and the total heat