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Experimental study of a non-isothermal wall jet issued by a displacement ventilation system

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ABSTRACT

This paper reports a new set of experimental data and presents an in-depth analysis of the flow physics of a non-isothermal jet stream produced by a large quarter-round corner-mounted displacement diffuser. The air velocity, temperature and turbulence intensity inside the displacement ventilation (DV) jet have been thoroughly analyzed and compared with the reported findings of previous studies and model predictions. Through the experiment, it is observed that the DV jet development is significantly altered by buoyant forces and can be divided into four distinctive zones. The results of the present study refine the physical understanding of the coupled thermal-fluid fields characteristic of a DV jet stream, and are useful for improving the design of the DV system tested.

1. Introduction

Since its first application in Scandinavia in 1978, use of displacement ventilation (DV) has become popular for air conditioning in modern public buildings such as airports, libraries, theaters and stadiums. In a well-designed displacement ventilation system, only the occupied zone of a room is cooled. In comparison with the traditional mixing ventilation systems which require the entire indoor environment be conditioned, this unique feature of DV systems allows for a significant reduction in building energy consumption. Furthermore, a DV system is advantageous for improving the indoor air quality, because air contaminants can be effectively displaced from the occupied zone by buoyant forces. In order to achieve maximum energy efficiency and thermal comfort, the physical mechanisms underlying turbulent heat, mass and momentum transfer in a DV system need to be thoroughly studied.

Over the past two decades, extensive studies have been conducted to improve the system performance and simplify the design procedure of DV systems. According to the study of Skistad [1], Chen and Glicksman [2] and Nielsen [3], the flow rate, supply air temperature difference, diffuser type and location are the key parameters in determining the flow characteristics of a DV system. In a DV system, the cold air is supplied through a low-level diffuser. Due to buoyant forces, the air falls close to the supply diffuser and generates a jet stream along the floor. The DV jet stream strongly influences the air distribution, energy efficiency and system performance. Also, the characteristics of a DV jet stream are of great importance to thermal comfort, because an airflow of a relatively high speed and low temperature at the lower-leg region can cause draft discomfort. Nielsen et al. [4], Zhang et al. [5], Lau and Chen [6], and Einberg et al. [7] have studied the flow dynamics of different types of diffusers under a variety of room and air supply conditions. However, thus far, only a limited number of experiments have focused on the flow characteristics inside a DV jet (i.e., the flow region downstream of a diffuser and bounded by the floor, side walls and free-surface jet envelope). Here, the jet envelope refers to the dynamic interface between the jet stream and the low-speed or even stagnant background room air. Li et al. [8], and recently, Cehlin and Moshfegh [9] and Magnier et al. [10] conducted detailed measurements on the velocity and temperature fields inside DV jet streams in order to investigate the coupled momentum and thermal energy transport processes. Furthermore, previous experimental studies of DV jet streams have been conducted primarily based on jets issued from a small wall-mounted displacement diffusers, and measurement data based on DV systems of different types and sizes are still very limited in current literature. Also, the far downstream region of the DV jet stream has not been thoroughly studied in the previous experiments. In contrast to the

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previous studies, this research aims at reporting and analyzing a new set of experimental data on the jet stream in a large room supplied by a relatively large corner-mounted quarter-round displacement diffuser.

A DV jet is a prototypical example of thermal wall jets, in which, the flows are often weakly turbulent and the transports of the momentum and thermal energy are tightly coupled. Previous efforts (e.g., Rajaratnam [11]) on this subject have concentrated on investigation of flow development in isothermal wall jets and empirical models for describing neutrally-buoyant jet velocity profiles. Studies on thermal wall jets are still relatively rare in literature and highly referenced velocity models for DV jets proposed by Nielsen [3] and Nordic Innovation Center [12] have only focused on the prediction of the maximum velocity decay of the jets. The development of a DV jet is indeed complicated in flow physics. In a thermal jet, when buoyant forces are significantly smaller than inertial forces, the jet behaves like an isothermal one. On the other hand, when the buoyant forces are much greater than inertial forces, the jet develops like a thermal plume and the airflow is dominated by natural convection. In a DV jet, the ratio of buoyant forces to inertial forces is neither overly small nor overly large, and the flow, therefore, features mixing of forced and natural convection. Furthermore, as a DV jet develops in space, the velocity and temperature fields vary considerably along the jet. This means the ratio of the buoyant forces to inertial forces varies significantly along the jet stream, which further complicates the jet dynamics.

In present study, multiple measurement techniques based on low-temperature thermal anemometry and resistance temperature detectors have been used to gather detailed information on the velocity, temperature and turbulence intensity fields of the DV jet stream. An in-depth analysis of the experimental results and flow physics of the DV jet is presented. The obtained results are compared with the reported findings of previous studies and existing empirical models for the wall jet flow distribution. Furthermore, the influence of the relative strength between buoyant, inertial and viscous forces on the DV jet development is thoroughly analyzed based on the experimental data. The measured data shows that the velocity, temperature and turbulence intensity fields vary significantly along the jet stream, which in turn allows for a new refined division of the jet stream into four distinct zones.

This paper is organized as follows. In Section 2, the physical model and experimental procedure are introduced. In Section 3, the empirical models for predicting the velocity distribution of a DV jet are briefly reviewed. In Section 4, the obtained results from the experiment are analyzed and compared with the model predictions. Finally, in Section 5, the major conclusions of this research are summarized.

2. Physical model and experimental procedure

The experiment was carried out at the Price Industries research lab, in a large test room with interior dimensions of $10.7 \times 6.1 \times 2.7$ m (length by width by height, see Fig. 1). The air was supplied through a floor-level, corner-mounted, quarter-round displacement diffuser with a radius of $r = 0.43$ m and a height of $h = 1.52$ m. The diffuser grille has a porosity of 20%, with 2.38 mm diameter circular holes, spaced by 4.76 mm (center to center). The supply airflow rate and temperature were adjusted to $\dot{Q}_s = 208$ l/s and $T_s = 16.4$ °C, respectively. The air leaves the test room at $T_o = 22.3$ °C through a square opening (0.58×0.58 m) located on the ceiling which is shown as the outlet in Fig. 1. Given the supply flow rate and temperatures at the inlet and outlet of the room, the total ventilation cooling power was approximately 1500 W. The air temperature in the center of the room at the height 1.1 m was used

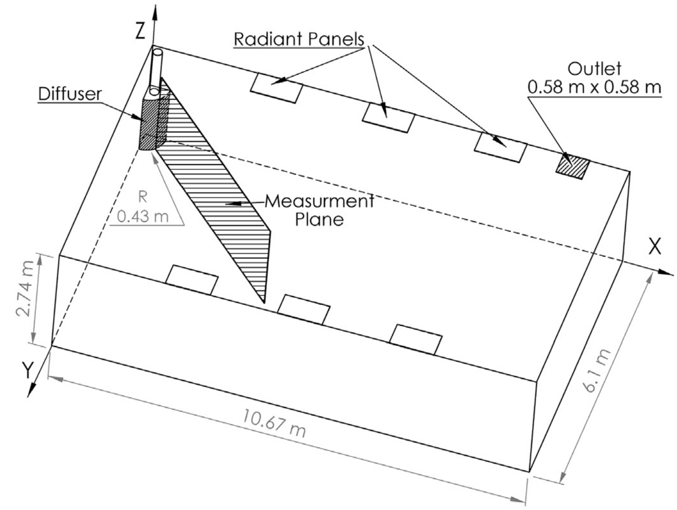

Fig. 1. Layout of the DV system and testing room.

as the room reference temperature following ASHRAE Standard 113 [13], which was fixed to $T_{ref} = 21$ °C. The heat balance in the testing room was maintained using 6 adjustable ceiling-mounted radiant panels, each with maximal nominal power of 750 W. The radiant panels (in terms of actual operating power and time) were controlled automatically by a computer monitoring system during the entire experiment, so that the room reference temperature maintained constant at 21 °C. The shortest distance between a radiant panel and the intersection between the floor and the measurement plane (see Fig. 1) is 4 m. As such, the ceiling-mounted radiant panels were sufficiently far from the central measurement plane to avoid any direct alteration of the DV jet stream under study.

The room airflow can be weakly turbulent, with velocities varying in magnitude, direction and fluctuating frequency. It has been indicated by Finkelstein et al. [14] that in the occupied zone of a room, mean air velocities range from slightly below 0.05 m/s to 0.6 m/s, turbulence intensities range from less than 10% up to 70%, and frequencies of velocity fluctuations at approximately 2 Hz contribute up to 90% of the measured standard deviation of the fluctuating velocity (or root mean squares (RMS)).

Accurate measurement of a low air velocity is a challenging task. Available methods at present for indoor airflow measurements include thermal anemometers, ultrasonic anemometers, laser

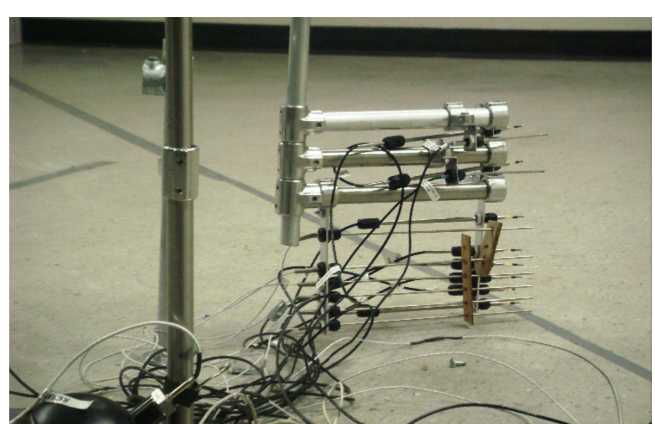

Fig. 2. Arrangement of the velocity and temperature probes.