Building and Environment 114 (2017) 483–494

Contents lists available at ScienceDirect

Building and Environment

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

Three-dimensional model of air speed in the secondary zone of displacement ventilation jet

Laurent Magnier-Bergeron [a], Dominique Derome [b], Radu Zmeureanu [a, *]

[a] Department of Building, Civil and Environmental Engineering, Concordia University, 1455 de Maisonneuve Blvd. W, Montreal, Quebec H3G 1M8, Canada
[b] Laboratory for Multiscale Studies in Building Physics, EMPA, Duebendorf, Switzerland

ARTICLE INFO

Article history:
Received 10 November 2016
Received in revised form
28 December 2016
Accepted 4 January 2017
Available online 5 January 2017

Keywords:
Displacement ventilation
Air jet
Model
Air speed
Experiments

ABSTRACT

This paper presents a new three-dimensional model for the distribution of air speed in the secondary zone of a displacement ventilation jet, combining both physical analysis and correlations-based models. For this purpose the measurements on two wall-mounted DV diffusers are used along with other published data. The maximum air speed at the end of primary zone is predicted by using the supplying conditions at the outlet, the thickness of air jet at the end of the primary zone, and the air entrainment in the jet. The longitudinal profile of maximum air speed in secondary zone is modeled using a new normalization and a generalized profile developed using correlation-based models obtained from experimental data. The vertical and transversal air speed profiles are also presented and analyzed. Finally all air speed profiles in the secondary zone are combined into a three-dimensional air speed model in the DV jet.

1. Introduction

Displacement Ventilation (DV) has attracted a growing interest in North America as a way to save energy and increase indoor air quality. The basic mechanism of displacement ventilation is the supply of clean air at low velocity [1], at floor level and at a temperature slightly lower than room temperature (typically between 17 °C and 20 °C), although in some cases it can be supplied at temperature above 20 °C when the room air temperature is kept at higher temperature (e.g. 27 °C). The occupants and other heat sources inside the room act as plume convectors, which create temperature and contaminant stratification in the room. The advantage of displacement ventilation over mixing ventilation is that the air brought at breathing level is not or only slightly mixed with the indoor air, leading to a better indoor air quality.

As displacement ventilation relies on air temperature stratification, only the occupied zone of a room needs to be cooled, while leaving the higher portion at a higher temperature. As a result, the supply air flow rate required to make the room comfortable is smaller. Overall the higher supply air temperature and the lower supply air flow rate lead to smaller cooling loads for the air handling units, and lower electricity use for mechanical refrigeration as well as for supply fans. Displacement ventilation also allows a higher use of free cooling over the year, leading to further energy savings. Beyond the energy impact, there is also an impact of people response. For instance, in a study on people response to displacement ventilation different effects on occupants' thermal comfort and perceived air quality were found between the cases of displacement ventilation with less supply air at low temperature versus design with more supply air at increased temperature [2].

Despite these advantages, the use of displacement ventilation is still limited in North America. A problem frequently associated with DV is the risk of draft discomfort at foot level. Temperature stratification can also lead to discomfort due to excessive temperature difference between the head and the ankle. The issue of local comfort, closely related to the velocity and temperature distributions within the DV jet, needs to be addressed before DV can be used at a greater scale. Mathematical models for the prediction of air velocity and temperature in the DV jet in the vicinity of room occupants should be used at the design stage, when the location of DV diffusers in the room and supply conditions are set.

2. Literature review of models of DV jet

Numerous displacement ventilation studies have been published over the last decades. Most papers about the DV used in

---

* Corresponding author.
E-mail address: radu.zmeureanu@concordia.ca (R. Zmeureanu).

http://dx.doi.org/10.1016/j.buildenv.2017.01.003
0360-1323/

buildings, found in our literature review, presented measurements or models of the vertical thermal stratification in rooms such as [3–8]. Other papers such as [9,10] compared the measurements and predictions by Computational Fluid Dynamics (CFD) of the velocity and temperature distribution in a displacement ventilation air jet. Many studies focused on the velocity field on the central axis of the diffuser [11]. Experimental results away from the axis, studying the air temperature variation in the jet, or studying the vertical gradients in the jet, are scarce [12]. Many studies focused on measuring at 0.1 m from the floor [13,14].

It is beyond the scope of this paper to discuss all publications about all aspects of DV in buildings. Only a few papers present mathematical models for the distribution of air speed in the secondary zone of a displacement ventilation jet. These papers are discussed in this section.

In most studies as well as in this paper, the DV jet is conceptualized as being composed of two distinct zones. The primary zone is a zone where the air jet from the diffuser falls onto the floor due to the action of buoyancy forces. The thickness of the air jet decreases and the air speed increases significantly. The limit of the primary zone is the point where the speed in the jet has reached its maximum. This limit is in the order of 1 m, depending on the supply characteristics [15]. The air speed in the jet at that point is generally several times greater than the face speed of the diffuser. The secondary zone is characterized by a decrease of the horizontal velocity, with relatively small variations in the thickness of the air layer. The secondary zone is of primary interest to designers since it generally corresponds to the occupied zone. Fatemi et al. [16] proposed to divide the DV jet into four apparent zones: falling zone, acceleration zone, fully-developed zone and fading zone, where, at the end of the acceleration zone, the air jet reaches its maximum air speed. Hence the falling and acceleration zones correspond to the primary zone of the two-zone model.

As discussed by Nielsen [17], DV flow can be considered using different theories such as the ones of wall-jets, confluent jets or gravity currents. The wall-jet theory is for instance very valuable to understand the vertical velocity profile of the DV flow. However, it is incompatible with some major parameters of DV flow such as the variation in thickness of the air layer or the horizontal velocity decay. The gravity current theory [18] might be useful to understand the flow behaviour in the primary zone. The information provided by the gravity current literature is however of little practical interest in the secondary zone.

2.1. Air speed increase in the primary zone

In terms of experimental data, the focus is generally found on the secondary zone, where the occupant is located. Some data for the primary zone can be found in some laboratory studies or in experiments performed for CFD validation [19]. These studies confirm the decrease of jet thickness in the primary zone, as well as the increase of speed. No model or correlation has however been developed in these studies. A conclusion that can be drawn from these studies is that, after about half a meter distance from the diffuser, the DV jet appears to follow a wall-jet-like vertical velocity profile [20], regardless of the air distribution profile at the diffuser exit.

Only a limited number of models are found in the literature for the air speed field in the primary zone of a DV jet. Sandberg and Blomqvist [21] proposed a formula to determine the maximum speed reached at the end of the primary zone, based on the conservation of kinetic and potential energy. Etheridge and Sandberg [15] proposed a formula to predict the length of the primary zone for a radial gravity current which fits well with experiments for a round wall-diffuser. Nordtest model [22] uses a two-coefficient correlation for the maximum speed reached at the end of the primary zone. The formula is based on the Archimedes number and on the buoyancy flux from the diffuser, and on coefficients specific to the diffuser. According to the authors of the model, those coefficients are independent of the supply conditions.

2.2. Air speed decay in the secondary zone

Nielsen model [17] predicts air speed decay in the secondary zone of a DV jet, for a wall diffuser with a radial distribution and along the central axis, using Equation (1):

$$\frac{V(x)}{V_f} = K_{dr}\frac{H_{diff}}{x} \tag{1}$$

where: V(x) is the maximum speed at a distance x from the diffuser [m/s]; V_f is the face speed of the diffuser [m/s]; K_{dr} is an experimentally determined constant [-]; H_{diff} is the height of the wall-mounted diffuser [m].

Nielsen's model is the most accepted air speed model in the literature and has shown good agreement with various experimental data [23]. It is also referenced in major design guidelines such as the REHVA's guidebook [24] and ASHRAE's design guidelines [25].

The use of the K_{dr} constant in Nielsen's model is intended to characterize the flow from a diffuser using a single value, as it is the case with classical high-velocity free jets. In the case of displacement ventilation, however, K_{dr} value is valid only for a specific diffuser, with a specific outlet size and aspect ratio, and a specific under-temperature. Nielsen [11] proposed a linear relation between K_{dr} and the root of the Archimedes number (Ar). However, there is no satisfactory relationship in the literature that relates the K_{dr} constant with the diffuser characteristics or the supply temperature. Therefore, for each diffuser, K_{dr} needs to be determined through laboratory measurements for each pair of sizes and under-temperatures of interest.

The Nordtest model [22] predicts the air speed decay in a DV jet. This model was developed based on laboratory measurements and on the work of [26,27]. The maximum air speed at a radius R from the diffuser and an angle ϕ from the longitudinal axis can be described in terms of Archimedes number, buoyancy flux and three experimentally determined coefficients, which are independent of the supply conditions and are constant for a given aspect ratio of a diffuser.

The only theoretical model found in the literature, specifically aimed at the displacement ventilation jet, is from Ref. [21]. The air speed model is based on assumptions such as a constant temperature difference between the air in the jet and the ambient air, and a constant jet thickness. However, the air temperature difference between the jet and the ambient air was found in several experimental studies to vary with the distance from the diffuser [28], and the jet thickness was also found to vary with the distance from the diffuser [11].

While several air speed decay models have been developed over the last decades, a validated model with coefficients independent of supply conditions is still not available. For instance, Nielsen's model is limited by the case-specificity of coefficient K_{dr}. The Nordtest model is independent of the supply conditions, but a significant amount of experimental data is required to determine its three correlation coefficients. This model is also very recent and there is no publication regarding a validation. Studying the different models in the literature, it is also noteworthy that there is no strong agreement in the literature regarding how to relate the air speed with the distance from the diffuser. A simple inverse function is used in Nielsen model, a case specific power function is used in