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Determining thermal stratification in rooms with high supply momentum

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ABSTRACT

Computational Fluid Dynamics simulations of a typical occupied office were performed to study the effects of ventilation parameters (supply momentum and heat gain intensity) and inlet geometry (height and area of the supply) on the temperature profile of the air in the space. A knowledge of this profile is critical to ensure that the occupants are comfortable according to commonly used standards. Different room configurations were characterized in terms of their Archimedes number, which compares the effects of buoyancy and supply momentum, and dimensionless geometric variables. A high Archimedes space was found to be divided into a warm region of uniform temperature above the occupants and a zone where the temperature increases approximately linearly with height. In a low Archimedes space the air is mixed by the supply jet in the lower part of the room, especially near the outlet, resulting in this area having uniform temperature. However, the supply jet was found to be less efficient at mixing the air near the ceiling, resulting in higher temperatures in this zone than with higher Archimedes numbers. For a given Archimedes number, as the supply area increased, the air temperature was found to decrease in the lower part of the room but to increase near the ceiling. A high inlet increased the vertical mixing in the room. Correlations were proposed to establish the temperature profile within 5% of the temperature rise of the room. The inputs of the correlations are readily available in multi-zone software, facilitating their integration in this kind of software. The proposed correlations will allow the user of the multi-zone software to evaluate comfort conditions more accurately, while maintaining the high speed, simplicity and design flexibility of the multi-zone models.

1. Introduction

A knowledge of the temperature profile of the air is critical to evaluate comfort conditions in a space. To use the ASHRAE 55-2010 graphic comfort zone method or the adaptive comfort model for naturally ventilated buildings, for example, it is necessary to know the local temperature of the air immediately surrounding the occupants [1]. These standards are commonly used to ensure that a building design meets the thermal comfort requirements of the occupants. Currently, multi-zone or multi-node building design tools assume that the temperature in a space is uniform and equal to the exhaust temperature. This simplification is known as the “well-mixed” assumption, because this is the temperature that a space with perfect air mixing would have. Unfortunately, this assumption has been shown to substantially overestimate the temperature of the air near the occupants [2]. As a consequence, thermal comfort is not assessed correctly [3], airflow rate in buoyancy-driven natural ventilation might be predicted inaccurately [4] and natural ventilation and other passive cooling strategies might be underutilized [2].

Although several researchers have looked at the problem of estimating the air temperature profile, the majority of this work has been focused on spaces under so-called displacement ventilation, a special case in which the air is supplied at the floor level at very low velocity. The low supply velocity allows researchers to neglect the effect of the supply momentum, focusing instead on buoyancy effects. However, the most common ventilation strategy, mixing ventilation, relies on the high momentum of the supply air to mix and dilute the pollutants in the space [5]. Therefore, the assumption of negligible momentum is not valid for the majority of the ventilation systems. Furthermore, it has been demonstrated that, although the supply momentum is high, the air temperature in mixing ventilation is not equal to the well-mixed temperature,

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Nomenclature

Greek symbols

β	volumetric thermal expansion coefficient of air
$\Delta\theta_{ac50}$	difference in dimensionless temperature of air near ceiling and at half the height of room
$\Delta\theta_{acf}$	difference between dimensionless air temperature near ceiling and near floor
ΔT_r	air temperature rise across room
θ_{ac}	dimensionless air temperature near ceiling
θ_{af}	dimensionless air temperature near floor
θ_a	dimensionless air temperature

Roman symbols

A	fitting constant
A_{ac50}	fitting constant
Ar_{h_w}	Archimedes number based on inlet height
A_w^*	dimensionless inlet area
B	fitting constant
B_{ac50}	fitting constant
C	fitting constant
e_{rms}	root-mean-square error
H	room height
h^*	dimensionless height coordinate
h_w	inlet height
h_w^*	dimensionless inlet height
L	room length
l^*	dimensionless length coordinate
$\dot{q}$	heat gains per unit floor area
T_a	air temperature
T_{inlet}	inlet temperature
T_{outlet}	outlet temperature
u	inlet velocity
x	x coordinate
y	y coordinate
z	z coordinate

because air mixing is far from perfect [2]. Thus, there is a pressing need to develop a simple methodology to predict the thermal stratification in spaces where the momentum of the supply air is not negligible.

This paper presents such a simple method. The proposed method is based on inputs that are readily available in multi-zone models, so it can be implemented easily in multi-zone design and analysis tools. With this method, multi-zone tools can be used to better predict the temperature of the air near the occupants, thereby allowing for a better assessment of thermal comfort conditions. Hence, the method addresses one of the main shortcomings of multi-zone models, while keeping their high simulation speed, their main advantage over Computational Fluid Dynamics (CFD) simulations. Unlike CFD, multi-zone tools are practical when comparing multiple building geometries and designs. Moreover, multi-zone tools are better suited to design and analyze naturally ventilated buildings, which are subject to weather conditions that are constantly changing.

2. Previous work

Previous research in this field has used both experimental and theoretical models to estimate the thermal profile of the air in a space. Although it was common in early studies to assume that the temperature profile was linear with height [6,7], subsequent work found this to not be the case [6,8]. Some researchers developed simple qualitative relationships between conditions in the space (ventilation rate, heat source type and position, etc.) and its thermal stratification based on their experimental results (e.g. Refs. [9,10]). Lately, quantitative models have been put forward mainly for rooms under displacement ventilation.

2.1. Stratification in rooms under displacement ventilation

Linden et al. [11] presented a model based on the assumption that the room is divided into two zones of uniform temperature, a lower region at the supply temperature and an upper warm zone at the exhaust temperature. This model was based on experimental results on buoyancy-driven ventilation obtained from scale models that used water of different salinities to represent air at different temperatures. In this model, no heat transfer (radiation or convection) occurred between the ceiling, the floor and the air. Li [12] extended this model to account for heat transfer between these surfaces and the air. To do so, this researcher proposed two "four-node" profiles, with the name given by the fact that the magnitude of the temperature is determined at four locations along the height of the room. The conditions of a space that would lead to one profile or the other were not given, so these four-node profiles are of very limited use when predicting stratification in real cases. All these models assumed a single heat source and a rather simple room geometry. In addition, it has been shown that scale models that use water instead of air are unable to reproduce the stratification seen in real spaces due to the stark difference in radiation transport properties of these fluids, casting further doubt on the accuracy of the theoretical models based on them [13,14].

Chen and Glicksman [6] developed a semi-empirical model to predict the thermal stratification of the air in displacement ventilation, focusing particularly on the temperature gradient between the head and the feet of the occupants. The authors simulated typical geometries of small and large offices, classrooms and workshops using a CFD code, so the results are relevant to realistic spaces with more than a single occupant and accounting also for different ventilation rates and types of heat sources. Glicksman introduced a version of this model later valid for wide rooms [4].

More recently, Mateus and Carrilho da Graça [15] presented a three-node stratification model for displacement ventilation based on energy balances for three air layers of assumed uniform temperature and for the surfaces in the room (ceiling, floor, walls). This model is more complicated than that by Chen and Glicksman [6] because it requires solving seven non-linear equations simultaneously as well as calculating view factors and heat transfer coefficients associated with every surface in the room. Nevertheless, the work by Mateus and Carrilho da Graça [15] has been validated using experimental data by different researchers and provides insight into the physical processes that give rise to the air temperature profile when the inlet air has negligible momentum.

2.2. Stratification in rooms under mixing ventilation

The thermal stratification in spaces served by mixing ventilation has not been as extensively studied as in displacement ventilation, so the assumption of perfect air mixing is commonly used in this