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A validated three-node model for displacement ventilation

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ABSTRACT

Displacement ventilation (DV) systems are characterized by thermal stratification that cannot be adequately modeled using the fully mixed room air approach that is common in overhead air conditioning system design. This paper presents a simplified approach for DV that models the room thermal stratification using three air temperature nodes: lower layer (floor level), occupied zone and upper layer. The proposed approach is a development of one of the two models currently available in the thermal simulation tool EnergyPlus. A methodology for locating the neutral height in temperature profiles was developed. This methodology was used to verify the applicability of Morton et al. (1956) plume flow equation to predict the neutral level in DV rooms. The proposed model was successfully validated using nine different scenarios from three independent experimental studies. The model provides significantly improved precision when compared to existing DV nodal models, in particular in the floor level and occupied zone temperatures.

1. Introduction

Displacement ventilation systems (DV) were initially developed in the 70's for applications in industrial halls in Nordic countries. The ability of these systems to concentrate heat and pollutants above the occupied zone led to increased popularity and subsequent use in service buildings (starting in the early 80's [1]). In an effective DV system, fresh air inserted near the floor is drawn to the heat sources in a low velocity, self-regulating flow. Initial scientific studies of DV systems (Sandberg and Sjoberg [2] and Skaret [3]), showed that the thermally stratified environment that occurs in DV rooms cannot be adequately modeled using the fully mixed room air approach that is common in overhead air conditioning systems.

The need to fine-tune the design of DV systems led to the development of several models with variable complexity. Sandberg and Lindstrom [4] proposed a simplified model for mechanical DV. This model divides the room into two layers: the lower occupied zone and the mixed upper layer. The model defines the lower boundary of the mixed upper layer (the neutral height) as the point where the total buoyancy induced plume flow equals the inflow rate [5]. Beyond the neutral height the continuously increasing plume flow is fed by room air, generating a mixed upper layer (the two layer structure is visible in Fig. 1a). Linden et al. [6] developed a similar two-layer model for the more complex case of natural DV. These studies were based on an experimental setup of scaled salt-water models. In this experimental approach buoyancy is generated by varying water salinity level in a container whose walls are impervious to salt. As a result, salt-water flows only display buoyancy effects due to the internal plume sources (see Fig. 1a). In contrast, DV flows in air have internal heat sources that are part convective, part radiative. For this reason, even in the nearly adiabatic test chambers that are often used in DV system performance assessments, the room air exchanges heat with the room surfaces (that are heated by radiation from the internal heat sources). This exchange results in vertical air temperature profiles that exhibit a smoother transition than the salinity, CO2 or other non-buoyant pollutant profiles (see Fig. 1b). The radiative heat transfer and resultant internal surface convective heat transfer mixes part of the heat gains in the occupied zone. Still, the DV vertical temperature variation profiles exhibit an upper mixed layer where the vertical temperature gradient is close to zero. Most DV application cases have a coincidence between heat and pollutant sources, resulting in a mixed layer region that contains the indoor pollutants and, therefore, should be kept above the occupants head height (above 1.3 m for seated occupants or 1.8 m for standing occupants). For this reason, controlling the lower boundary of the upper layer (neutral height) is a DV system's design objective. Increasing the room airflow-rate raises the neutral height by raising the point where the total thermal plume flow matches inflow. In addition to the neutral height, a successful DV system design must be able to control occupied zone and ankle level air temperatures.

Currently, designers of DV systems have three methodologies for system sizing and prediction of energy consumption: simplified

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Nomenclature

DV	displacement ventilation
CFD	computational fluid dynamics
HVAC	Heating, Ventilation, and Air Conditioning
Θ	a dimensional temperature
T	temperature (°C)
T_{in}	temperature of inflow air (°C)
T_{out}	room exhaust air temperature (°C)
z^{*}	a dimensional height (m)
z	height (m)
z_{total}	total room height (m)
F	inlet flow rate (m^3/s)
α	plume entrainment constant
g	acceleration of gravity (m/s^2)
β	coefficient of thermal expansion (K^{-1})
W	Heat flux plume (W)
h	neutral height (m)
ρ	air density (Kg/m^3)
C_p	thermal capacity of air at constant p ($W\ m^3/(kg\ K)$)
n	number of thermal plumes
NTG	average normalized temperature gradient along the total room height
Z_0	virtual origin of thermal plume
T_{OC}	temperature of room air in the occupied zone (°c)
T_f	temperature of floor surface (°c)
T_{Af}	temperature of room air in the horizontal layer adjacent to the room floor (°c)
T_{wl}	temperature of lateral surface that is below the mixed layer (°c)
T_{wu}	temperature of lateral surface that is above the mixed layer (°c)
T_{Mx}	temperature of mixed layer node (°c)
T_c	temperature of ceiling surface (°c)
T_{in}	inflow air temperature (°c)
A_f	floor surface area (m^2)
A_{wl}	lateral area exposed to the lower zone surface area (m^2)
A_{wu}	lateral area exposed to the upper zone surface area (m^2)
A_c	ceiling surface area (m^2)
A_t	total area (m^2)
h_f	heat transfer coefficient of floor surface (W/(m K))
h_{wl}	heat transfer coefficient of the lateral surface that is below the mixed layer (W/(m K))
h_{wu}	heat transfer coefficient of the lateral surface that is above the mixed layer (W/(m K))
h_c	heat transfer coefficient of ceiling surface (W/(m K))
h_{rc}	radiative heat transfer coefficient of ceiling surface (W/(m K))
h_{Rf}	radiative heat transfer coefficient of floor surface (W/(m K))
h_{rwl}	radiative heat transfer coefficient of the lateral surface that is below the mixed layer (W/(m K))
h_{rwu}	radiative heat transfer coefficient of the lateral surface that is above the mixed layer (W/(m K))
G	total internal heat gains (W)
F_{MO}	fraction of the convective heat gains that is mixed into the occupied zone
F_{GC}	fraction of total heat gains that are convective
F_{GR}	fraction of total heat gains that are radiative
I_M	inflow degree of mixing
Sim	simulation result
Meas	measurement result
Avg. Error	average error
Avg. Dif.	average difference
Avg. Bias	averaged bias
h_{TMx}	room height where zero temperature gradient region begins

design methods [8], simplified models implemented in dynamic thermal simulation tools [9–11], and computational fluid dynamics (CFD) models [12–14]. With the widespread use of computer simulation, simplified sizing methods are becoming less popular due to their inability to predict whole year energy consumption. CFD is becoming more accessible, and should play an increasing role in HVAC design in the coming decades, but remains, for the moment, too time-consuming to be used in whole year simulation design scenarios. Simplified models implemented in dynamic thermal simulation tools are the most accessible option for design and building energy certification. Furthermore, a successful simplified model can provide insight and understanding of the design parameters that control the room flow field and air temperature.

This paper presents a simplified model for DV that approximates the room thermal stratification using three air temperature nodes: lower layer (floor level), occupied zone and upper layer. It is a development of one of the two models currently available in the thermal simulation tool EnergyPlus [10,11]. The proposed developments increase modeling accuracy and robustness by minimizing the need for user supplied coefficients. The remainder of this paper is structured as follows. Section 2 presents a review of existing experimental studies and simplified DV models, followed by an evaluation of their accuracy. Section 3 presents an analysis of

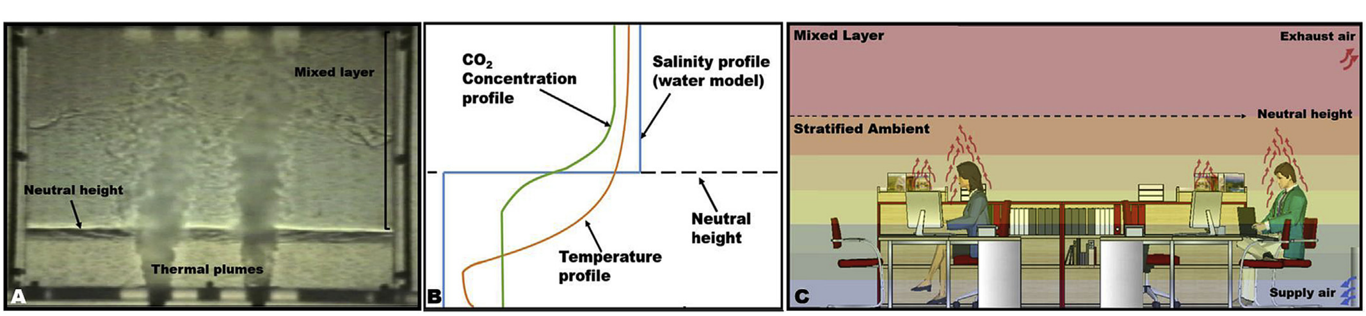

Fig. 1. Image of DV flow in a scaled salt water mode (left [7]), typical temperature, concentration and salinity profiles (center), and a schematic depiction of a DV flow (right).