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A study on flow stratification in a space using displacement ventilation

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ABSTRACT

This paper presents a theoretical analysis approach and experimental results on the stratified flow in a reduced-scale model using mechanical and natural displacement ventilation. Theoretical analysis is based on fundamental conservation equations and turbulent plume theory. The salt-bath technique is employed to conduct the analogous experiments to building ventilation problems and the reduced-scale acrylic model is used to observe the flow patterns in the laboratory. The light-attenuation method is used to analyze flow stratification in the analogous experiments. The model is divided into two rooms, which have the same cross-section area and volume, by an interior divider. The room having a buoyancy source is denoted as the 'forced room', and the other room is denoted as the 'supply room', which provides a constant flow rate into the space for mechanical displacement ventilation cases. This research focuses on analyzing convection flow properties and stratification distribution in the forced room. The research results show that the stratified flow in the forced room is controlled by the supply flow rate and slightly by the buoyancy source strength for mechanical displacement ventilation. The flow properties are normalized to be dimensionless parameters under the condition of a fixed buoyancy flux, and the dimensionless interface level and the dimensionless reduced gravity of the buoyant layer change with the dimensionless flow rate. As the supply flow rate increases, the stability of stratification becomes weak and there is an intermediate stratified layer formed between the fresh ambient and polluted buoyant layers. This study shows that the stability of stratification and the thickness of the intermediate stratified layer are dependent on the ratio of buoyancy force to inertia force in the room using displacement ventilation.

1. Introduction

Building ventilation is an important issue because of the needs of improving the indoor air quality and providing a comfortable environment for occupants. It is essential to adopt an appropriate ventilation strategy to attain the purposes of the energy saving and a comfortable indoor environment. Building ventilation is usually classified as natural and mechanical ventilation systems according to the driving forces. Natural ventilation is driven by the natural pressure drop between the interior and exterior environment. Without artificial energy consumption, it becomes a popular alternative for many new buildings. A book by Etheridge [1] provides a comprehensive and detailed account of natural ventilation. The driving force of mechanical ventilation depends on the mechanical equipment, such as air-conditioners or supply fans. The advantage is that the ventilation flow rate can be easily adjusted by controlling the equipment.

Displacement ventilation is an approach that utilizes flow stratification in space to provide more efficient heat transfer than the traditional well mixing ventilation. Different stratification distributions result in distinct flow rates and ventilation efficiencies in the space [2,3]. This stratification is one of the most beneficial factors in displacement ventilation over conventional mixing-type ventilation, because the displacement ventilation systems only take account of a part of the total load considered in the mixing ventilation systems. Furthermore, the displacement ventilation systems improve indoor air quality in the lower level by separating contaminated air from clean air through stratification. Therefore energy savings as well as good indoor air quality can be controlled efficiently by the use of displacement ventilation. Many researchers have reported the advantages of displacement ventilation theoretically and experimentally for different HVAC applications [4–6]. There are different flow characteristics for natural and mechanical displacement ventilation, as discussed in [7].

Demand-controlled displacement ventilation is a strategy which uses mechanical systems to supply conditioned air in order to meet the thermal comfort and indoor air quality (IAQ) criteria

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Nomenclature

a_x	opening area at location x (m^2)
B	buoyancy flux ($m^4\ s^{-3}$)
C	universal constant of the plume (–)
c_p	specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
F_B	buoyancy force on the outlet opening (N)
F_I	inertia force at the inlet opening (N)
g	gravitational acceleration ($m\ s^{-2}$)
g'	reduced gravity ($m\ s^{-2}$)
g'_f	reduced gravity in the buoyant layer ($m\ s^{-2}$)
$g'_p(H)$	reference reduced gravity for normalization ($m\ s^{-2}$)
H	height of the room (m)
h_f	interface level of the buoyant layer (m)
I	light intensity (–)
i	index of the pixel (–)
Q	volumetric flow rate ($m^3\ s^{-1}$)
$Q_p(H)$	reference volumetric flow rate for normalization ($m^3\ s^{-1}$)
Q_{sup}	supply volumetric flow rate ($m^3\ s^{-1}$)
u_{in}	flow velocity at the inlet opening ($m\ s^{-1}$)
W	heat flux ($J\ s^{-1}$)
z	vertical coordinate with the origin at the source level (m)

Dimensionless parameters

$\hat{g}'_f$	dimensionless reduced gravity in the buoyant layer $\left(=\frac{g'_f}{g'_p(H)}\right)$
$\hat{h}_f$	dimensionless interface level of the buoyant layer $\left(=\frac{h_f}{H}\right)$
$\hat{Q}$	dimensionless volumetric flow rate $\left(=\frac{Q}{Q_p(H)}\right)$
$\hat{\delta}$	dimensionless thickness $\left(=\frac{\delta}{H}\right)$

Greek symbols

α	entrainment constant (–)
β	coefficient of thermal expansion (K^{-1})
Δ	magnitude of the difference (–)
δ	thickness of the intermediate stratified layer (m)
ρ	density ($kg\ m^{-3}$)
σ	weighted intensity slope (m^{-1})

Subscripts

a	exterior environment
in	inlet opening
f	the buoyant layer of the forced chamber
o	real plume source
out	outlet opening
p	inside the plume
th_o	theoretical plume origin
v	virtual origin correction

for occupants. The supply air flow rate is adjusted according to the heat load or indoor air quality threshold in the space. Mysen et al. [8] and Wachenfeldt et al. [9] reported that demand-controlled displacement ventilation based on carbon dioxide sensor (one of IAQ criteria) might reduce the ventilation air flow rate by 65–75% during daytime operation, compared with traditional constant air volume mixing-type ventilation. The system provides an energy efficiency alternative to control indoor environment.

Awad et al. [10] studied stratified airflow patterns under several different scenarios in real-scale mechanically ventilated enclosures by varying the locations of the inlets and the outlets, and also their supply volume flow rates. The supply hot and cold air flow rates were adjusted to investigate the relationship between the buoyancy and inertia forces in the spaces and they claimed that the ratio of two forces was a determinant factor for the stratification characteristics, including the interface height, the thickness and the stability of stratified layers. In another paper by Awad et al. [11], they used a dimensionless parameter, Richardson number, to discuss the flow stratification distribution in the space.

Yang et al. [12] investigated thermal stratification behavior due to buoyancy-driven flows in a reduced-scale model experimentally. The buoyancy-driven flow was produced by a fire and the exhaust flow rate was varied to change the shear intensity between the top hot and bottom cold air layers. They measured horizontal air traveling velocity, vertical air temperature profile and stratification interface height of the buoyant flow, and claimed that there were three regimes of stratification patterns dependent on the ratio of inertia and buoyancy forces. The ratio of two forces was represented by the Froude number or the Richardson number. The flow visualization shows three flow patterns against different force ratio. At the low exhaust velocity, the pattern shows distinct two-layer stratification, the upper buoyant smoke layer and the lower ambient air layer. At the moderate exhaust velocity, overturning turbulent vortexes appear at the interface region. As the velocity increases, mixing between two layers results in an indistinguishable interface.

According to a review paper by Linden [13], the heat flux W released by a heat source is equivalent to the imposed buoyancy flux, B in the flow

$$B = \frac{g\beta W}{\rho c_p}, \tag{1}$$

where g is the gravitational acceleration, β is the coefficient of thermal expansion of the fluid, ρ is the density and c_p is the specific heat at constant pressure. In this study, we focus on convection flow with the displacement ventilation pattern and flow stratification due to a localized source with the buoyancy flux, B, and the supply flow rate, Q_{sup}, near the source level of an enclosure, as shown in Fig. 1. Lin and Lin [14] presented preliminary results of this study. According to a study by Nielsen [5], this forced room arrangement is similar to a space having a wall-mounted air diffuser on the partition wall and the exhaust opening on the ceiling. In this research, this configuration is fixed to investigate the relative influence of the buoyancy and inertia forces on the stratified flow in the enclosure.

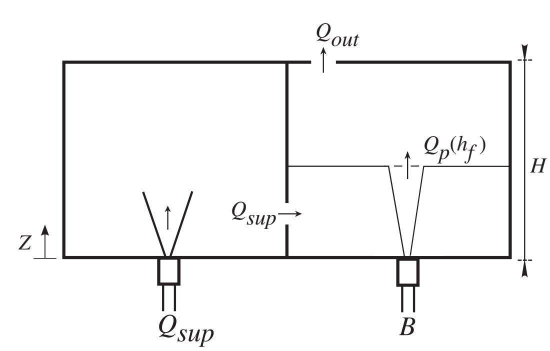

Fig. 1. A schematic diagram of mechanical displacement ventilation of two connected chambers.