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A study on density stratification by mechanical extraction displacement ventilation

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ABSTRACT

The purpose of this study is to investigate the stratified flow driven by mechanical extraction displacement ventilation and compare the effects of the supply source and the extraction sink on the flow in the ventilated space. The extraction sink effect, which has rarely been addressed in the previous research, is discussed in this paper. This study investigates the flow stratification, the thickness of the intermediate stratified layer and their relationships with the suction, buoyancy and inertia forces in the space. The salt-bath technique was employed to conduct experiments simulating mechanical extraction displacement flow by using an acrylic reduced-scale model. According to the connection opening area on the partition, experiments were categorized into two series, denoted as Ex(I) and Ex(II). Experimental results show that as the extraction flow rate increases, the distance between the plume source and the interface height increases and the reduced gravity of the dense layer decreases as predicted by the two-layer stratification model. The stratification stability highly depends on the magnitude of the force ratio in the ventilated space. Similar to the previous research, the inflow inertia force has a clear influence on the formation of the intermediate stratified layer. The strong suction force in this study seems to aid the flow stratification and diminish the intermediate stratified layer thickness. The linear fit relationship between the intermediate stratified layer thickness and the force ratio gives a close result to the previous study. Similar to the previous study on displacement ventilation, the density in the dense layer is observed to be uniform when the extraction flow rate is small. The density distribution along a horizontal level with a certain non-zero gradient in the dense layer is clearly identified when the flow rate is high and the location is near the extraction sink, an observation that is very different from the previous study on displacement ventilation.

1. Introduction

Ventilation (cooling and heating) in buildings consumes a large amount of energy nowadays. According to Refs. [1,2], non-industrial buildings account for 30–50% of all primary energy consumption in Organization for Economic Cooperation & Development countries, and ventilation operation consumes as much as 50% of the amount attributed to the non-industrial buildings section. Building ventilation is an important issue, because of the needs for improving the indoor air quality and providing a comfortable environment for occupants. It is essential to adopt an appropriate ventilation strategy to achieve the purposes of energy saving and a comfortable indoor environment.

Building ventilation is usually classified as natural and mechanical ventilation systems according to the driving forces. The driving force of mechanical ventilation depends on the mechanical equipment, such as fans or jet flow producing devices. The ventilation flow rate could be easily adjusted according to the demand for the space using mechanical ventilation.

Displacement ventilation has been used over the past few decades as an energy-efficient approach compared to conventional overhead mixing systems. 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 [3,4]. This stratification is one of the most beneficial factors of 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

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Nomenclature

A_j	jet flow source opening area (m^2)
a_x	opening area at location x (m^2)
B_o	buoyancy flux of the plume source ($m^4\,s^{-3}$)
C	universal constant of the plume (–)
C_j	universal constant of the jet (–)
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)
F_S	suction force on the outlet 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_0	light source intensity (–)
l	distance away from the jet virtual origin (m)
M_j	jet specific momentum, $\frac{Q_j^2}{A_j}$ ($m^4\,s^{-2}$)
Q	volumetric flow rate ($m^3\,s^{-1}$)
$Q_p(H)$	reference volumetric flow rate for normalization ($m^3\,s^{-1}$)
Q_{ex}	extraction volumetric flow rate ($m^3\,s^{-1}$)
R_1	constant coefficient (–)
R_2	constant coefficient (–)
r	radius distance away from the extraction sink (m)
u	flow velocity at the opening ($m\,s^{-1}$)
V	velocity ($m\,s^{-1}$)
W_o	heat flux of the heat source ($J\,s^{-1}$)
x	horizontal coordinate (m)
z	vertical coordinate with the origin at the source level (m)

Dimensionless parameters

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

Greek symbols

α	entrainment constant of the plume (–)
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_g	deviation on the reduced gravity
σ_h	deviation on the interface level

Subscripts

$-ex$	experimental result
$-th$	theoretical prediction
a	exterior environment
f	the buoyant layer
in	inlet opening
j	jet
o	real plume source
out	outlet opening
p	inside the plume
s	extraction sink
th_o	theoretical plume origin
v	virtual origin correction

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 [5–7].

Displacement ventilation has its potential advantages of indoor thermal comfort (ITC) and indoor air quality (IAQ). In a space using the displacement ventilation system, the conditioned fresh air is directly delivered to the occupied zone, and thermal stratification is established in the space. The thermal stratification performance is critical to the ITC and IAQ.

Lin and Xu [8] studied the effect of a point heat source at different levels in a space with natural displacement ventilation and found that the stratification performance of natural displacement ventilation is different from that of mechanical displacement ventilation having the same heat source condition which was investigated by Park and Holland [9].

Lin and Lin [10] studied the stratified flow in the space using mechanical or natural displacement ventilation and used a reduced-scale model in a water tank to conduct laboratory experiments. Their experimental results showed that the stability of flow stratification is highly dependent on the force components in the space and the high flow rate provided by mechanical displacement ventilation may result in serious disturbance on the flow stratification. The previous research on mechanical displacement ventilation mostly address it with one or more controllable flow supply sources, and this type could be categorized as mechanical supply displacement ventilation (hereinafter referred to as MSDV).

In this study, the flow in a ventilated enclosure due to a localized source having a constant buoyancy flux, B_o, combined with the mechanical extraction displacement ventilation system having a flow rate, Q_{ex}, as shown in Fig. 1 is investigated. According to a review paper by Linden [11], the heat flux W_o released by a heat source is equivalent to the imposed buoyancy flux, B_o in the flow

$$B_o = \frac{g\beta W_o}{\rho c_p}, \tag{1}$$

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. The configuration in Fig. 1 is fixed to investigate the relative influence of different force components, namely the suction, buoyancy and inertia forces, on the flow in the space. The ventilated space is divided into two connected chambers, denoted as the forced and unforced rooms, by a partition with an opening. The forced room has a constant buoyancy source inside

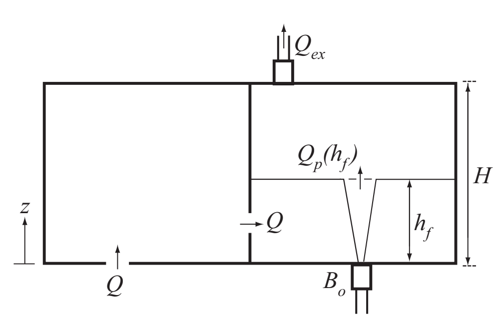

Fig. 1. A schematic diagram showing mechanical extraction displacement ventilation of two connected chambers.