The displacement ventilation patterns in two parallel-connected chambers with a mechanical extraction device

Y J P Lin¹,∗ and S Q Li¹

¹ Department of Mechanical Engineering, National Taiwan University of Science and Technology
∗ peteryjlin@mail.ntust.edu.tw

Abstract. This research studies the mechanical extraction ventilation in two parallel-connected chambers. A buoyancy source is located in one chamber, denoted as the forced room, and there is an extraction device in the other chamber, denoted as the extraction room. Two chambers have their own connecting openings to the ambient in the parallel-connected model. This paper focuses on the displacement ventilation pattern with a mechanical extraction device in the steady state. The flow driving forces include the buoyant and inertia forces in the mechanically ventilated space. The buoyant force results from a buoyancy source, and the inertia force, or suction force, is due to the mechanical extraction device. In this research, two different flow regimes are found in two parallel-connected chambers depending on the control extraction flow rate magnitude, and the upstream forced chamber is found to have a certain maximum flow rate limit in this configuration. When the control extraction flow rate is less than or equal to the limit value, both of the forced and extraction chambers have the same flow rate as the control extraction flow rate and the supply fluid from the exterior only goes through the forced chamber into the interior space. However, when the extraction flow rate is larger than the limit value, the enhancement flow rate of the forced chamber is more than the maximum flow rate limit, and the extraction chamber starts to bring some complementary flow rate from the exterior.

1. Introduction

Buoyancy-driven displacement ventilation applies temperature or density stratification by supplying fresh cool air at the low-level location and removing polluted warm air at the high-level location. A stable interface forms between the two uniform layers in the indoor space. This type of ventilation is characterized by clear vertical temperature variations, as shown in Mundt [1]. For the same temperature difference and vent opening size, the displacement ventilation pattern provides a more efficient approach for removing heat and pollutant than the conventional mixing ventilation pattern. A flow may be driven by natural forces, such as a buoyant or wind force, or by some mechanical equipment, such as a fan or bellows. Two types of ventilation have some different characteristics.

In general, an indoor space is separated into several different rooms by walls, dividers, or floors in order to achieve their individual functionality. In multiple connected spaces, different arrangements of ventilation openings induce various flow patterns. For example, the natural buoyancy-driven displacement ventilation flow patterns are categorized as the pull-type ventilation, as shown by Lin et al. [2] or Gage et al. [3], and the push-type ventilation, as shown by Lin and Tsai [4]. Two ventilation modes are categorized according to the additional driving force required for ventilation in the adjoining unforced chamber without any buoyant source.

Holford and Hunt [5] investigated naturally ventilated building designs of two connected spaces which consist of an atrium and adjoining room, and there was only a point heat source inside the adjoining room. The case of a ‘ventilated atrium’ in Ref. [5] should be regarded as two parallel-connected spaces with natural ventilation. Ji et al. [6] investigated this geometric problem in both of the transient and steady states by using computational fluid dynamics modelling.
The location and size of the opening connecting the interior and exterior environments play important roles in the ventilation performance in the indoor environment. For single-chamber ventilation, Fitzgerald and Woods [7] discussed the effect of the location of an intermediate-level opening on the flow in a chamber. Phillips and Woods [8] studied the transient exchange flow through a doorway. In addition, Tovar et al. [9] and Tovar and Campo Garrido [10] investigated the effect of the exterior vent on natural ventilation in two interconnected rooms. The location and strength of the heat (or buoyant) source also play important roles in the flow patterns. Livermore and Woods [11] studied a natural ventilation flow, which was driven by two different floors, using a common stack. A floor with a relatively low heat load was connected to another floor with a higher heat load through a common stack. This space can be regarded as two rooms that are parallel-connected with a common stack at two different levels. Chenvidyakarn and Woods [12] studied the buoyancy-driven ventilation of two spaces connected to each other by a common low-level opening, and each of them was connected to the outside environment through its own high-level vent. Each space was heated uniformly by an independent source, which provided buoyancy to drive the ventilation flow. The problem can be regarded as two series-connected chambers with different heat loads.

Lin and Lin [13] and Lin and Wu [14] investigated the mechanical ventilation patterns in a single chamber with a buoyant source. Lin and Lin [13] presented the stratified flow in a single chamber with a mechanical supply source. Lin and Wu [14] showed the flow driven by a mechanical extraction device and compared the effects of the supply source and extraction sink on the stratified flow in a ventilated chamber. In both conditions, the flow rate and density stratification in a single chamber are controlled feasibly by the mechanical devices, but the supply source and extraction sink have different influences on the formation of the intermediate stratified layer.

This research investigates the flow patterns and density stratification in two parallel-connected chambers with a mechanical extraction device and a localized buoyant source. This paper focuses on displacement ventilation patterns in the steady state. A derived theoretical model is presented in Section 2. In Section 3, analogous salt-bath experiments are used to simulate the ventilation patterns in the laboratory. In Section 4, experimental results are presented. In Section 5, the conclusions of this research are drawn.

2. Theoretical analysis

In this research, the salt-bath technique is employed to simulate the displacement ventilation patterns in two parallel-connected chambers. A negative buoyant source is placed in the forced room and an extraction device is used in the extraction room, as shown in figure 1. The location of the density source is taken as the origin level of the vertical coordinate, \( z_o = 0 \). When a thermal source is considered, it has an inverse configuration to that in figure 1. The similarity theory of dimensional analysis for the salt-bath experiments and the real buildings was presented in a review paper by Linden [15], Hunt and Linden [16] or Lin and Tsai [17].

This theoretical model considers two parallel-connected rooms, which are denoted as the forced and extraction rooms, as sketched in figures 1(a) and 1(b) for two possible flow regimes. The mechanical extraction device is connected to the outlet of the extraction chamber. Two equal-height chambers are connected parallelly to the exterior environment through their own connecting openings and are connected to each other by one internal connection opening at the level of \( z_i \) on the shared divider.

The volume conservation equation of two parallel-connected chambers is shown as

\[
Q_{ex} - Q_{ex,0} = Q_f = Q_p = Q_i, \tag{1}
\]

where \( Q_{ex} \) is the adjustable extraction volume flow rate, \( Q_{ex,0} \) is the volume flow rate at the inlet opening of the extraction chamber, \( Q_f \) is the volume flow rate at the inlet opening of the forced chamber, \( Q_p \) is the volume flow rate in the plume at the interface level, \( Q_i \) is the volume flow rate at the internal connecting opening.

The buoyancy conservation equation gives

\[
B_o = Q_o g' = Q_f g' f = Q_{ex} g' ex, \tag{2}
\]
where $B_o$ is the source buoyancy flux, $Q_o$ is the source volume flow rate, $g'_o$ is the source reduced gravity, $g'_f$ is the reduced gravity of the dense layer in the forced chamber, $g'_ex$ is the reduced gravity of the density layer in the extraction chamber.

In this research, we found that there are two possible regimes for two parallel-connected chambers dependent on the interface level in the extraction room or the control extraction flow rate, $Q_{ex}$. Two respective regimes are denoted as the small and large flow rate regimes respectively. If the internal connecting opening is fully covered by the dense layer of the extraction room, then $Q_{ex,0}$ should be zero and figure 1(a) shows the sketch diagram for this small flow rate regime.

![Figure 1](image.png)

**Figure 1.** Schematic diagrams of (a) the small flow rate regime and (b) the large flow rate regime.

When the extraction flow rate becomes large, the internal connecting opening is not immersed in the dense layer of the extraction room. Figure 1(b) shows the flow pattern for the large flow regime. There is a critical extraction volume flow rate, $Q_{crit}$, separating two different flow regimes.

3. **Laboratory experiments**

These experiments were conducted in a reduced-scale model, with the internal dimensions of 38.5 cm long, 17 cm wide and 17 cm high. The diameter of each opening in the reduced-scale model was 2 cm, and its cross-sectional area was $\pi$ cm$^2$. This reduced-scale model was placed in a large plexiglass cubic tank with the side length of 83 cm. Fresh water having the density of 0.9983 g/cm$^3$ was replenished when the experiment was running.

The flow rates of the plume source and the reduced-scale model were controlled by two individual rotameters, and a water pump was used to extract fluid in the reduced-scale model. The salt plume was provided by a nozzle with the volume flow rate of 1.5 cm$^3$/s and the buoyancy flux of 180 cm$^4$/s$^3$.

The flow rates of the reduced-scale model were regulated to be 9, 18 and 27 cm$^3$/s in three experiments. Each experiment took 7,200 seconds. The density solution samples of 2 to 16 cm locations were measured once every 1,000 seconds interval between the 3,000th and 7,000th second by using an Anton Paar density meter with an accuracy of $5 \times 10^{-5}$ g/cm$^3$.

The image acquisition system consists of a CCD camera (1,392×1,036 pixel resolution), a recording computer and a LED light source. The image intensity data are analyzed by the DigiFlow (v3.5.0) software.

4. **Results**

For the small flow rate regime, i.e. $Q_{ex} < Q_{crit}$ there is no net flow through the opening between the exterior environment and the extraction chamber, as shown in figure 1(a). There is only one flow pathway from the exterior to the interior, and the two chambers are as series-connected. The replaced fluid in the extraction chamber comes from the forced chamber via the internal connecting opening $a_i$ and is drawn out by the extraction device.

Although the theoretical model assumes two-layer stratification in both chambers, two-layer stratification seems to develop in the forced chamber only, and the extraction chamber actually has different density distributions for the small flow rate regime, as shown in figure 2(a). There is a
continuous stratified layer with a less dense fluid than that of the uniform dense layer in the extraction chamber. This continuous stratified layer in the extraction chamber is formed between the initial state and the steady state, because the forced chamber provides less dense fluid in the early stage, and some less dense fluid is trapped between the fresh water and uniform dense layers.

Figure 2(a) shows an image of experiment Exp-P1 in the steady state at the 7000th s. The ambient fluid from the exterior goes into the forced chamber and is mixed with the source brine to form a uniform dense layer inside it. Then, the dense fluid in the forced chamber enters the extraction chamber, and the internal connecting opening \( a_i \) between two parallel-connected chambers is always immersed in the dense layer in the small flow rate regime. The flow in the forced chamber is not only controlled by the sizes of its entrance and exit openings, but also by its flow driving force. Experimental results of the interface levels of two chambers against the time for Exp-P1 are shown in figure 2(b).

When the flow regime changes to another one, \( Q_{ex} > Q_{crit} \), the margin of the internal connecting opening starts to be in contact with the ambient fresh water layer in the extraction chamber, and there are two individual flow pathways, as shown in figure 1(b). The dense fluid from the forced chamber is mixed with the ambient fresh water into the extraction chamber in this regime. The forced chamber maintains its maximum flow rate, and the extraction chamber starts to bring some complementary flow rate from the exterior. Therefore, the magnitude of the reduced gravity of the dense layer in the extraction chamber is always less than that in the forced chamber.

Experimental observations show that the two chambers had two-layer stratification inside them in the large flow rate regime. Figure 3(a) shows an image of experiment Exp-P2 at the 7000th s in the steady state. Because the control flow rate of Exp-P2 is just slightly larger than the maximum flow rate limit \( Q_{crit} \), figure 3(a) shows that only a very small portion of the internal connecting opening in the extraction chamber is covered by the ambient fresh water, and the rest of it is still covered by the dense fluid in this experimental run. Experimental results of the interface levels of two chambers against the time for Exp-P2 are shown in figure 3(b).

As the mechanical control flow rate increases, a larger portion of the internal connecting opening in the extraction chamber is covered by the ambient fresh water. It allows more ambient fresh water to be mixed with the dense fluid from the forced chamber. An image of experiment Exp-P3 in the steady state is presented in figure 4(a). The internal connecting opening in the extraction chamber is completely covered by the ambient fresh water. Therefore, the dense fluid from the forced chamber is able to be mixed with more ambient fresh water, and a layer of less dense fluid is formed in the extraction chamber. The ambient fresh water from the exterior to the two individual chambers replaces the displacement flow inside them. Experimental results of the interface levels of two chambers against the time for Exp-P3 are shown in figure 4(b).

Experimental observations show that the forced chamber always has two-layer stratification for either the large or small flow rate regime in this geometric arrangement, but the extraction chamber has two-layer stratification only in the large flow rate regime. There is a continuous stratified layer formed
in the extraction chamber between the ambient fresh water and uniform dense fluid layers in the small flow rate regime.

(a)  
(b)  

**Figure 3.** (a) An experimental image of Exp-P2 at the 7000th s. (b) Experimental results of the interface levels of two chambers against the time for Exp-P2.

(a)  
(b)  

**Figure 4.** (a) An experimental image of Exp-P3 at the 7000th s. (b) Experimental results of the interface levels of two chambers against the time for Exp-P3.

5. Conclusions

The effect of the adjoining room with a mechanical extraction device on the ventilation flow patterns in two parallel-connected chambers is investigated in this study. This paper presents a simple theoretical model using the two-layer stratification assumption and several analogous salt-bath experiments to investigate the characteristics of the ventilation flow in two parallel-connected rooms. Two flow regimes are observed in experiments according to the extraction flow rate magnitude.

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