A NUMERICAL STUDY ON NATURAL VENTILATION OF TWO CONNECTED CHAMBERS IN CONNECTION WITH AN AMBIENT ENVIRONMENT

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ABSTRACT

A numerical simulation study on natural ventilation of two connected chambers in connection with an ambient environment is presented in the paper. Extending a model of single-room displacement ventilation, this study addresses a space consisting of two chambers connected by one opening at the low level of the shared wall. A thermal load is placed only in one chamber, referred as a forced chamber, and the other chamber, unforced chamber, has no heat load. The space is connected to the outside ambient environment to have displacement ventilation in both chambers. The numerical simulation study of the flow pattern in this geometrical arrangement is presented. This study focuses on different schemes of connecting openings to the ambient environment in the unforced chamber and discusses their effects on natural ventilation in the space. The study shows that the opening areas in the forced and the unforced chamber affect the effective opening area in the space and modify the air change rate in the space. The important parameters, such as the position of the opening, determining air change rate in the space are discussed to understand thermal comfort designs in the built environment.

KEYWORDS

Displacement ventilation, numerical simulation, double chambers

INTRODUCTION

The motivation for this research is to expand our understanding of displacement ventilation in a single room to the space of two connected chambers while in connection with an ambient environment. Many of previous works on natural ventilation were on the single-space ventilation problem. Linden, Lane-Serff & Smeed (1990) [1] developed the mathematical model of steady-state natural ventilation in the single-room. The room in this model is connected to the infinite homogenous environment via the top opening and the bottom opening in the space (see Figure 1). After the buoyancy source injects buoyancy fluid for some time, a steady-state interface forms in this room. This model has been verified by agreeing with the experimental results successfully. The mathematical equation states that the interface in the room with one heat source only depends on the size of connecting openings. This provides a simple and useful guideline for ventilation designs.

Afterward many researches on natural ventilation started from this model to the more complicated problems. Cooper and Linden (1995) [2] extended this model to consider the problem of two buoyancy sources with different strengths in an enclosure. And Linden and Cooper (1996) [3] considered the problem of multiple sources in an enclosure. Hunt & Linden (1999 & 2000) [4], [5] did the work on buoyancy force assisted by wind, and also that resisted by wind in an enclosure (Hunt & Linden, 2004, [6]). These researches were based on the model developed by [1].

However, buildings always have separated spaces divided by walls, barriers or floors. How these

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dividers affect the flow patterns in the different spaces draws research attentions of this study. In this paper, the issue of two connected rooms is studied to understand the steady-state exchange flows in this geometry.

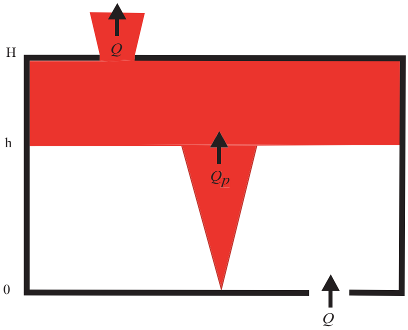

Figure 1. A schematic of the displacement flow caused by one single heat source in a single room.

The two rooms are connected via the bottom opening on the shared vertical wall. Figure 2 depicts the relative orientation of this study. This arrangement of openings induces the displacement ventilation in both rooms. Displacement ventilation happens in the region of the unforced chamber between its two openings, from the inlet of the unforced chamber to the inlet of the forced chamber. This geometrical arrangement is similar to Wong & Griffiths (2000) [7], except there is no any connection to the ambient environment in their experimental apparatus. The forced chamber in this study is the same as that of [1], however, there is no any consideration on the effect of adjunction rooms in their study.

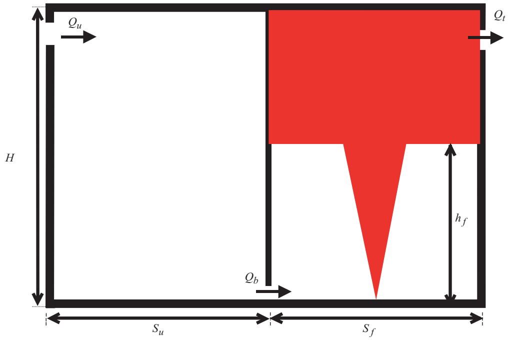

Figure 2. The schematic of two connected chambers in connected with the ambient environment.

Lin & Linden (2002) [8] present a physical model of two connected chambers without any opening to the outside ambient environment. One chamber is forced by an isolated point source of buoyancy, the other one does not have any heat load, and the partition between the chambers has both a floor- and ceiling-level opening. Individually, two chambers have displacement ventilation in this geometrical arrangement and have a time-dependent interaction resulting from changing stratification in the two chambers.

Holford & Hunt (2003) [9] present naturally ventilated building designs of two connected spaces consisting of an atrium and an adjoining room. In the paper, they focus on the flow enhancement achieved by an atrium, when itself is ventilated directly, by a low-level opening to the ambient environment. A theoretical model is developed to predict the steady stack-driven displacement flow and thermal stratification in the building, due to heat gains in the adjoining room and solar gains in the atrium. Direct ventilation of the atrium does not help the ventilation of the adjoining room and the best design is identified as a compromise that provides adequate ventilation of both spaces. They also show extremes of design for which an atrium provides no clear enhancement of the flow, and an atrium only enhances the flow in the adjoining room if its upper opening is of an intermediate size, and its lower opening is sufficiently small.

Livermore & Woods (2006) [10] extend the natural ventilation of buildings to drive the flow of different floors by the use of stacks. They connect the floor with a relatively low heat load to a floor with a higher heat load through a common stack. The warm air expelled from the warmer space into the stack drives a flow through the floor with no heat load. Therefore the secondary ventilation of a low level floor is driven by a heat source in a higher level floor.

Flynn & Caulfield (2006) [11] extend the model discussed in [8], however, there are floor- and ceiling-level external openings in the forced and unforced chambers, respectively, to the ambient space in this new study. They find the flow evolves on the time scale over which the volume flux associated with the plume at the ceiling would fill both chambers. The steady state in the forced chamber is analogous to the single chamber flow described by [1], with a well-mixed buoyant upper layer which is deeper than in the single chamber flow due to the extra pressure drop caused by the unforced chamber at the upper interior opening. The steady state in the unforced chamber inevitably exhibits vertical stratification, and depends on the transient flow, all the opening areas, and the relative plan area of the two chambers.

METHOD OF SIMULATION

This research uses a CFD program [12] that solves the governing equations for the conservation of mass, momentum, heat and turbulence quantities. The CFD program uses the KE approach and accounts for the effect of stratification, because the indoor heat source is the main driving force for the buoyancy flows which relate density variation with temperature change. The simulations use finite-volume differencing scheme and Cartesian meshes are used to discretize the cases studied in this paper.

The CFD models (Figures 3 and 4) use air as the working fluid and the dimensions of single room are about twenty-five times greater than those used in the salt-bath experiments [1]. In practice the flow inside the connected spaces is mixed by conduction, convection and radiation effects. In this work, radiation effect was neglected and conduction effect was examined to have small influence on the flow. Therefore the mathematical model of [1] is used to compare with the numerical simulations.

The base case of single room displacement ventilation has the total number of grids, 48 (width) × 47 (height) × 48 (depth), for calculation domain 7 m (width) × 6 m (height) × 7 m (depth), which includes a semi-confined room, 5 m (width) × 4 m (height) × 5 m (depth), and ambient environment. The single room has one top and one bottom openings, each having the dimensions of 0.5 m (height) × 0.5 m (depth). A 0.5 meter permeable cubic heat source, which maintains the air at a constant temperature of 45 degree Celsius, is placed in the middle of the room and raised away from the floor 0.25 meter. Finer grids were applied to more critical areas, such as the openings and the regions near to the wall and heat source.

The two connected rooms of displacement ventilation has the total number of grids, 69 (width) × 59 (height) × 54 (depth), for calculation domain 14 m (width) × 6 m (height) × 7 m (depth). The domain includes a forced room, an unforced room, each having a volume size of 5 m (width) × 4 m (height) × 5 m (depth), and ambient environment. The heat source of the same conditions as that in the single room is placed in the middle of the forced room.

The position of inlet opening in the unforced chamber is varied to investigate its effect on indoor environment. Four different heights of the inlet on the sidewall and, the inlet of on the ceiling and the floor at the location from the sidewall 0.5 m, are discussed as well.

We used adiabatic walls as the boundary condition in the calculation. A constant relative pressure of 0 Pa to atmosphere pressure was imposed across the inlet, the outlet and connection openings. The ambient air of 20 degree Celsius was used as the initial condition.

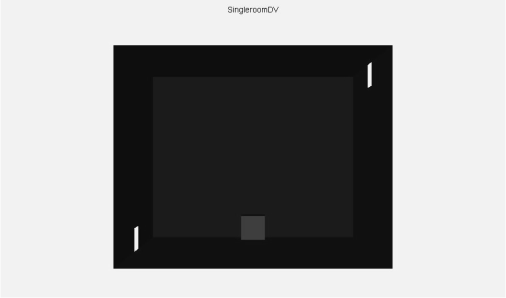

Figure 3. Geometry of the single room used in CFD simulations.

Figure 4. Geometry of the two connected rooms used in CFD simulations.

RESULTS ANALYSIS AND DISCUSSION

The numerical simulation results of two-room displacement ventilation with different opening schemes are presented in this study. The single room displacement case is used as a base case to compare with two-room cases. The single room case here is regarded as a two-room case which the unforced chamber has an infinite inlet opening. The numerical experimental results show that the space with the larger effective area results in higher air change rate and the lower temperature in it (compare single room case with two-room case in Table 1.

The space with the same effective area has very similar air change rate (we can see two-room case 1 to 6 in Table 1). However, when the position of inlet opening in the unforced chamber connect to the inlet of the forced chamber fluently as case 4, the air change rate in the space may increase up to 15%.

The pressure distributions are represented in Figure 5, where P_f , P_u and P_a denote the pressures in the forced, unforced chambers and ambient environment, respectively. The neutral level is the height where pressures are equal in the forced chamber and the ambient environment and is denoted by h_n in Figure 5. The figure illustrates the both chambers have the displacement ventilation pattern.

The distance between the inlets of the unforced chamber and the forced chamber only have small effect on air change rate in this study, less than 5%, however, the case of shorter distance results in the higher air change rate. It is a reasonable result; since the longer distance between two openings in the unforced chamber, the more air mass needs be motivated to induce airflow and the more energy is required in the unforced chamber.

The source of maintaining the medium at a constant temperature of 45 degree Celsius in our simulation results in different values of output power as shown in Table 1. The heat source power is used to compare with the theoretical model, since it relates to the buoyancy flux in the space and is the main driving force of indoor air flow in our study.

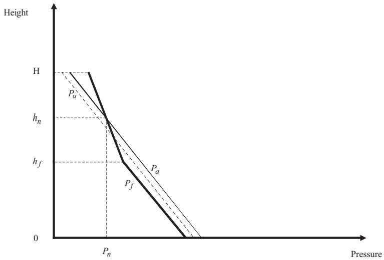

Figure 5. The pressure profile in the forced chamber, the unforced chamber and the ambient environment.

From the numerical results, we can verify the entrainment mechanism of the heat source by compare the exchange volume flow rate of the space of the forced chamber, and the flow in and out the heat source (see Table 2). These two flows also determine the mixing status in the space and the heat flow through the space.

Table 1. The results of numerical simulation cases in this study.

Simulation case	The position of unforced chamber opening	Exchange volume flowrate (m^3/s)	Exhaust air temperature (deg C)	Heat source power (KW)
Single room	N/A	0.223	34.7	3.97
Two room case 1	X=0, Y=3.5 m	0.177	37.5	3.70
Two room case 2	X=0, Y=2.5 m	0.180	36.1	3.46
Two room case 3	X=0, Y=1.5 m	0.181	36.1	3.48
Two room case 4	X=0, Y=0	0.201	35.9	3.84
Two room case 5	X=0.5 m, Y=4 m, on the ceiling.	0.177	36.1	3.43
Two room case 6	X=0.5 m,Y=0, on the floor.	0.177	36.1	3.44

Note: here X is the dimension of the width, and Y is the dimension of vertical height.

Table 2. The entrainment flow by the heat source

Simulation case	Exchange volume flowrate (m^3/s)	The flow in and out of the heat source (m^3/s)
Single room	0.223	0.136
Two room case 1	0.177	0.147
Two room case 2	0.180	0.131
Two room case 3	0.181	0.131
Two room case 4	0.201	0.133
Two room case 5	0.177	0.130
Two room case 6	0.177	0.130

CONCLUSIONS

This study investigates different schemes of connecting openings to the ambient environment in the unforced chamber and discusses their effects on natural ventilation in the space. The steady-state cases of numerical simulation are investigated to look into their performance characteristics. Geometrical arrangements in this study have displacement ventilation in both rooms.

Our study shows that the exchange flow in the space can be controlled by varying one of the series openings for the air path. If one of the series openings in the space is close, the air path of the displacement ventilation is blocked and that results in different pattern of ventilation.

The study shows that the larger effective area results in higher air change rate and the lower temperature in the space. The space with the same effective area has very similar air change rate, however, the relative position of inlet opening in the unforced chamber may change some properties of indoor environment. The distance between the inlets of the unforced chamber and the forced chamber seems to only have secondary effect on air change rate in this study. However, when the inlet and outlet of the unforced chamber are connected smoothly, that helps the efficiency of ventilation.

The position of inlet opening of the unforced chamber and the inlet of the forced chamber decide the region of low air change rate. In this numerical simulation study, the region in the unforced chamber outside the main airflow stream results in poor air change rate. For the case of inlet opening (Two room case 1 to case 4) at the sidewall, the region above the inlet opening of the unforced chamber has small air change rate and may result in bad air quality.

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