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AN EXPERIMENTAL AND NUMERICAL STUDY OF THE RELATIONSHIP BETWEEN VENTILATION EFFICIENCY AND AIR SUPPLY/EXHAUST SYSTEM OF AN ATRIUM SPACE

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ABSTRACT

The buildings with atrium space are often built for the purpose of providing amenity in city areas. In a cooled or heated atrium space, the temperature difference between the lower and the upper part have the tendency to be large. Therefore, the ventilation and air-conditioning systems must be selected carefully to consider the characteristics of the space shape and the heating or cooling loads. In this paper experiments with full size model and CFD simulations of the relationship between ventilation efficiency and air supply/exhaust system of an atrium space are carried out. The age of air and air exchange efficiency of the occupied zone (εm) have been measured by tracer gas method and calculated by CFD analysis.
The main results are as follows.
(1) In the case of cooling and the occupied zone being limited to the lower part of the atrium, arranging the supply outlet to be in the lower parts increases the ventilation efficiency.
(2) In the case of a vertical supply from the floor, exhausting to the ceiling is more desirable than exhausting to the wall.
(3) As the supply flow rate from the ceiling or the wall increases εm dose not increase because the high velocity jet adheres to the room surfaces and does not provide good ventilation in the occupied zone.
(4) The most effective arrangement for both the heating and the cooling modes is to supply the air from the wall at a height of 3500mm and exhaust it to the wall or supply it from the floor and exhaust it to the ceiling.

KEYWORDS

Ventilation efficiency, Air conditioning system, Model experiment, Numerical simulation, Computational fluid dynamics(CFD), Atrium space

INTRODUCTION

With recent development in building technology, the buildings with atrium space are often built for the purpose of providing amenity in city areas. In a cooled or heated atrium space, the temperature difference between the lower and the upper part have the tendency to be large. Therefore, the ventilation and air-conditioning systems must be selected carefully to consider the characteristics of the space shape and the heating or cooling loads. In an atrium, the occupied zone exists usually only in the lower part so that the ventilation and the air-conditioning systems are planed to target this area only. Therefore, the occupied zone is relatively small in comparison with normal office buildings, and this requires efficient ventilation and air-conditioning system for the atrium. Normal design guidelines that can be applied in practice to select the ventilation and air-conditioning system are not enough. In particular, there is a lack of knowledge about the relationship between ventilation system and ventilation efficiency for atrium.

In this paper, the results from a mock-up experiment and CFD simulations of an atrium are presented. The local and mean air exchange efficiency of the occupied zone have been measured and calculated and these are used to evaluate the ventilation effectiveness.

MODEL EXPERIMENT FOR THE VENTILATION EFFICIENCY

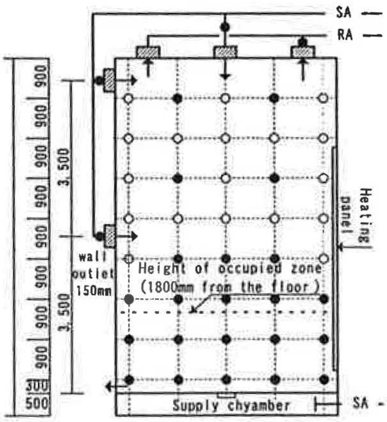
Experimental atrium

A full size experimental atrium (5,000mm W~ 3,600mm D~ 8,000mm H) that has been installed in the laboratory which is shown in Figure 1. The model atrium is made from thermal insulation panel. The arrangement and the air temperature of the supply outlet and exhaust inlet can be controlled. Heating panel are arranged on the wall to represent the cooling load by conduction heat from the walls.

Table 1 Experimental Conditions and Results of εp

Case	Experimental condition							Results	
	Supply/Exaust		Air volume	Cp	Ts	Ti	ΔT	εm	
	Supply	Exaust	[m3/h]	[ppm]	[°C]	[°C]	[°C]	S-up	S-dn
C1	Wall at height of 3500mm	ceiling	284	19.0	15.9	26.3	10.4	1.53	1.22
C2	Wall at height of 3500mm	wall	275	19.6	14.6	25.7	11.1	1.26	1.00
C3	Wall at height of 7000mm	ceiling	250	21.6	15.9	25.7	9.8	1.07	0.93
C4	Wall at height of 7000mm	wall	262	20.6	15.8	25.5	9.7	0.92	0.87
C5	ceiling	ceiling	266	20.3	15.2	25.8	10.5	1.02	0.95
C6	ceiling	wall	253	21.3	15.8	26.0	10.2	1.01	0.97
C7	Two supplies from the floor	ceiling	301	17.9	15.3	25.0	9.7	2.87	2.30
C8	Two supplies from the floor	wall	289	18.7	15.2	26.3	11.1	1.65	1.56
D1	Wall at height of 3500mm	ceiling	560	19.3	15.8	26.5	10.7	0.90	0.97
D2	Wall at height of 3500mm	wall	556	19.4	15.7	26.3	10.7	0.92	0.90
D7	Two supplies from the floor	ceiling	637	17.0	15.5	23.8	8.3	1.16	1.21
D8	Two supplies from the floor	wall	598	18.1	14.7	23.8	9.1	1.49	1.21
G1	One supply from the floor	ceiling	296	18.3	15.4	26.7	11.3	1.56	1.49
G2	One supply from the floor	wall	298	18.1	15.5	28.0	12.5	1.21	1.21
G3	Four supplies from the floor	ceiling	301	18.0	15.1	23.6	8.5	2.25	2.09
G4	Four supplies from the floor	wall	298	18.1	15.5	25.1	9.6	1.22	1.45

Cp:Standard concentration,, Ts:Supply air temperature, Ti:Room air temperature, T:Ti - Ts



(1) Measuring points

Figure 1 Full size experimental chamber and measureing points

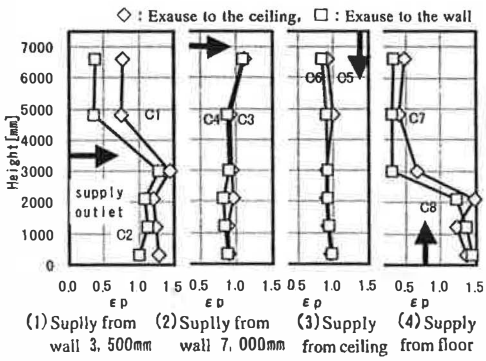


Figure 2 Vertical distribution of εp for the cooling conditions

Experimental method

Tracer gas (SF_6) is injected in the supply duct at a fixed rate, and the change in concentration at each measurement point is recorded until the concentrations at each point become a constant (step up method). After that, the injection of tracer gas is stopped and the concentration decay is measured (step down method). To measure the concentration of the tracer gas, 6 sets of multi-gas monitors (BK1303) were used. The number of measuring points of the tracer gas is 28 points inside the room, 2 points in the supply outlet (before and after injection point) and 1 point in the exhaust inlet.

The local air exchange efficiency (εp) at each measuring point is calculated from the gas concentration history. In this research, the occupied zone is defined to be the region from the floor to a height of 1800mm in the atrium. The local mean air exchange efficiency in the occupied zone (εm) is calculated from εp.

Experimental conditions

Table 1 shows the experimental conditions. Four kinds of supply outlets (horizontal supply from the wall at heights of 3500mm and 7000mm using 150mm diameter nozzle, vertical supply from the ceiling at a height 7500mm using 150mm diameter nozzle, and vertical supply from the floor using 150mm diameter nozzle). Two kinds of exhaust inlet (exhaust to the ceiling and exhaust to the wall), three values of ventilation rate ($3.0m^3/min$, $4.5m^3/min$ and $9.0m^3/min$) have been used in the experiments. Experimental CASE A is isothermal, CASE B is heating and CASE C is cooling condition. The actual ventilation rate for the atrium model has been calculated from tracer gas concentration measurement using constant gas injection in the supply outlet and the step up method. This provided an accurate measurement of the airflow rate.

EXPERIMENT RESULTS

Figure 2 shows the results of the vertical distribution of εp value at the central section of the atrium.

In the case of a horizontal supply from the wall at a height of 3500mm (CASEs C1 and C2), the difference between the value of εp in the two zones above and below the supply openings becomes large. Specially in the case of the exhaust inlet is arranged on the wall, the value of εp becomes over 1.0 below a height of 3000mm. However above the supply outlet, the value of εp becomes very low and it is about 0.4. On the other hand, in the case of a horizontal supply from a height of 7000mm (CASEs C3 and C4), the vertical variation εp becomes small and it is within the range of 0.9 to 1.1, which is similar to the isothermal condition case.

In the case of a vertical supply from the ceiling (CASEs C5 and C6), the vertical difference of the εp value becomes small and it is about 1.0.

In the case of vertical supply from the floor (CASEs C7, C8), the value of εp below a height of 2000mm is within the range of 1.3 to 1.5, but above a height of 3000mm, the value of εp becomes very small and it is about 0.5.

CALCULATION OF THE VENTILATION EFFICIENCY BY CFD

Each experimental condition was simulated using the CFD code STREAM, Software Cradle co.ltd(1990), with a standard K-ε model. The airflow distribution was analyzed, and local air exchange efficiency was calculated from the value of SVE3. The room symmetry has been taken into consideration and in the CFD simulation by solving the flow for 1/2 of the atrium. The boundary conditions used in the CFD simulation is given in Table 2. The number of computational cells were 50(x)×25(y)×73(z) in the case of supply from the ceiling or the wall, and 100(x)×25(y)×73(z) in the case of supply from the floor. The local mean air exchange efficiency in the occupied zone εm represents the weighted averages of all the computational cells from the floor to a height of 1800mm. The thermal and inlet/outlet conditions used in the CFD simulations and the results for εm are given in Table3. The airflow by the CFD simulation can be compared the differences of various arrangement of inlet/outlet under the same conditions. On the other hand, the experiments have the influence of the outdoor environment. The CFD and experiment results for εm (which was averaged from the floor to a height of 1800mm) are in good agreement, therefore the ventilation efficiency for the occupied zone can be evaluated from the value of εm obtained from the CFD simulations.

CFD RESULTS

Airflow distribution and ventilation efficiency in the cooling cases

CFD values of the local air exchange efficiency (εp) and the local mean air exchange efficiency in the occupied zone (εm) are given in Figure3.

The values of εp and εm from the experiment and the CFD are in good agreement except near the supply outlet in the case of a horizontal supply from the wall. In the case of a horizontal supply from the wall at a height of 3500mm (CASEs C1, C2), the supply jet reaches the opposite wall and then the jet descends along the wall to the floor creating a circulating flow in the occupied zone. The value of εp in the occupied zone is higher than that in the upper part of the atrium. In the case of a vertical supply from the ceiling, the supply air spread efficiently over the occupied zone and exhausted to the outlet on the ceiling, resulting in a value of εm of 1.2. In the case of a

Table 2 Calculation method for CFD

Turbulence model	:Standards k- ε model
Spatial derivative	:Quick scheme for convection term, first-order upwind scheme for others
Supply outlet	:Supply outlet on the ceiling,supply outlet on the floor
Exaust inlet	:Exaust inlet on the ceiling,exaust inlet on the wall
Heating loads	:Heating panel
Calucilatin of ε p	:SVE3:S.Kato,S.Murakami(1986)

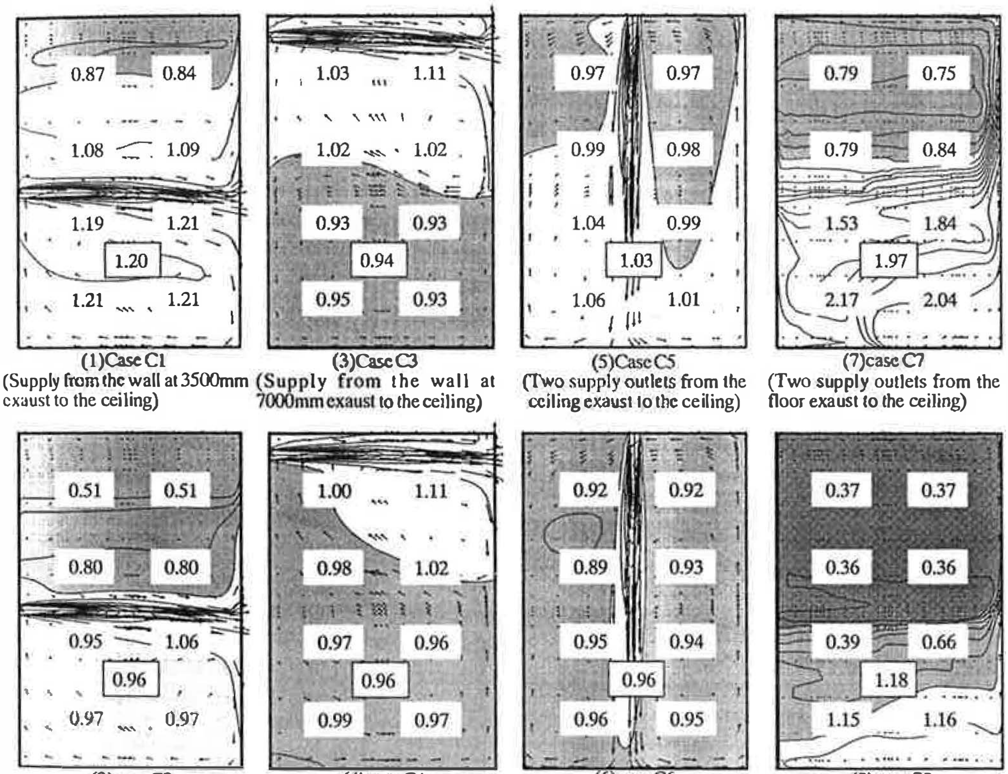
Table 3 CFD condition and results of εm

		Cfd conditins							Results
	case	Supply/Exaust supply	Supply/Exaust exaust	Air volume [m3/min]	supply [m/s]	Exaust [m/s]	T s [℃]	Heater [W]	εm
cooling condition	C1	Wall at height of 3500mm	ceiling	4.5	4.2	0.06	16.0	777.8	1.20
	C2	Wall at height of 3500mm	wall		4.2	2.08			0.96
	C3	wall at height of 7000mm	ceiling		4.2	0.06			0.94
	C4	wall at height of 7000mm	wall		4.2	2.08			0.99
	C5	Ceiling	ceiling		4.2	0.06			1.03
	C6	Ceiling	wall		4.2	2.08			0.96
	C7	Two outlet feom the floor	ceiling		0.15~0.3	0.06	17.2		1.97
	C8	Two outlet feom the floor	wall		0.15~0.3	2.08	17.2		1.18
	D1	Wall at height of 3500mm	ceiling		8.4	0.12			0.90
	D2	Wall at height of 3500mm	wall		8.4	4.16			0.97
	D7	Two outlet feom the floor	ceiling		0.3~0.6	0.12			1.26
	D8	Two outlet feom the floor	wall		0.3~0.6	4.16			1.17
	G1	One outlet from the floor	ceiling	4.5	0.15~0.3	0.06	17.2	777.8	1.02
	G2	One outlet from the floor	wall		0.15~0.3	2.08			1.00
	G3	four outlet from the floo	ceiling		0.08~0.2	0.06			2.03
	G4	four outlet from the floo	wall		0.08~0.2	2.08			0.61

horizontal supply from the wall at a height of 7000mm (CASEs C3, C4), the supply jet from the supply outlet descended along the wall, but before it reached the occupied zone it collide with the buoyant flow from the heated wall. This caused the indoor air to mix well and the value of εm becomes about 1.0. In the case of a vertical supply from the ceiling (CASEs C5, C6), the jet from the supply outlet descended to the floor and ascended to the ceiling along the heated wall. The vertical variation in εp becomes small and it is about 1.0. In the case of a vertical supply from the floor and exhaust to the ceiling (CASE C7), the jet from the supply outlet on the floor spread over the occupied zone then exhausted to the ceiling. As a result, the value of εp for the occupied zone becomes high and εm is 2.0 which is similar to the piston flow. However the value of εp above a height of 3000mm where the jet from the supply outlet can not reach the upper zones is less than 0.8. On the other hand, in the case of exhaust to the wall (CASE C8), the air supplied from the floor spread over the occupied zone and then exhausted to the wall outlet near the floor, in which case the value of εp near the ceiling becomes very small, about 0.3.

Relationship between supply air velocity and ventilation efficiency

The CFD results for CASE D in which the air velocity from the supply outlet is twice that for CASE C are given in Figure 4. When the supply air velocity is increased, the vertical variation in the εp becomes small for all cases of the supply outlet and the exhaust inlet arrangements. In the case of a horizontal supply from the wall at a height of



(1)Case C1 (Supply from the wall at 3500mm exaust to the ceiling)

(3)Case C3 (Supply from the wall at 7000mm exaust to the ceiling)

(5)Case C5 (Two supply outlets from the ceiling exaust to the ceiling)

(7)case C7 (Two supply outlets from the floor exaust to the ceiling)

(2)case C2 (Supply from the wall at 3500mm exaust to the wall)

(4)case C4 (Supply from the wall at 7000mm exaust to the wall)

(6)case C6 (Two supply outlets from the ceiling exaust to the wall)

(8)case C8 (Two supply outlets from the floor exaust to the wall)

Figure 3 Local mean air exchange efficiency for the cooling condition

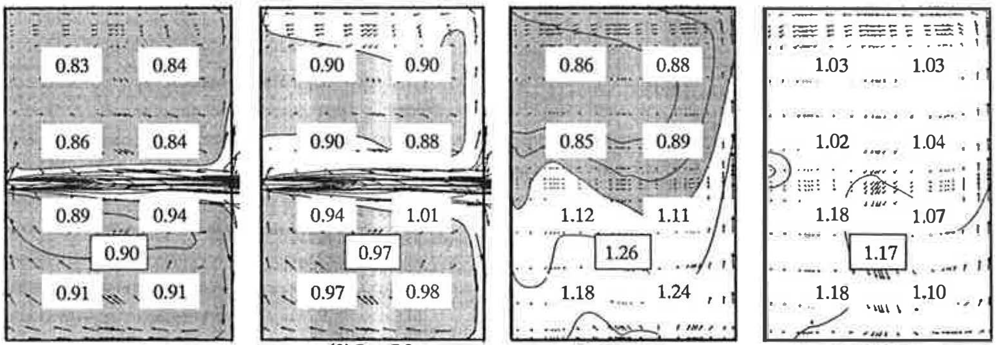
3500mm (CASEs D1, D2), the value of εm becomes 0.9 which is smaller than that for CASE C. When the air velocity at the supply outlet increases, the supply jet traveled along the ceiling or the wall and then short-circuited to the exhaust on the ceiling or the wall before the supply air reached to the occupied zone.

Relationship between the airflow rate from the floor supply outlet and ventilation efficiency

The supply airflow rate from the floor was 270m³/h with two supply outlets (CASEs D7, D8), 270m³/h with one supply outlet (CASEs G1, G2) and 67.5m³/h with four supply outlets (CASEs G3, G4). The results from the CFD simulations are shown in Figures 4 and 5. It is shown that as the airflow rate for each supply outlet is increased, the value of εm becomes 1.0 for all cases. When the number of supply outlet is increased and arranged uniformly on the floor, the velocity at the supply outlet decreased, so that the projected height of supply jet was reduced. Therefore, in the case of exhaust to the ceiling, the room flow was similar to a piston flow, and εm was high. But in the case of exhaust to the wall, εm decreased because the airflow from the floor is short circuited to the exhaust on the wall before the supply air reached the occupied zone.

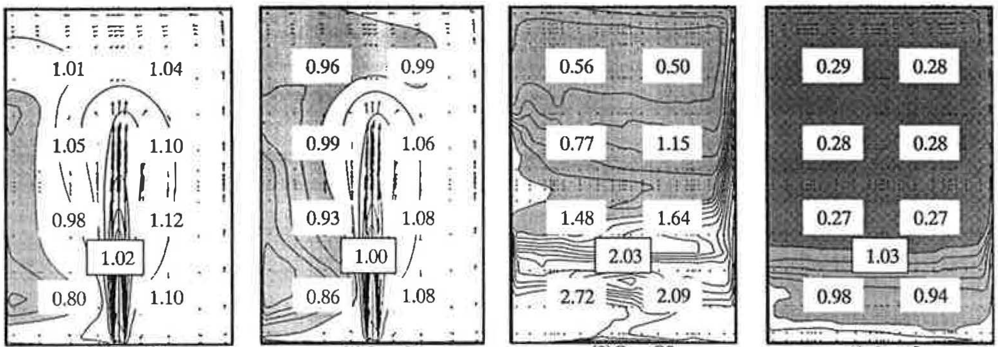
Relationships between temperature difference of the supply and the exhaust air and the ventilation efficiency

Figure 6 shows the relationship between εm and in the case of a supply outlet flow rate of 270m³/h.



(1)Case D1 (Supply from the wall at 3500mm exaust to the ceiling)
(2)Case D2 (Supply from the wall at 3500mm exaust to the wall)
(3)Case D7 (Two supply outlets from the floor exaust to the ceiling)
(4)Case D8 (Two supply outlets from the floor exaust to the wall)

Figure 4 Local mean air exchange efficiency for the cooling condition (air volume 540m³/h)



(1)Case G1 (One supply outlet from the floor exaust to the wall)
(2)Case G2 (One supply outlet from the floor exaust to the wall)
(3)Case G3 (Four supply outlets from the floor exaust to the wall)
(4)Case G4 (Four supply outlets from the floor exaust to the wall)

Figure 5 Local mean air exchange efficiency for the cooling condition(supply outlet from the floor)

In the case of a horizontal supply from the wall at a height of 3500mm and exhaust to the ceiling, the value of εm becomes more than 1.2 for the cooling condition. But in the case of exhaust to the wall in the heating condition, εm is within the range of 0.8 to 1.0.

In the case of a horizontal supply from the wall at a height of 7000mm, εm for the heating condition was a very low value, about 0.3, because the supply air remained close to the ceiling. In the case of the isothermal and the cooling conditions the value of εm is within the range of 0.8 to 1.2.

In the case of a vertical supply from the ceiling, the influence of ΔT,s is small in comparison with the other cases, and the value of εm is within the range of 0.8 to 1.2.

In the case of a vertical supply from the floor, the value of εm becomes 1.0 in the case of heating and isothermal conditions. But in the case of cooling the value of εm increased when ΔT,s decreased and when ΔT=-10C it was 2.0 which is similar to a piston flow.

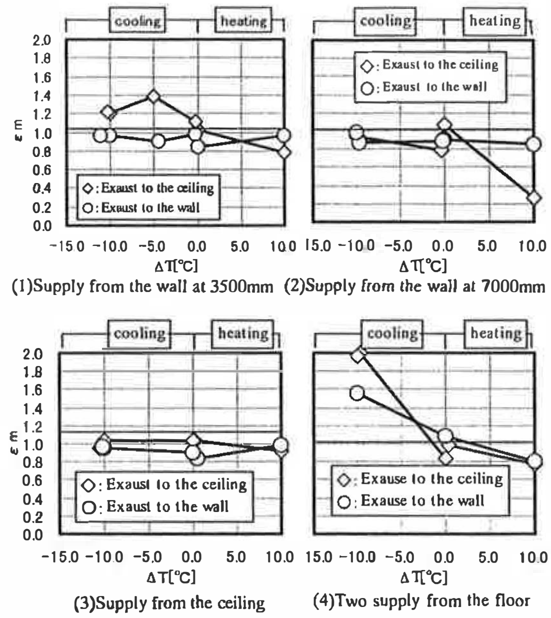


Figure 6 Relationship between εm and ΔT

CONCLUSIONS

(1) In the case of isothermal conditions, the values of εm is within the range of 0.9 to 1.2 which is close to the perfect mixing value for all supply outlet and the exhaust inlet arrangements.
(2) In the case of cooling, the vertical variation in εp becomes high when the supply outlet is situated in the lower part of the wall. Therefore, in the case of the occupied zone being limited to the lower part of the atrium, arranging the supply outlet to be in the lower parts increases the ventilation efficiency.
(3) In the case of a vertical supply from the floor, exhausting to the Ceiling is more desirable than exhausting to the wall. In particular when the number of supply outlets is increased and arranged uniformly over the floor, the velocity at the supply outlet decreases, so that the room flow becomes similar to a piston flow, and εm becomes high.
(4) As the supply flow rate from the ceiling or the wall increases εm dose not increase because the high velocity jet adheres to the room surfaces and does not provide good ventilation in the occupied zone.
(5) The most effective arrangement for both he heating and the cooling modes is to supply the sir from the wall at a height of 3500mm and exhaust it to the wall or supply it from the floor and exhaust it to the ceiling.

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