STUDY ON THE EFFECTIVENESS OF AIR-CONDITIONING AND VENTILATION SYSTEMS BY CFD ANALYSIS IN HOUSES

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ABSTRACT

The purpose of this paper is to analyze the indoor thermal environment and ventilation efficiency created by various heating and ventilation systems using CFD. In the case of one room, the value of mean local air exchange efficiency （ε_p） *1 of breathing zone*2 becomes about 1.0, because fresh air spreads completely in the room when air-conditioners are operated. In contrast, when air-conditioners are not operated, the mean ε_p becomes smaller than 1.0, and the area of poor ventilation efficiency becomes large. Air exchange efficiency is influenced by the layout of both the supply outlet and the exhaust inlet. In the case when the distance of the supply outlet and exhaust inlet is long, ventilation efficiency may be good. In the case that the whole house is analyzed, the air exchange rate while heating becomes more than the mechanical ventilation air exchange rate (0.5〔1/h〕) due to the buoyancy effect. And those cases are much in order of the ventilation system of mechanical supply and natural exhaust, natural supply and mechanical exhaust, mechanical supply and mechanical exhaust. There are no differences in the amount of distribution of ε_p between the cases of heating by air-conditioner and floor heating.

KEYWORDS

Local air exchange efficiency, Indoor thermal environment, Age of air, Residential building, Breathing zone

INTRODUCTION

Standard building regulations for Japan were revised in July 2003, and mechanical ventilation systems were required to be installed in every room of a house from July, 2004. In addition, recently high insulation and high air-tightness houses have spread not only in cold climate regions but also in temperate regions. However, it is very difficult for house designers to show the indoor thermal environment or ventilation efficiency to their customers.

The purpose of this paper is to analyze indoor thermal environment and the ventilation efficiency of various heating methods and ventilation systems using CFD. The first subject of this paper is a room of a house. The vertical temperature difference and local air exchange efficiency is changed by the position of an air-conditioner and a ventilation system, which are described. Furthermore, the next object is a whole house, and the effect on the indoor thermal environment and ventilation efficiency between heating by an air-conditioner and floor heating are analyzed and compared.

OUTLINE OF THE ANALYZED ROOM

Analyzed subject of the room

Analytical model

Figure 1 shows the plan of a standard AIJ house model, and figure 2 shows a room of the analytical model. The subject of the analytical model is a living room (16.6 m^2) with an air-conditioner; supply outlets and exhaust inlets are installed in standard AIJ house models.

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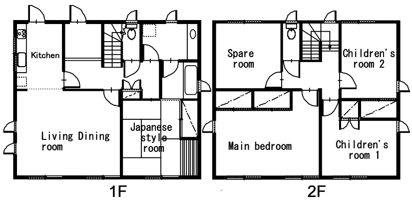


Figure 1. The plan of a standard AIJ house model

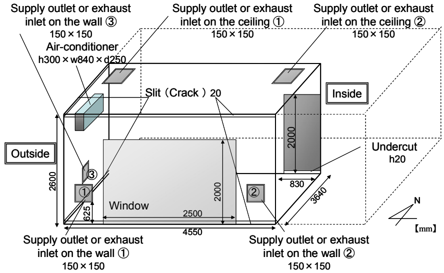


Figure 2 . A room of the analytical model

Analysis method

Figure 3 shows the outline of the ventilation system, and figure 4 shows the position of air-conditioners. house). Table 1 shows analyzed cases (A room of the house), and table 2 shows the analysis condition using CFD (A room of the house).The layout of supply outlets and exhaust inlets and the position of air-conditioners are changed. Ventilation efficiency by the age of air*3 and indoor thermal environment is analyzed using CFD (STREAM).

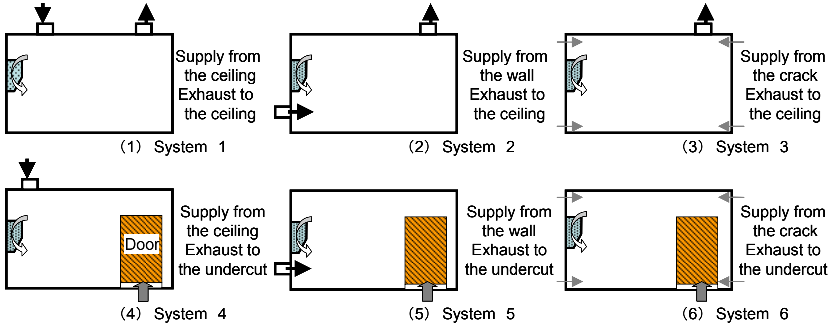


Figure 3. The outline of the ventilation system

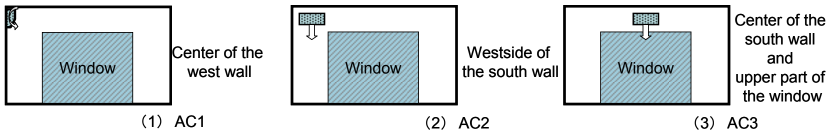


Figure 4. The position of air-conditioners

Table 1. Analyzed cases (A room of the house)

Case	Ventilation system			Position of the air-conditioner	Case	Ventilation system			Position of the air-conditioner
	System	Supply	Exhaust			System	Supply	Exhaust	
case1-1	System1	Ceiling ①	Ceiling ②	AC1	case6-1	System4	Ceiling ①	Undercut	AC1
case1-2				AC2	case6-2				AC2
case1-3				AC3	case6-3				AC3
case1-4				AC 3 (Not-operated)	case6-4				AC 3 (Not-operated)
case2-1	System2	Wall ①	Ceiling ②	AC1	case7-1	System5	Wall ①	Undercut	AC1
case2-2				AC2	case7-2				AC2
case2-3				AC3	case7-3				AC3
case2-4				AC 3 (Not-operated)	case7-4				AC 3 (Not-operated)
case3-1	System2	Wall ①	Ceiling ①	AC1	case8-1	System4	Ceiling ②	Undercut	AC1
case3-2				AC2	case8-2				AC2
case3-3				AC3	case8-3				AC3
case3-4				AC 3 (Not-operated)	case8-4				AC 3 (Not-operated)
case4-1	System2	Wall ③	Ceiling ①	AC1	case9-1	System5	Wall ②	Undercut	AC1
case4-2				AC2	case9-2				AC2
case4-3				AC3	case9-3				AC3
case4-4				AC 3 (Not-operated)	case9-4				AC 3 (Not-operated)
case5-1	System3	Slit	Ceiling ②	AC1	case10-1	System6	Slit	Undercut	AC1
case5-2				AC2	case10-2				AC2
case5-3				AC3	case10-3				AC3
case5-4				AC 3 (Not-operated)	case10-4				AC 3 (Not-operated)

Table 2. The analysis condition using CFD (A room of the house)

Numerical computation code	Software CRADLE STREAM Ver.6
Turbulence model	Standards k−ε model
Boundary condition	Boundary condition of wall surface : Generalized log-law, Thermal log-law Adiabatic condition : Floor surface, ceiling surface, east wall surface and north wall surface Heat load of wall surface : Window surface 324.0W West wall surface 68.1W South wall surface 47.2W
Emission condition	Emissivity 0.9 : Inboard surface of each wall
Supply outlet	Air change rate of mechanical ventilation : Air change rate 0.5〔1/h〕 Ceiling, wall : U=0.266〔m/s〕,k=7.07E-04〔m^2/s^2〕,ε=2.94E-04〔m^2/s^3〕,T=0〔℃〕 Slit(crack) : U=0.018〔m/s〕,k=3.33E-06〔m^2/s^2〕,ε=7.14E-07〔m^2/s^3〕,T=0〔℃〕
Exhaust inlet	Surface pressure boundary condition : Surface pressure 0 Pa
Air-conditioner	Supply velocity (6.55〔m3/min〕) : U=2.17〔m/s〕,k=4.69E-02〔m^2/s^2〕,ε=3.98E-01〔m^2/s^3〕,T=24.5〔℃ Return velocity : U=0.722〔m/s〕

RESULTS

Local air exchange efficiency (ε_p)

Figure 5 shows the mean ε_p of the breathing zone. When air-conditioners are operated, the value of mean ε_p of the breathing zone becomes about 1.0. Therefore, fresh air spread completely in the room, regardless of ventilation systems and position of air-conditioners. In contrast, when air-conditioners are not operated, the value of mean ε_p of case5-4 and case10-4, supplying from the crack outlet in the wall increased in comparison to when air-conditioners are operated.

Figure 6 shows the distribution of ε_p in case5-3 and case5-4. In case5-3, the distribution of ε_p becomes 1.0. But in case5-4, the distribution of ε_p ranges from 0.4 to 1.9. When air-conditioners are not operated, the difference of ε_p becomes large. In this case, the ventilation efficiency value widens greatly.

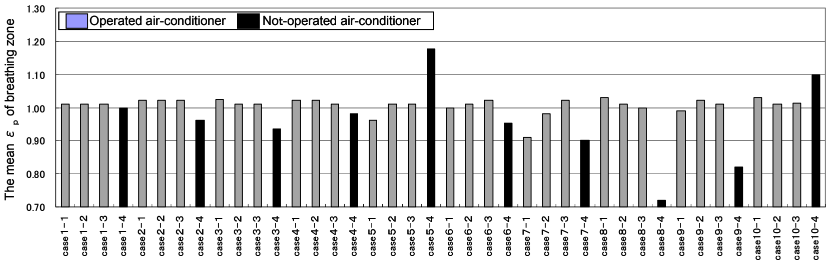
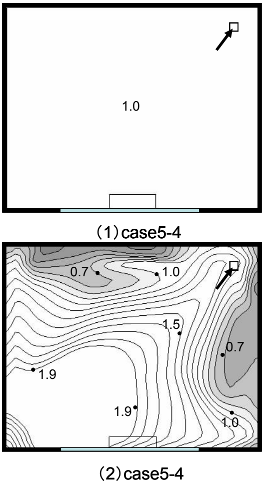


Figure 5. The mean ε_p of the breathing zone

Figure 7 shows the distribution of ε_p within the occupied zone. In cases 1-4 and 3-4, the exhaust inlet is installed on the ceiling. In case 1-4, the value of ε_p ranges from 0.9 to 1.2, because outdoor air is supplied from the ceiling and the distance between supply outlet and exhaust inlets is longer. But, in case3-4, the value of ε_p ranges from 0.8 to 1.0, because the distance between the supply outlet and exhaust inlets is shorter.

In cases 6-4 and 8-4, the exhaust inlet is installed at the undercut of the door. In case 6-4, the value of ε_p ranges from 0.8 to 1.1, because the supply outlet is installed at a remote position from the undercut. But, in the case of 8-4, the value of ε_p ranges from 0.6 to 1.0, because the supply outlet is installed very near to the undercut. Therefore, when the distance of supply outlet and exhaust inlet is longer, ventilation efficiency may be good. Distance of supply outlet and exhaust inlet greatly influences ventilation efficiency.



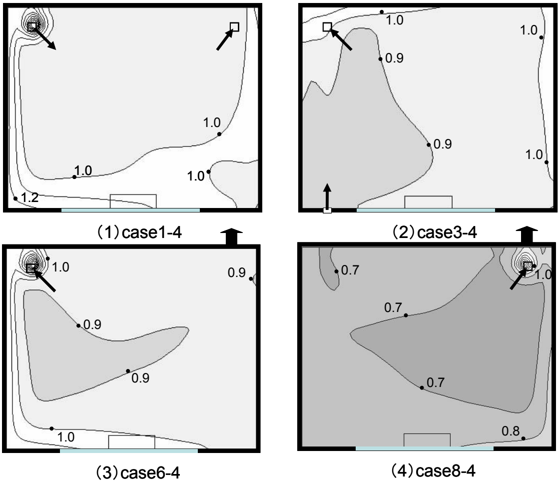


Figure 6. The distribution of ε_p in case5-3 and case5-4

Figure 7. The distribution of ε_p within the occupied zone

Indoor vertical air temperature difference

Figure 8 shows the room air temperature and vertical air temperature difference between 0.1m and 1.1m height above the floor level at a distance of 325mm from the window. Figure 9 shows the room air temperature and vertical air temperature difference between 0.1m and 1.1m above the floor level at a vertical section including the supply outlet. When outdoor air is supplied from the ceiling, vertical air temperature differences near the window are 2 degrees Celsius or lower. There is little effect of cold air from the window surface and outdoor air supply. In the case of supply from the wall, vertical air temperature differences between 0.1m and 1.1m at a vertical section including the supply outlet are more than 3 degrees Celsius. In this case the position of the air conditioner is AC1 (the west wall center) and AC2 (south wall / the west). When the position of the air conditioner is AC3 (Center of the south wall and upper part of the window), air temperature difference is 2 degrees Celsius or lower.

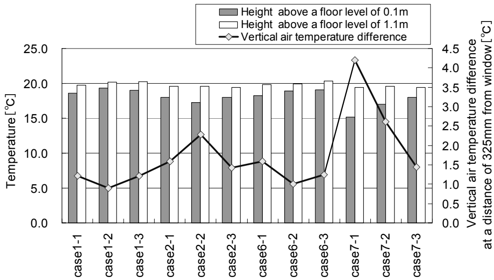


Figure 8. The room air temperature and vertical air temperature difference between 0.1m and 1.1m above the floor level at a distance of 325mm from the window

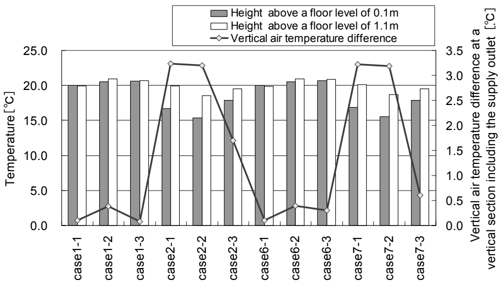


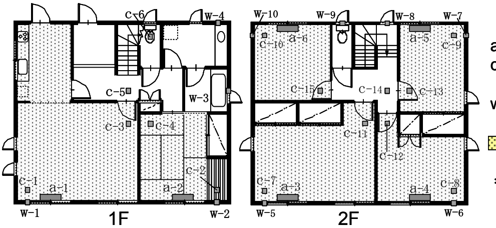
Figure 9. The room air temperature and vertical air temperature difference between 0.1m and 1.1m above the floor level at a vertical section including the supply outlet

OUTLINE OF ANALYSIS OF A WHOLE HOUSE

Analysis subject to a whole house

Analytical model

Figure 10 shows the analytical model house. Air-conditioners (Center of the south face and upper part of the window) and floor heaters are installed in each room. Shelter performance shall meet the next energy-saving standards for Japan (Area Ⅳ).



a: air-conditioner (h300×w840×d250㎜)
c: supply outlet or exhaust inlet on the ceiling (150×150㎜)
w: supply outlet or exhaust inlet on the wall (150×150㎜)
: floor heating zone

＊undercut in the indoor door(w200×h100㎜)

Figure 10. The analytical model house

Analysis method

Table 3 shows analyzed cases (The whole house), and table 4 shows the analysis condition using CFD (The whole house). The position of supply outlets or exhaust inlets of the ventilation systems, and the heating systems (heating by air-conditioner or floor heating) are changed. Indoor thermal environment and ventilation efficiency are analyzed by CFD. The temperature of the floor surface (plywood) when heating by radiation, and supply temperature of the air conditioner in heating are calculated by adjusting, so that the SET* becomes about 22℃.

Table 3. Analyzed cases (The whole house)

case	Ventilation system	Supply/Exhaust: Supply	Supply/Exhaust: Exhaust	Heating system
case1-1-1	Mechanical supply Mechanical exhaust	Ceiling	Ceiling	Not-heating
case1-1-2		c-1 c-2 c-7	c-5	Heating by air-conditioner
case1-1-3		c-8 c-9 c-10	c-14	Floor heating
case1-2-1		Wall	Ceiling	Not-heating
case1-2-2		w-1 w-2 w-5	c-5	Heating by air-conditioner
case1-2-3		w-6 w-7 w-10	c-14	Floor heating
case2-1-1	Mechanical supply Natural exhaust	Ceiling	Wall	Not-heating
case2-1-2		c-1 c-2 c-7	w-1 w-2 w-5	Heating by air-conditioner
case2-1-3		c-8 c-9 c-10	w-6 w-7 w-10	Floor heating
case2-2-1		Ceiling	Wall	Not-heating
case2-2-2		c-3 c-4 c-11	w-1 w-2 w-5	Heating by air-conditioner
case2-2-3		c-12 c-13 c-15	w-6 w-7 w-10	Floor heating
case3-1-1	Natural supply Mechanical exhaust	Wall	Wall	Not-heating
case3-1-2		w-1 w-2 w-5	w-3 w-4 c-6	Heating by air-conditioner
case3-1-3		w-6 w-7 w-10	w-8 w-9	Floor heating

Table 4. The analysis condition using CFD (The whole house)

Numerical computation code	Software CRADLE STREAM Ver.6
Turbulence model	Standards k-ε model
Boundary condition	Boundary condition of wall surface : Generalized log-law, Thermal log-law Outside air temperature 0〔℃〕, Initial temperature 20〔℃〕
Emission condition	Emissivity 0.9 : Inboard surface of each wall
Heating condition	Heating by air-conditioner : Supply air T=35℃ Floor heating : Floor surface given temperature 40℃
Supply outlet	Air change rate of mechanical ventilation : Air change rate 0.5〔1/h〕 Mechanical supply : Supply air T=0℃ Natural supply : Natural inflow T=0℃
Exhaust inlet	Air change rate of mechanical ventilation : Air change rate 0.5〔1/h〕 Mechanical exhaust : Room air temperature Natural exhaust : Room air temperature
Leakage of air	Airtightness of house is 2.0cm^2/m^2 Leakage of air is set by natural in and out airflow condition established with 16 crack holes in the wall made by 4cm^2 hole

RESULTS

Air exchange rate

Figure 11 shows the ratio of supply and exhaust air exchange rate and the air exchange rate of mechanical ventilation (0.5[1/h]). In the cases of heating, the air exchange rate is more in order of the ventilation system of ①mechanical supply and natural exhaust, ②natural supply and mechanical exhaust, ③mechanical supply and mechanical exhaust. There is no difference of the air exchange rate between heating by air-conditioner and floor heating. In the case of the ventilation system using a mechanical supply and natural exhaust, outdoor air supply from the exhaust inlets when heating by air-conditioner is 4.3 times as much as the supply from the cracks in the wall. When using floor heating it is 3.4 times as much. Moreover, in the case of the ventilation system with a natural supply and mechanical exhaust, outdoor air exhaust from the supply outlets when heating by an air-conditioner is 1.9 times as much as the exhaust to the cracks in the wall. And in this case floor heating is 2.6 times as much. Therefore, in the case of the ventilation system of mechanical supply and natural exhaust, the reverse air flow rate from the natural exhaust inlets is larger than the case of the ventilation system of natural supply and mechanical exhaust.

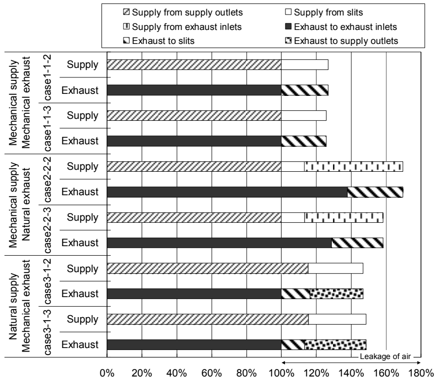


Figure 11. The ratio of supply and exhaust air exchange rate and air change rate of mechanical ventilation (0.5[1/h])

Figure 12 shows the air exchange rate between the rooms of each ventilation system with floor heating. Air exchange rate of mechanical ventilation in case1-1-3（mechanical supply and mechanical exhaust） is 142.5 m^3/h; in addition, the first floor has inflow and outflow from the cracks in the wall, and the second floor has outflow from the cracks in the wall. In case2-2-3 (mechanical supply and natural exhaust), outdoor air is supplied from the exhaust inlets of the first floor, air exchange rate increases in comparison with case1-1-3（mechanical supply and mechanical exhaust）; 160.4 m^3/h airflow in the first floor flows into the second floor. In case3-1-3（natural supply and mechanical exhaust）, outdoor air flow rate from supply outlets in the first floor increases as dose exhaust from supply outlets on the second floor. The height of the neutral zone is higher than on the second floor due to thermal buoyancy.

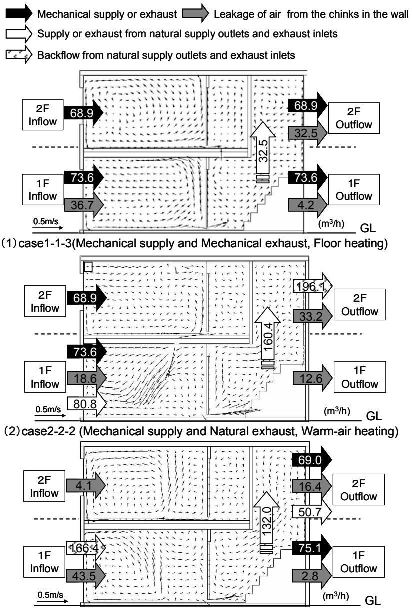


Figure 12. The air exchange rate between the rooms of each ventilation system with floor heating

The relationship between indoor thermal environment and Local air exchange efficiency(ε_p) of the occupied zone*4

Figure 13 shows the relationship between the coefficient of vertical air temperature difference*5 and the mean ε_p at the LDK and the main bedroom. In the case of floor heating, the coefficient of vertical air temperature difference is small. Therefore, the indoor thermal environment in the case of floor heating is better than when heating by an air-conditioner. The distribution of ε_p is no different between heating by air-conditioner and floor heating.

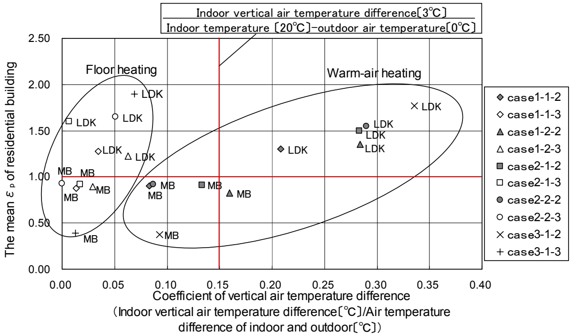


Figure 13. The relationship between the coefficient of vertical air temperature difference and the mean ε_p at the LDK and the main bedroom

Local air exchange efficiency (ε_p)

Figure 14 shows the distribution of ε_p of the representative cases. In case1-1-2 (mechanical supply and mechanical exhaust, heating by air-conditioner) and case1-1-3 (mechanical supply and mechanical exhaust, floor heating), there are few differences of the distribution of ε_p. In case2-2-3 (mechanical supply and natural exhaust, floor heating), the value of ε_p of the rooms on the first floor ranges from 1.6 to 2.0 because outdoor air is supplied from the exhaust inlets of the first floor. And the value of that on the second floor becomes 1.0. In this case, ventilation efficiency is good. In case3-1-3 (natural supply and mechanical exhaust, floor heating), the value of ε_p of all rooms on the first floor becomes larger than 1.0, and ventilation efficiency is good. But the value of ε_p of the rooms on the second floor becomes smaller than 1.0, because air of the first floor flows into the second floor so that the fresh air is not supplied from the supply outlets on the second floor.

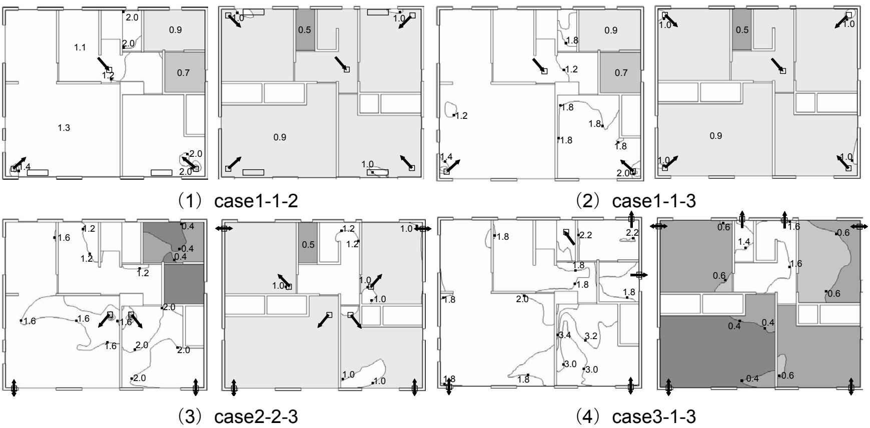


Figure 14. The distribution of ε_p in the representative cases

CONCLUSION

Analysis of a room

(1) The value of mean local air exchange efficiency (ε_p) of breathing zone becomes about 1.0, because fresh air spread completely in the room when air-conditioners are operated.

(2) In the case when air-conditioners are not operated, the mean ε_p becomes smaller than 1.0, and

the poor area of ventilation efficiency becomes large.
(3) Ventilation efficiency is influenced by the layout of the supply outlets and exhaust inlets. In the case when the distance from the supply outlet to the exhaust inlet is long, ventilation efficiency may be good. In the case when the distance of supply outlet to the exhaust inlet is short, it causes a short-circuit, and the bad zone of ventilation efficiency increases.
(4) When an air-conditioner is placed above the window, and a supply outlet is installed on the ceiling, there is little effect of a cold air from the window surface, and the air supply / vertical temperature difference is 2 degrees Celsius or lower.

Analysis subject to a whole house
(1) In the cases of heating, the air exchange rate is more in order with the ventilation system of ① mechanical supply and natural exhaust, ②natural supply and mechanical exhaust, ③mechanical supply and mechanical exhaust. There is no difference of the air exchange rate between heating by air-conditioner and floor heating.
(2) In the case of mechanical supply and natural exhaust, the backflow volume from the natural exhaust inlets into the first floor by influence of buoyancy. In the case of natural supply and mechanical exhaust, the backflow volume from the natural supply outlets into the second floor by influence of buoyancy.
(3) In the case of floor heating, the vertical air temperature difference and air temperature difference between rooms are small; indoor thermal environment is good in comparison with that of the case of heating by air-conditioner.
(4) There are no differences in the amount of distribution of ε_p between heating by air-conditioner and floor heating.
(5) There are different ventilation efficiencies in different ventilation systems. In the case of mechanical supply and mechanical exhaust, and mechanical supply and natural exhaust, the value of ε_p in the living space becomes or 1.0 and above; ventilation efficiency is good. And in the case of natural supply and mechanical exhaust, the value of ε_p in living space on the second floor becomes 1.0 and below; ventilation efficiency is bad.

＊1: Local air exchange efficiency (ε_p) is an indicator of ventilation efficiency in the room. In the case of fresh air spreading completely in the room, the value of ε_p becomes 1.0. If it is larger, the ventilation efficiency improves.
＊2: Breathing zone is the range of 0.5m to 1.8m above the floor level.
＊3: Age of air is the average time from supplying fresh air until arriving at a point. The shorter it is, the more fresh air is supplied.
＊4: Occupied zone is the range from 0m to 2.0m above the floor level.
＊5: The coefficient of vertical air temperature difference is defined by dividing vertical the vertical air temperature difference by the air temperature difference of indoors and outdoors.

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