Dynamic Insulation System applied to Window Frames (Part 2)

Energy saving effects of the proposed system in residential buildings

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Abstract
This paper describes the energy-saving effects of the proposed system with an active ventilation function and a heat pump for heat recovery. First, the temperature of the air supplied through the porous material versus the outdoor temperature was calculated using computational fluid dynamics to set the boundary conditions for the energy simulation. Then, the cooling/heating loads of a typical residential building in Japan were calculated and comparisons were made with and without the proposed system installed. In addition, in order to evaluate the energy-saving rate under different climatic conditions, the annual air-conditioning loads in several areas (Tokyo and Sapporo in Japan, and Seoul in the northwest of South Korea) were calculated. As expected, dynamic insulation applied to window frames was effective from the point of view of its insulation efficiency. The calculated results indicate that residential buildings making use of the proposed system could achieve energy savings of 14~34%. Especially it is more effective when the outdoor temperature is low in winter. In summer, the energy saving potential depends on the performance of an installed heat pump. A comparison of different climatic conditions showed that the energy-saving rate was especially high in areas with a large annual temperature difference between the indoor and outdoor environment.

Keywords: Dynamic insulation, Thermal insulation efficiency, Energy simulation, Ventilation system

Introduction

How best to reduce home energy consumption in Japan is a serious concern. Although the basic approach to reducing home energy consumption is to insulate and to seal up residences, adequate ventilation must be provided in order to maintain indoor air quality. Therefore, various architectural technologies have been designed to achieve this result. Dynamic insulation blocks heat transport by making the airflow coming into the house pass through a porous material. Because dynamic insulation reduces heat loss and also helps maintain the indoor air quality, many different systems for dynamic insulation have been proposed and successfully applied to the building envelope, including walls and windows [1], [2], [3]. However, it is especially important to insulate the window frame efficiently because it usually contributes the greatest heat loss.

Objectives

In a previous paper, a new dynamic insulation system was proposed and a CFD simulation showed that application of dynamic insulation to window frames was effective in terms of its insulation efficiency [4]. In this paper, using the results of the CFD simulation, the air-conditioning load was calculated by means of a coupled simulation of TRNSYS V16 [5], with and without the system installed, to show how effectively the system could reduce energy consumption.

Methods

The heating/cooling loads of a typical residential building in Japan were calculated for four cases in terms of the heat pump system, heat recovery ventilator, and dynamic insulation applied to window frames.

1. Building models

Figure 1 shows the plan of the building model used for the calculation, which is proposed as a standard residence in Japan by the Institute for Building Environment and Energy Conservation (IBEC) [6]. The model differs a little according to the climate area: one is for a warmer area (building model type A), and another is for a colder area (building model type B). In this paper, model type A is used for calculations for Tokyo, and model type B is used for calculations for both Sapporo and Seoul.

2. Calculated cases

Table 1 shows the details of all cases. In all cases, the air change rate is 0.5 times per hour. In Case 1, the heat pump system, ventilation system with heat-recovery ventilator, and dynamic insulation are not installed. In Case 2, the model has only a heat recovery ventilator with 70% efficiency as a ventilation system. In Case 3, only a heat pump system is installed. In Case 4, dynamic insulation is applied to window frames with an exhaust heat pump system.

In this paper, for simplicity the cooling/heating loads of only the living room were calculated, using a transient system simulation program with a modular structure, TRNSYS. The calculated results show the differences between the four cases. In addition, in order to evaluate the energy-saving rate under different climatic conditions, the annual air-conditioning loads were calculated. Figure 3 shows a flowchart of all calculated cases.

3. Boundary conditions

Table 2 shows the boundary conditions of the building envelope. The U-value meets the standards established by IBEC [6]. Table 3 shows the boundary conditions of the windows. Dynamic insulation was applied only to the window frames in the living room. The frames contain porous materials. The ventilation air flow rates and the air temperature coming into the living room through the porous material were calculated by CFD simulation in a previous paper, with boundary conditions shown in Table 4 [4]. The porosity of the porous material is 0.5 [-] and the frame area is 15% of the window area. The pressure difference is assumed to be 10 Pa in this paper, although various cases with different given conditions were calculated in the CFD simulation. This value was selected because heat loss through the porous material surrounding windows is almost 0 W/m^2 when the pressure difference is 10 Pa, as determined by the CFD simulation [4].

The air temperature coming into the living room through the porous material is calculated as follows. First, the relationship of the temperature difference between indoor/outdoor and indoor surface/outdoor is calculated from the results of the CFD simulation [4]. Figure 2 shows the temperature contribution, and leads to Equation 1 as a linear approximation:

$$T_{di} = 0.655 \times \left[T_{indoor} - T_{outdoor}\right] + 0.653 + T_{outdoor} \qquad \text{(Eq. 1)}$$

where $T_{outdoor}$ [K] is ambient air temperature, T_{indoor} [K] is the indoor air temperature in the living room, and T_{di} [K] is the indoor surface temperature of the porous material.

4. Weather data

Data from AMeDAS (Automated Meteorological Data Acquisition System, developed by the Japan Meteorological Agency) in Tokyo (E139° 45’ N35° 41’), Sapporo (E141° 21’ N43° 04’), and data from Meteonorm (produced by METEOTEST) in Seoul (E126° 92’ N37° 53’), including solar insolation, temperature, wind velocity and wind direction, were used as input data in order to calculate heating/cooling loads.

5. Family structure/schedule

We assumed that the family unit consisted of a father (male, age 46), a mother (female, age 44) and two children (female, age 16; male, age 14). Table 5 (a) shows the family schedule. Tables 5 (b) and (c) show the air-conditioning and lighting/equipment schedules, respectively.

Results and Discussion

1. Annual air-conditioning loads

Figure 4 shows the annual air-conditioning load of a typical residential building in three different areas, based on energy simulations using weather data for Tokyo, Sapporo and Seoul, and comparing the cases. This shows that the dynamic insulation system proposed in a previous paper [4] is more effective for energy saving in the cold climate areas, Sapporo and Seoul. The ratio of the annual air-conditioning loads of Cases 2, 3 and 4 to that of Case 1 is shown in Table 6. In Sapporo, the annual air-conditioning load of Case 4 is decreased 34% relative to Case 1. Under warm climate conditions, in Tokyo, the annual air-conditioning load in Case 3 is less than in Case 4.

2. Heating/cooling loads

Figure 5 shows the different heating/cooling loads of the cases. The heating loads calculated in the three areas decrease in order of increasing case number. The cooling loads of Case 2 are the largest of the three areas.

3. Air-conditioning loads versus heat conduction

Figure 6 shows the air-conditioning load due to heat conduction in the three different areas. In all areas, the conduction load for heating in Case 4 is much less than that of the other cases. The dynamic insulation system proposed is so effective in Case 4 that it contributes very significant heating energy savings. However, conduction loads for cooling in Case 2 are much less than in the other cases, for two reasons. First, in winter solar radiation makes the room warm and heated outdoor air is also supplied by the heat-recovery ventilator. Second, with the cooling mode in summer, the air supplied from the heat-recovery ventilator is warmer than the room temperature when the outdoor temperature is lower than that indoors. These situations make the cooling loads of Case 2 greater than those in Case 1. In all areas, the cooling load due to heat conduction in Case 3 is less than that in Case 4. This means that the dynamic insulation system applied to the window frames in Case 4 insulates the room well, which keeps the indoor temperature warm.

4. Air-conditioning loads versus ventilation

Figure 7 shows the ventilation loads in the three different areas. Ventilation loads of Case 2 are less than those of the other cases in all areas. In Case 3, the indoor/outdoor temperature difference is larger than in Case 1 because the heat pump system makes the living room warm in winter and cool in summer for all 24 hours, which saves air-conditioning load. Compared to Case 3, the heating load versus ventilation in Case 4 is lower because the dynamic insulation system supplies heated outdoor air to the building.

Conclusions

This paper evaluates the energy-saving efficiency of a new dynamic insulation system by examining outdoor conditions and combined systems. A summary of the general findings of this study is as follows.

1. This dynamic insulation system, proposed in a previous paper [4], saves energy in cold climate areas. In Sapporo, residential buildings using the proposed system could achieve energy savings of 34%.

2. With this dynamic insulation system, the cooling load does not decrease as much as the heating load. Residential buildings with the proposed system in a hot and humid climate will be evaluated in future investigations.

3. In this paper, a dynamic insulation system is applied only to the window frames, which reduces the heating/cooling load. This airflow window system and a wall with dynamic insulation will be proposed and evaluated in future investigations.

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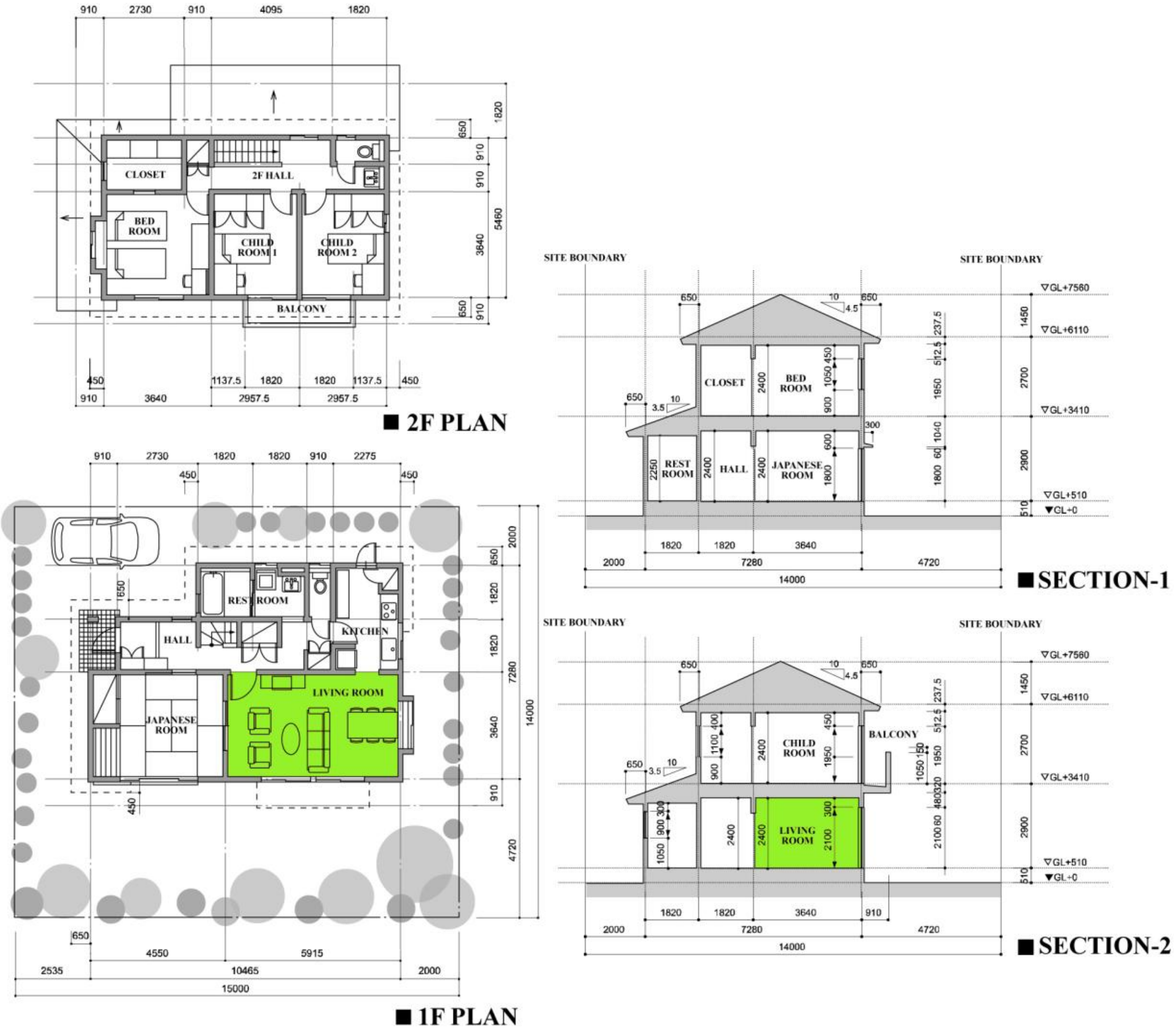


Fig. 1 Calculation model (model type A in warmer area in Japan by IBEC [6])

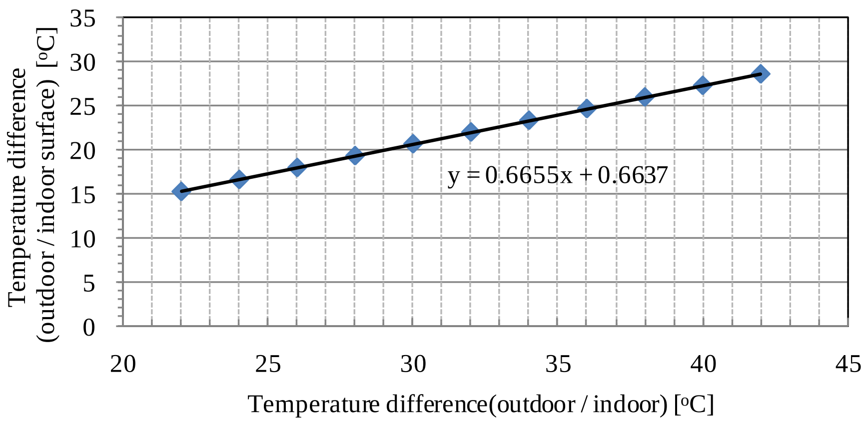


Fig. 2 Calculated supply air temperature through insulation by temperature difference

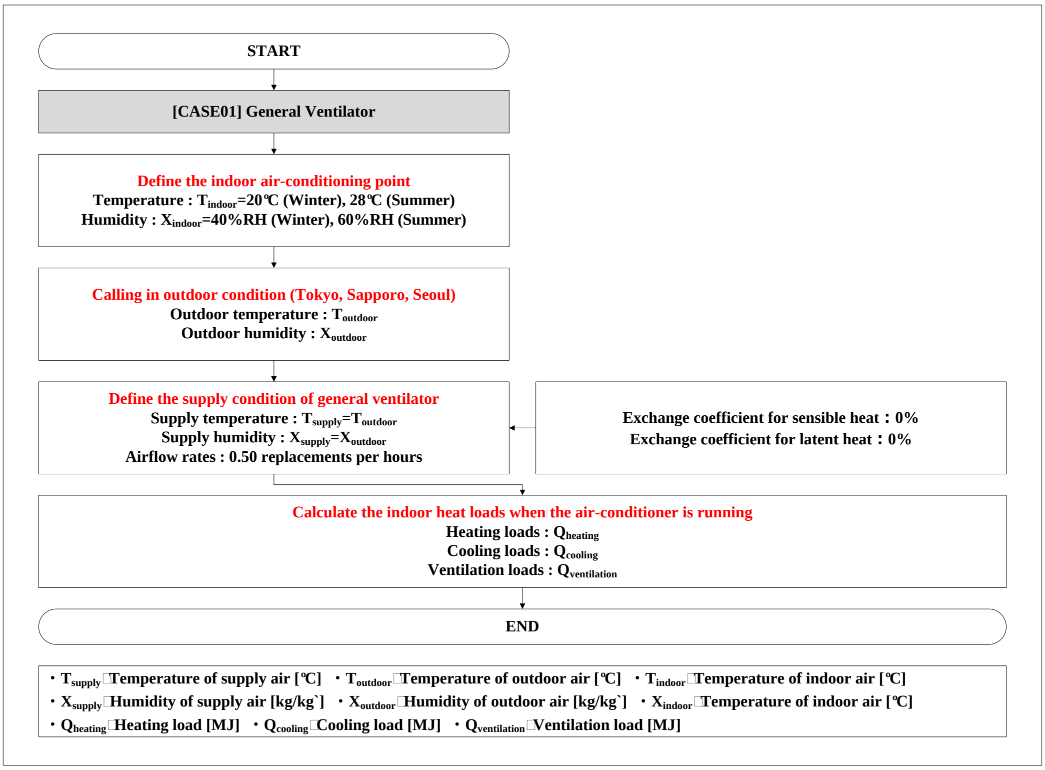


Fig. 3 (a) Flowchart of calculation (Case 1)

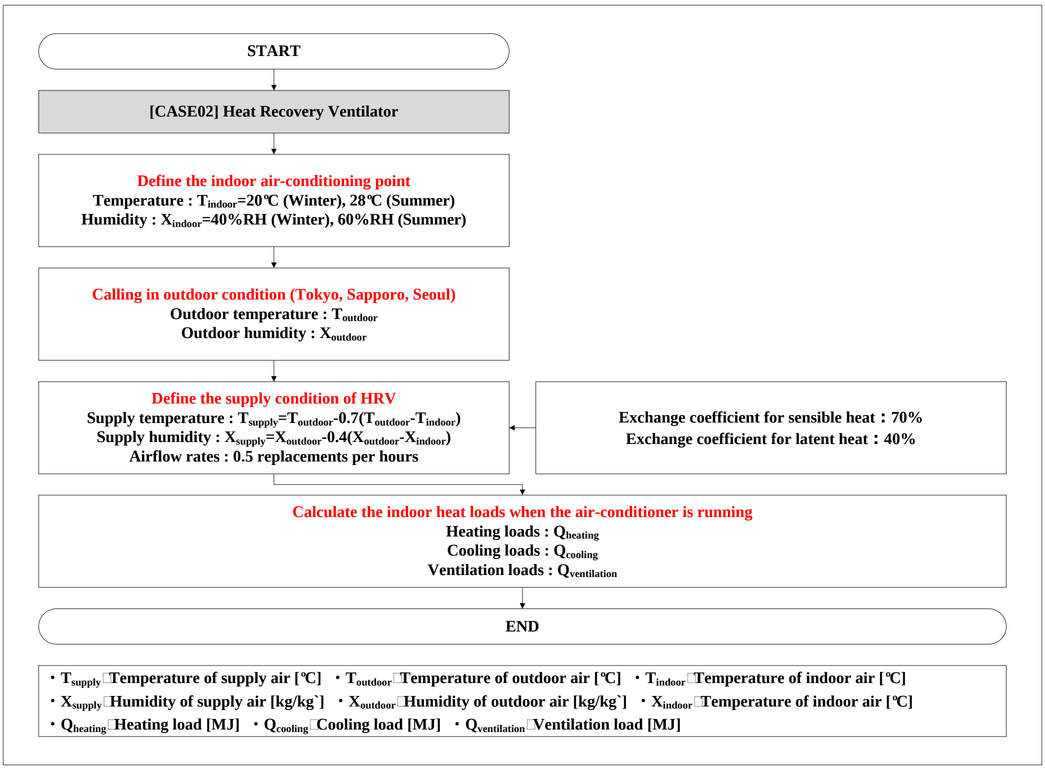


Fig. 3 (b) Flowchart of calculation (Case 2)

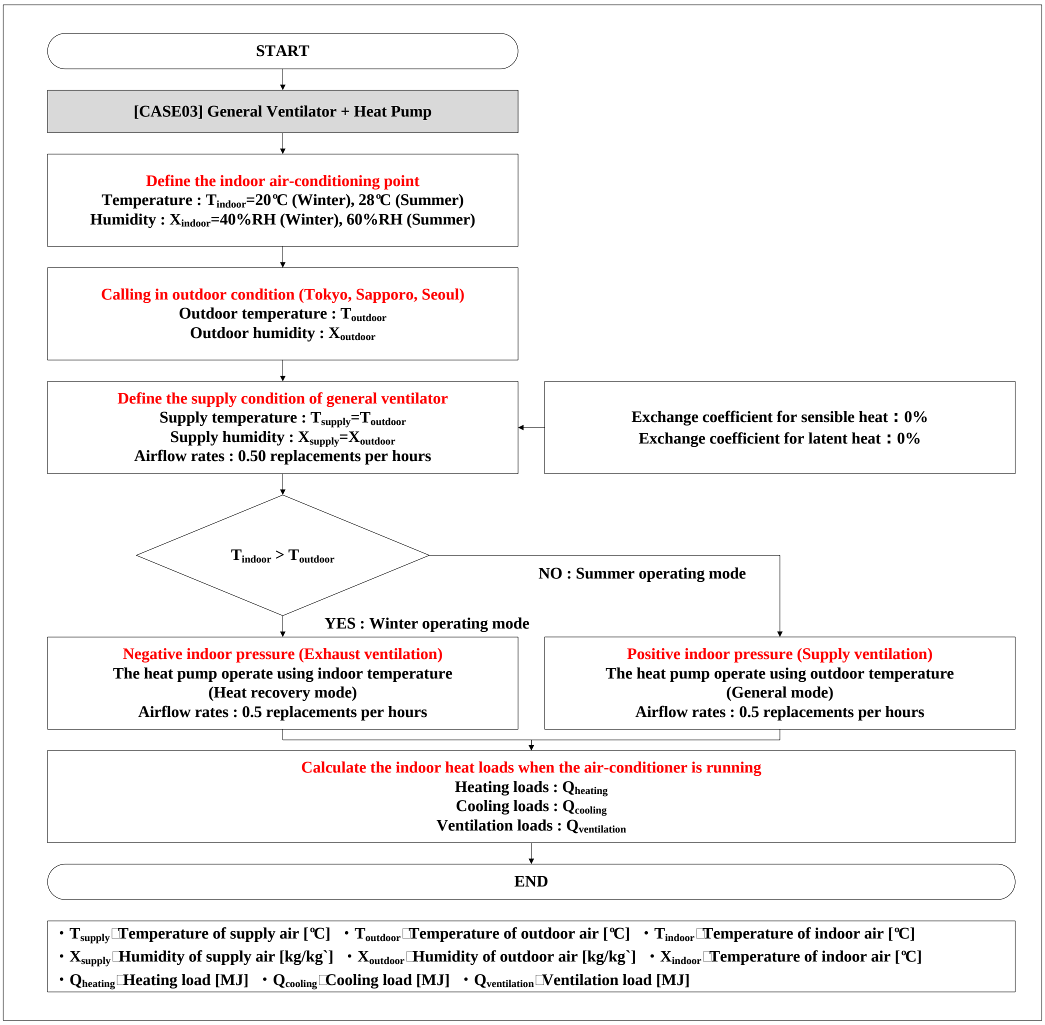


Fig. 3 (c) Flowchart of calculation (Case 3)

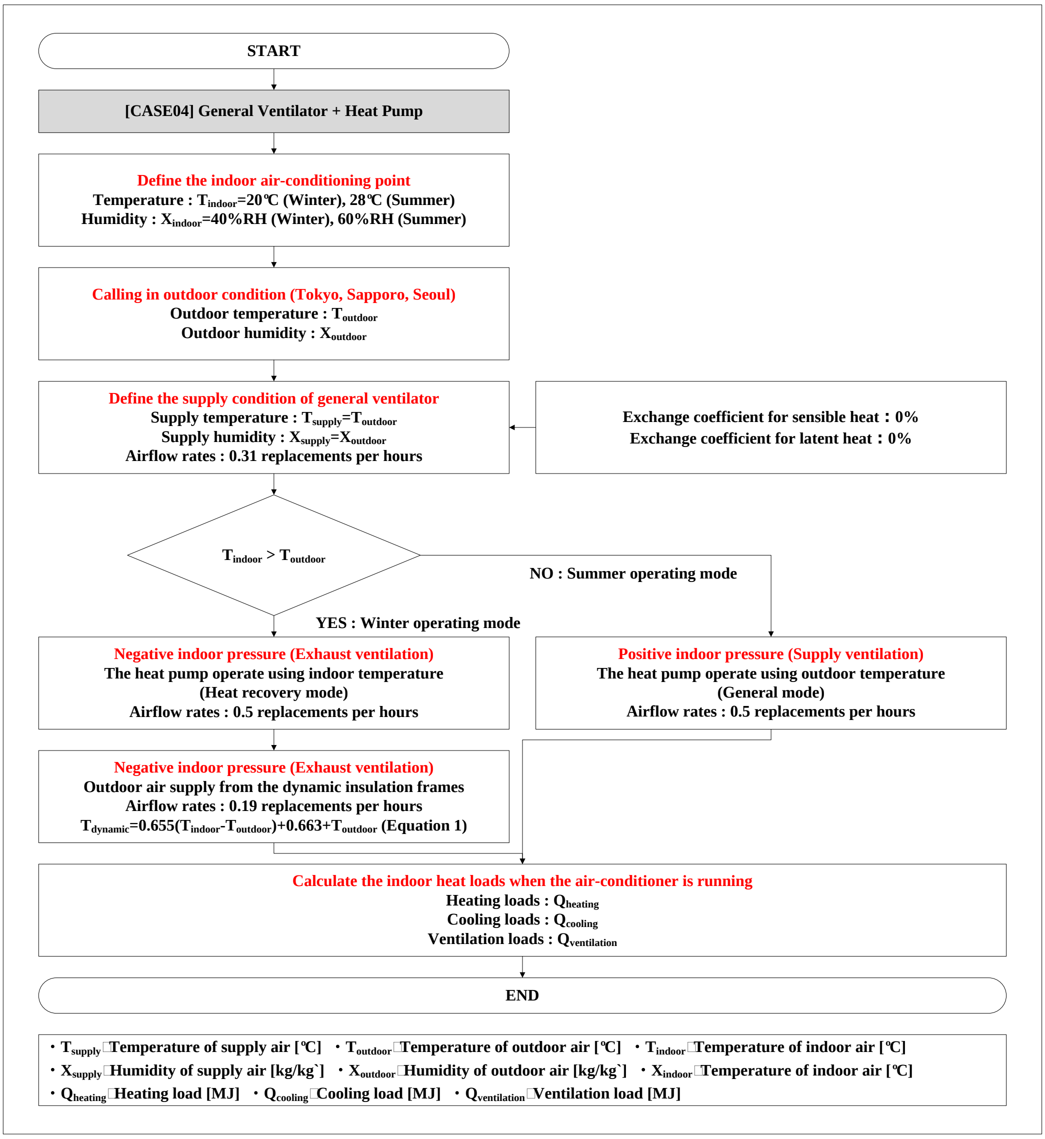


Fig. 3 (d) Flowchart of calculation (Case 4)

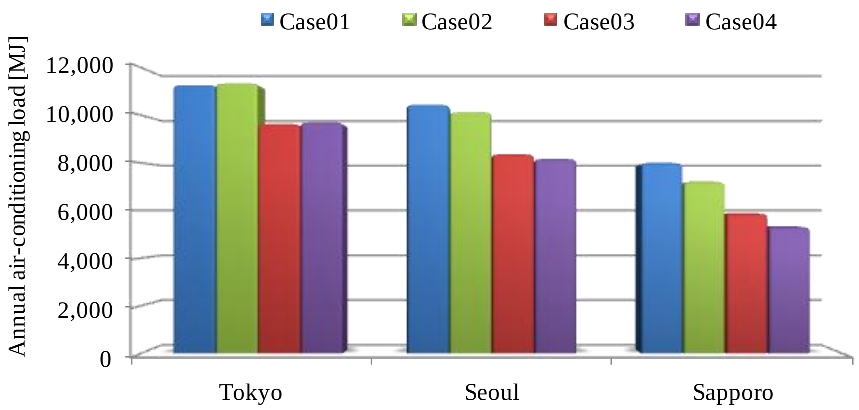
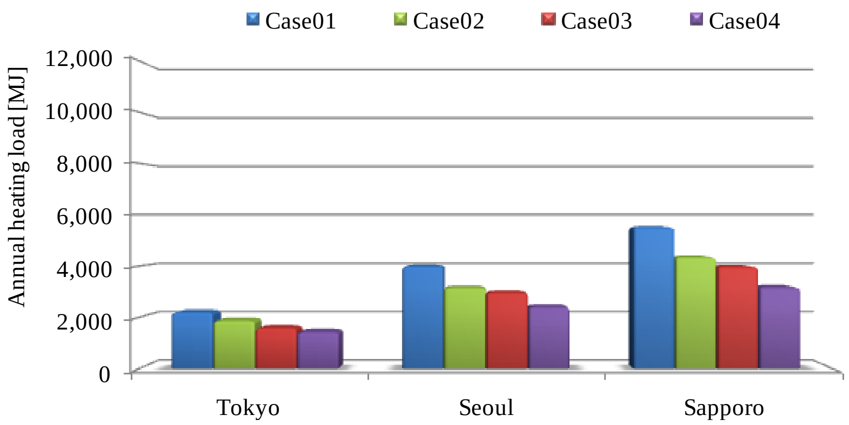
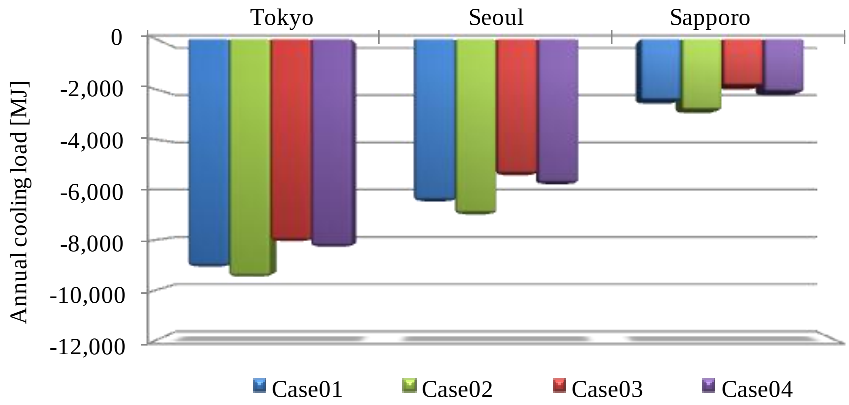


Fig. 4 Annual air-conditioning loads of each case

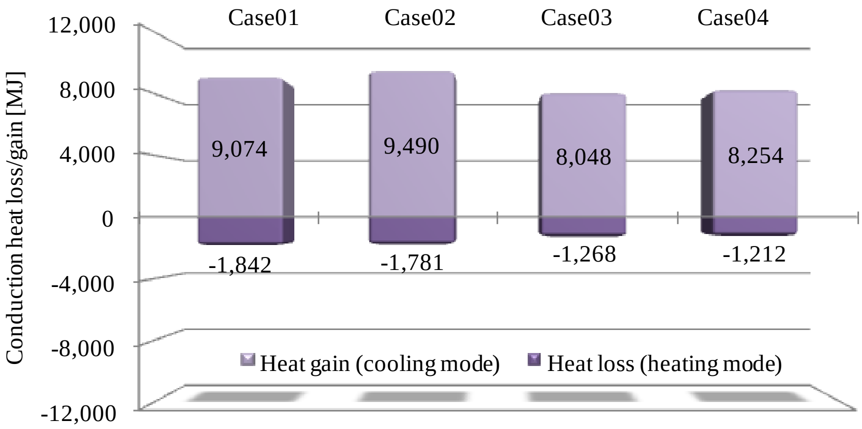


(a) Annual heating load

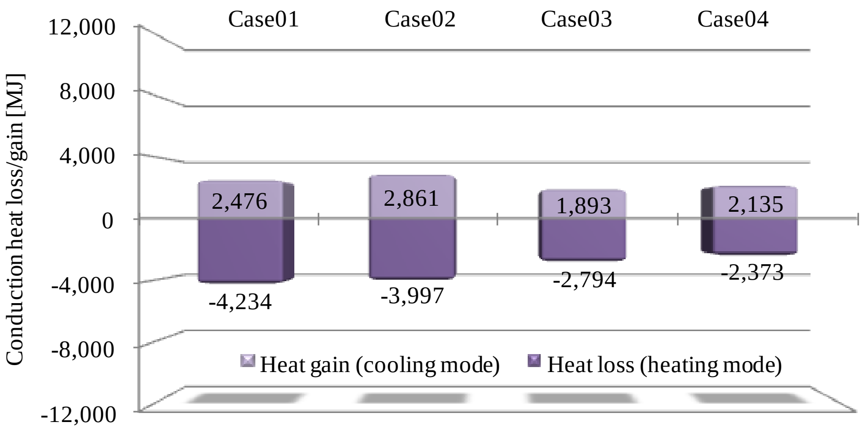


(b) Annual cooling load

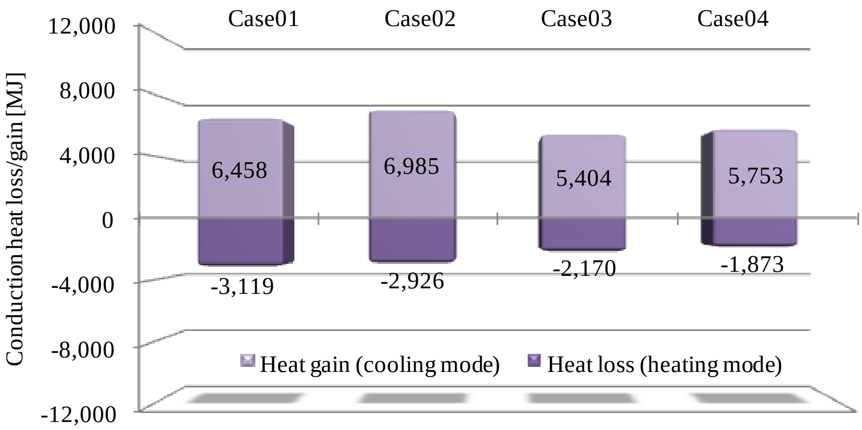
Fig. 5 Annual heating/cooling loads



(a) Tokyo, Japan

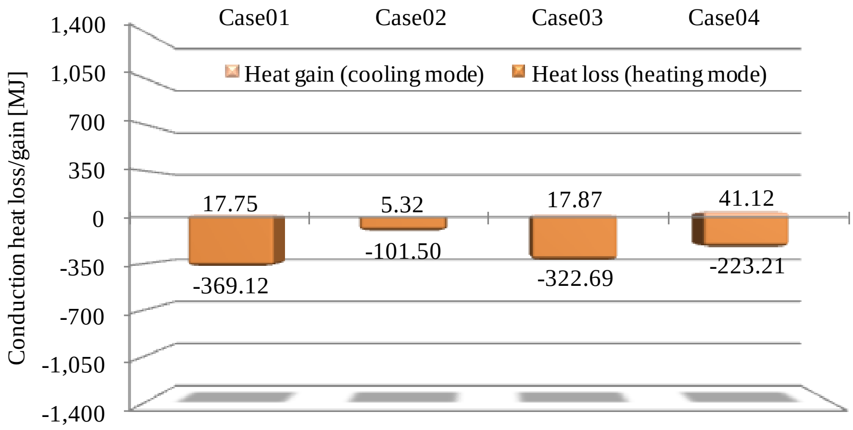


(b) Seoul, Korea

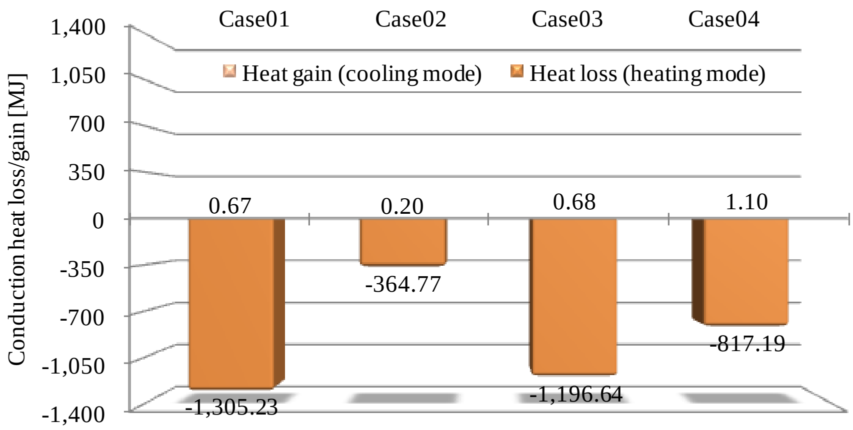


(c) Sapporo, Japan

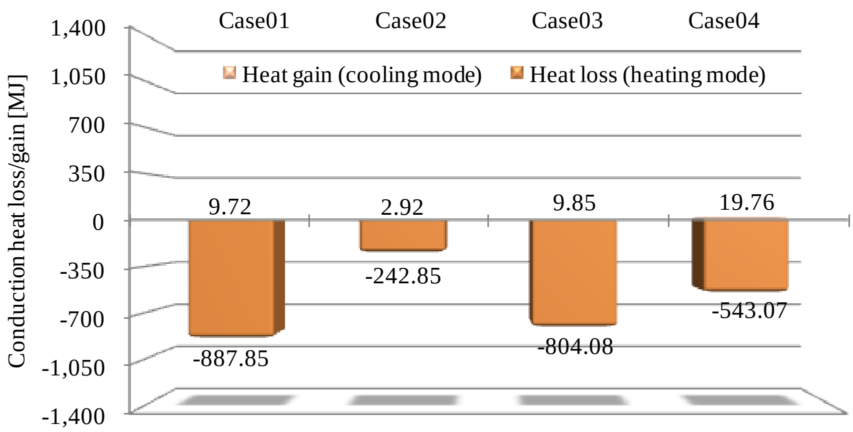
Fig. 6 Air-conditioning load due to heat conduction



(a) Tokyo, Japan



(b) Seoul, Korea



(c) Sapporo, Japan

Fig. 7 Air-conditioning load due to ventilation

Table 1 Calculated cases

Case1	General ventilator	○
	Heat recovery ventilator	×
	Heat pump system	×
	Dynamic insulation	×
Case2	General ventilator	×
	Heat recovery ventilator	○ (with 70% efficiency)
	Heat pump system	×
	Dynamic insulation	×
Case3	General ventilator	○
	Heat recovery ventilator	○ (with 70% efficiency)
	Heat pump system	○ Returning air : exhaust air from living room Mixed air : exhaust air from living room
	Dynamic insulation	×
Case4	General ventilator	○
	Heat recovery ventilator	×
	Heat pump system	○ Returning air : exhaust air from living room Mixed air : exhaust air from living room
	Dynamic insulation	○ (applied only to the window frames)

Table 2 Boundary conditions of building envelopes

	U-value [W/(m^2·K)] (building envelope)			
	Floor	Tatami [7]	Wall	Ceiling
Tokyo	0.403	0.344	0.385	0.294
Sapporo	0.208	0.191	0.254	0.167
Seoul	0.208	0.191	0.254	0.167

Table 3 Boundary conditions of windows

(a) B.C. of living room

<table>
<tr><th rowspan="3"></th><th>Glazing</th><th colspan="3">Window frame</th><th>Shading</th></tr>
<tr><th rowspan="2">U-value [W/(m²·K)]</th><th colspan="2">U-value [W/(m²·K)]</th><th rowspan="2">Area rate [%]
(frame/window)</th><th rowspan="2">Internal
shad. factor</th></tr>
<tr><th>Case 1, 3</th><th>Case 4</th></tr>
<tr><td>Tokyo</td><td>2.54</td><td rowspan="3">5.68</td><td rowspan="3">0.00</td><td rowspan="3">15.00</td><td rowspan="3">0.50</td></tr>
<tr><td>Sapporo</td><td>1.26</td></tr>
<tr><td>Seoul</td><td>1.26</td></tr>
</table>

(b) B.C. of the other room

<table>
<tr><th rowspan="2"></th><th>Glazing</th><th colspan="2">Window frame</th><th>Shading</th></tr>
<tr><th>U-value [W/(m²·K)]</th><th>U-value [W/(m²·K)]</th><th>Area rate [%]
(frame/window)</th><th>Internal
shad. factor</th></tr>
<tr><td>Tokyo</td><td>2.54</td><td rowspan="3">5.68</td><td rowspan="3">15.00</td><td rowspan="3">0.50</td></tr>
<tr><td>Sapporo</td><td>1.26</td></tr>
<tr><td>Seoul</td><td>1.26</td></tr>
</table>

Table 4 Boundary conditions for CFD simulation

Indoor temperature	22 [^{o}C]
Outdoor temperature	0, -2, -4, -6, -8, -10, -12, -14, -16, -18, -20 [^{o}C]
Indoor/outdoor pressure difference	-10 [Pa]
Porosity of insulation material	0.5 [-]
Area of porous material	0.0816 [m^2]
Velocity of porous material	0.002 [m/s]

Table 5 Schedule

(a) Family schedule

Room	Day		Occupants											
		AM	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
		PM	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
LDK	Weekly	AM							1	2	1	1		
		PM	1	1			1	2	2	3	3	2	1	1
	Weekend	AM									3	2	2	2
		PM	2	1			2	3	3	4	2	2	1	
Children room	Weekly	AM	1	1	1	1	1	1	1					
		PM									1		1	1
	Weekend	AM	1	1	1	1	1	1	1	1	1	1	1	1
		PM					1	1	1		1	1	1	1
Children room 2	Weekly	AM	1	1	1	1	1	1	1					
		PM							1			1	1	1
	Weekend	AM	1	1	1	1	1	1	1	1		1	1	1
		PM	1								1	1	1	1
Bed room	Weekly	AM	2	2	2	2	2	2	1					
		PM												1
	Weekend	AM	2	2	2	2	2	2	2	1				
		PM												2

(b) Air-conditioning schedule

Room		Preset temperature	
		Heating mode	Cooling mode
Living rooms	Wake time	20℃	27℃ / 60%
	Sleep time	-	28℃ / 60%
	Unused time	-	-
The other rooms		-	-

※ Living rooms : LDK(Living, Dinning, Kitchen), Japanese room, Children room, Bed room

(c) Equipment (ventilator) schedule

Room	Day	Supply / Exhaust air flow [m^3/h]												
		AM	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
		PM	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
Kitchen	Weekly	AM							75					
		PM	75						150	150				
	Weekend	AM						150			75			
		PM	75						150					
1F Rest room	Weekly	AM							6	2		0.8		
		PM	0.8				0.8	0.8	0.8	0.8	0.8	2.0		2.8
	Weekend	AM								4.0	4.0		1.2	1.2
		PM					2.0	0.8		2.0	0.8		2.0	0.8
Bath room	Weekly	AM												
		PM										50	25	100
	Weekend	AM												
		PM						75	25			25	25	100

Table 6 Annual air-conditioning load relative to Case 1

	Case 1	Case 2	Case 3	Case 4
Tokyo	100%	102%	85%	86%
Seoul	100%	97%	80%	78%
Sapporo	100%	90%	73%	66%