Energy Saving Performance of Buoyancy-Driven Natural and Hybrid Ventilation

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ABSTRACT

This paper presents the energy saving performance of buoyancy-driven natural and hybrid ventilation on simulations, and design methods to achieve effective energy saving without operational problems. Studies were conducted using two methods: 1) fact-finding survey on the existing naturally ventilated buildings in Japan, 2) simulation analysis of natural ventilation and hybrid ventilation system by "The BEST program", an integrated energy simulation tool for building and MEP system. The survey results showed a system design in existing naturally ventilated buildings. The simulation results indicated the influence of control method and system design on total operating hours and heat-load removal rate of natural ventilation. In conclusion, a control method of natural and hybrid ventilation in accordance with natural ventilation opening area and the operational issues for natural ventilation and hybrid ventilation are presented.

INTRODUCTION

The natural ventilation building design is now experiencing widespread application even for large office buildings. Natural ventilation systems have attracted increased attention as a means to realize a sustainable and resilient society and as a strategy for zero-energy building (ZEB) and business continuity planning (BCP).

In Japan, which is a hot and humid country, hybrid ventilation and switching control between natural ventilation and mechanical air conditioning have been introduced in many cases. However, the air conditioning energy saving effect of such a natural ventilation system has not been investigated. Therefore, this paper describes a natural ventilation system in Japan, evaluates the energy saving effect when using a combination of natural ventilation and mechanical air conditioning in the intermediate term through energy simulation, and presents a method to improve the energy saving effect. In the case study, we investigated the specifications of the natural ventilation system, natural ventilation permission condition, and ventilation control method in many existing buildings. We also derived the input conditions of the simulation to obtain generally reasonable results in an actual building. Results indicate that in a standard office building with a central heat source type air conditioning system, the cooling energy consumption was reduced by 13% for a ventilation area of 40 cm^2/m^2. In addition, we show that opening area ratio control, hybrid ventilation system, and improvement of the partial load efficiency of the air-conditioning system are effective in realizing the energy saving effect.

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Natural ventilation system in Japan

We conducted a survey on designers, managers, and owners of 72 natural ventilation buildings selected from Japanese literature. Figure 1 shows the percentage of building types with existing natural ventilation. The largest number of cases was the office building (Headquarter), which requires a high-quality work environment. There were 26 cases of offices, including tenant buildings. In addition, government offices often refrain from using air-conditioning systems during the interim period for the purpose of energy conservation; therefore, many properties have introduced natural ventilation. The ratio of adopting the control method of natural air supply and exhaust opening by application is shown in Table 1. In high-grade office buildings (Headquarter), it was verified that both natural air supply and exhaust openings were controlled automatically to realize energy savings and cooperative control between natural ventilation and mechanical air conditioning was implemented. In other building types, the supply opening introduced was mostly manual control by occupants, the exhaust opening introduced was automatic control according to natural ventilation operating condition and remote switching control by a facility operator.

The analysis results of energy conservation effects assumed by designers is presented in Table 2. The assumed median of the annual natural ventilation operating time was 500 h, while the average annual natural ventilation operating time was assumed to be 966 h. In addition, the air conditioning consumption energy reduction rate was assumed to be 10% in the median value and 15.1% in the average value, which ranged from 0.83% to 100% for each case. It was observed that the assumed suitable natural ventilation period was from April to June in the spring and from September to November in the fall.

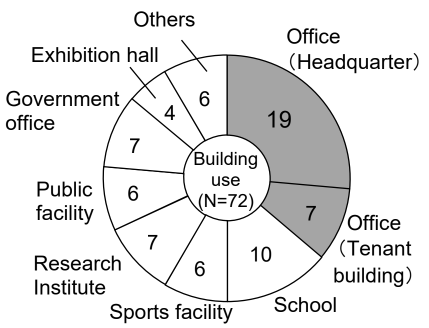


Figure1. Percentage of building type of existing natural ventilation buildings

Table1. Ventilator control methods by building type

Ventilator control method (supply / exhaust)	Building type				
	Office headquarter	Government office	School	Research Institute	Sports facility
Manual / Manual	2	1	2	4	0
Manual / Remote	0	2	1	0	2
Manual / Automatic	2	0	1	1	0
Manual / Always open	0	1	3	0	0
Remote / Remote	0	0	0	0	4
Automatic / Automatic	12	1	3	2	1
Others	3	0	0	0	1

Table2. Energy saving effect assumed at design phase (N=72)

	Energy saving rate of building [%]	Energy saving rate of air conditioning [%]	Annual operating time of natural ventilation	natural ventilation suitable period
Designer Questionnaire Result	0.1～9.0 median 3.0 average 3.4	0.83～100 median 10.0 average 15.1	100～8670 median 500 average 966	Apr. May. Jun. Sept. Oct. Nov.

Control Strategy Overview

The control flow in the natural ventilation system in Japan (Case A) is shown in Figure 2. A natural ventilation system diagram of the case is shown in Figure 3. It shows a natural ventilation system introduced to the Atrium Lounge, and automatic control of the ventilation opening was linked with mechanical air conditioning in consideration of labor management and reliable energy saving. As shown in Figure 2, natural ventilation was controlled only when the room temperature was lower than the set temperature (28 °C) under outside air conditions suitable for natural ventilation, and when the room temperature exceeds the set value, natural ventilation was discontinued and the air conditioning system was turned on.

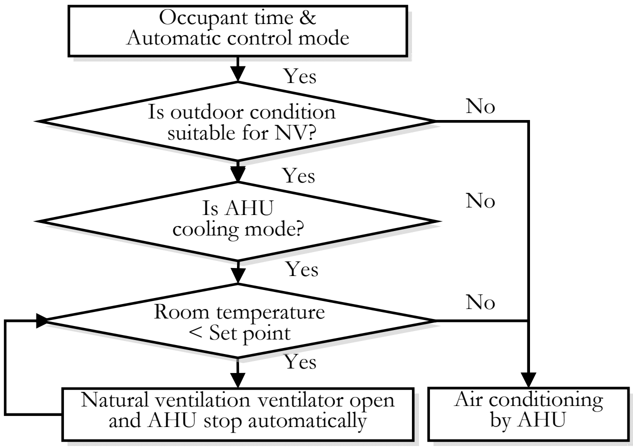


Figure2. An example of automated control flowchart (Case A)

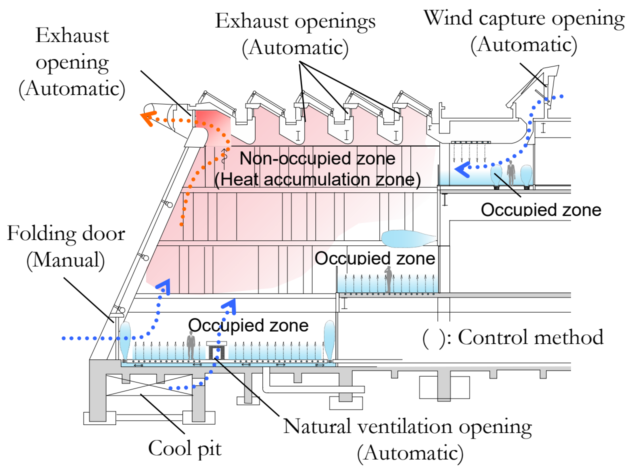


Figure3. An example of natural ventilation system (Case A)

We analyzed the criteria for outdoor conditions for operating natural ventilation openings. To achieve both energy savings and a comfortable indoor environment, it is important to determine the criteria for outdoor air conditions for introducing natural ventilation. The criteria for switching to natural ventilation was investigated in 42 buildings. Table 3 presents the trigger conditions for switching to natural ventilation. Rainfall was the most adopted trigger condition, followed by outside air wind speed, outside air temperature, and outside air enthalpy. In an actual building, a combination of these conditions was used as a scheme for operating natural ventilation. Figure 4 shows two schemes adopted by many buildings for controlling outside air temperature and humidity.

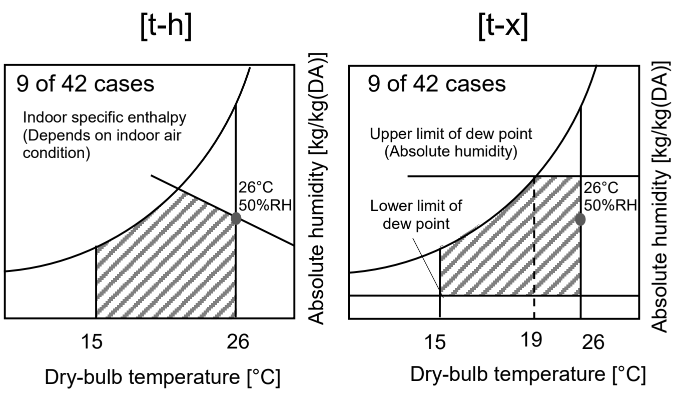


Figure 4. General ventilation opening conditions about outdoor air

Table 3. Trigger conditions for switching to natural ventilation

Conditions	Buildings
No rain	36
Upper wind velocity ≤ trigger point	35
Outdoor temperature within trigger range	33
Outdoor enthalpy < Room enthalpy	21
Outdoor temperature < Room temperature	18
Room temperature within trigger range	12
Dew point within trigger range	10
Relative humidity within trigger range	6

The scheme labeled [t-h] is the decision based on the outdoor air temperature (t) and a comparison of the indoor and outdoor enthalpy (h). The scheme labeled [t-x] is the decision based on the outdoor air temperature (t) and the dew point temperature (x). The set values described in the figure were derived as appropriate set values from the average values of the cases. As a result of evaluating each scheme using weather data (Tokyo, 9:00–18:00), the total operating time to switch to natural ventilation was 972 h for [t-h] and 1,010 h for [t-x].

Evaluation of energy saving effect by simulation program

From the case study of the natural ventilation system in Japan, we derived a standard natural ventilation building model with a control method that assists natural ventilation with machine air conditioning including hybrid ventilation. To evaluate the energy saving performance of a buoyancy-driven natural and hybrid ventilation, we used "The BEST program," an integrated energy simulation tool for building and MEP system, as simulation tools. The BEST program was developed in Japan and calculation algorithms have been described in published papers (H. Ishino et al. 2017).
A plan of the model building is shown in Figure 5, and the model building outline is presented in Table 4. The building was an open office without partitions, and the target room was the south side office on the second floor. The building height was set at 42 m, and the height difference of the target room from the neutral pressure plane was set at 20 m. The evaluation time of natural ventilation was set to 9:00 to 18:00 in the daytime and a schedule considering the holidays was implemented. In the program, the basic equation of temperature difference ventilation was used, assuming that the room temperature of the target room was the same as the temperature of the shaft, and the position of the neutral pressure plane was at 2/3 of the building height. In addition, the input value of the ventilation opening area was only the supply side, and the temperature difference ventilation air volume was calculated from the height difference (h_{NPL} - h_i) between the supply side and the supply opening area. In this program, wind-driven ventilation can be calculated by inputting an opening on the outer wall by orientation; however, in this study, only the temperature difference ventilation was evaluated. For details of the calculation method, refer to published papers (K. Kohri et al. 2014, 2017).

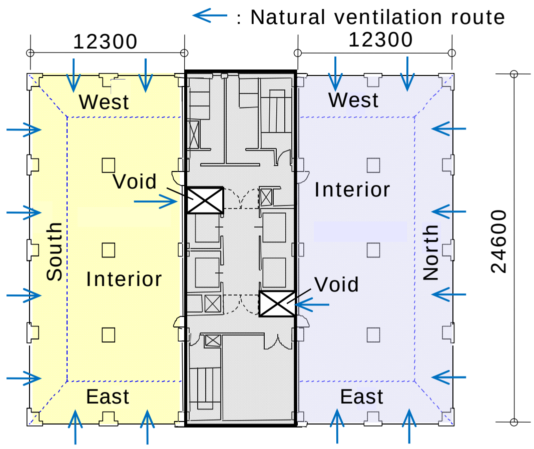


Figure 5. Plan of the model building

Table 4. Model building outline

Outline of building	Building type: office, Number of stories: 10 floors, Building height: 42 m, Floor height: 4.2 m, Ceiling height: 2.8 m
Blind	Intermediate color blind
Glass	Solar radiation shielding type Low-ε transparent multilayer glass (8 mm+A6 mm), Glass ratio to outer wall 60%
Outer wall	Plaster board 0.008, Non-sealed air layer, Extruded Polystyrene foam insulation 0.025, Ordinary concrete 0.15, Mortar 0.002, Tile 0.008 [m]
Inner wall	Mortar 0.0025, Ordinary concrete 0.15, Mortar 0.0025 [m]
Others	Personnel density 0.15 person/m^2, Light heat gain 10 W/m^2, Equipment heat gain 15 W/m^2

Basic study on the relationship between opening area and operating time

First, a basic study was conducted to verify the relationship between the selection of the supply opening area and the operating time during which natural ventilation is possible. If the processing load Q_{vent_cool} [W] caused by natural ventilation was the same as the room cooling load H_{cool} [W], and outside air cooling was equal and in steady state during natural ventilation, then equation (1) holds from the general thermal equilibrium equation.

$$H_{cool} = Q_{vent\_cool} \qquad \cdots\cdots(1)$$

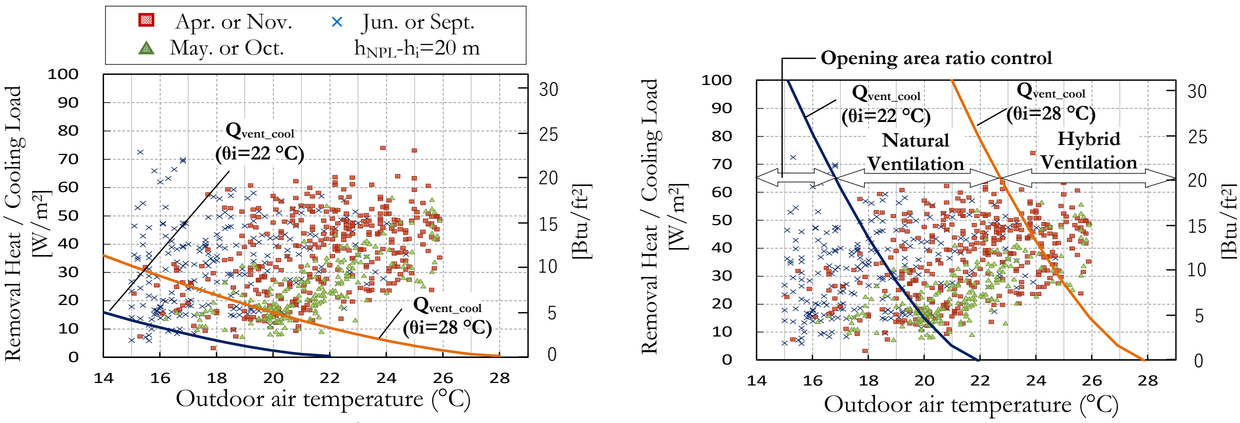
Q_{vent_cool} is caused by air volume of buoyancy-driven natural ventilation. V [m^3/s] is obtained as described below.

$$Q_{vent\_cool} = C_p \rho V \Delta\theta \qquad \cdots\cdots(2)$$

$$V = C_d A \sqrt{2g(h_{NPL} - h_i)\frac{\Delta\theta}{\theta_i}} \qquad \cdots\cdots(3)$$

where C_p is the specific heat of air [J/kgK], ρ is the air density [kg/m³], $\Delta\theta$ is the air temperature difference between indoor and outdoor environment [°C], C_d is the discharge coefficient, A is the ventilator opening area [m²], g is the gravitational acceleration [m/s²], h_{NPL} is the height from the ground to neutral pressure plane [m], h_i is the height from the ground to midpoint of the opening [m], and θ_i is the outdoor temperature [°C].

Q_{vent_cool} when the area of the ventilation opening is set to 5 cm²/m² and 40 cm²/m², then, the hourly cooling load H_{cool} due to heat load are shown in Figure 6. For Q_{vent_cool}, the acceptable room temperature range during natural ventilation was 22–28 °C. H_{cool} is the load at a time suitable for natural ventilation of outdoor air condition. The cooling load in the intermediate period in the calculation model was mostly distributed to 60 W/m² or less. For a ventilation area of 40 cm²/m², it can be seen that the room temperature was lower than 22 °C in the low load region where the outside air temperature was 18 °C or less, and it is necessary to narrow the ventilation port area. However, for an opening area of 5 cm²/m², it can be seen that overheating occurs in many time zones. Therefore, to maximize the number of hours of natural ventilation, it is effective to control the opening area automatically (opening ratio control) by a large ventilation area (40 cm²/m² or more) using the lower limit room temperature as a parameter. Further, for overheating at room temperature above 28 °C, assistance for natural ventilation by mechanical air conditioning (hybrid ventilation) is required.



(a)C_dA=5 cm²/m²　　(b)C_dA=40 cm²/m²

Figure 6. Relationship between H_{cool} and $Q_{vent\text{-}cool}$

Effect of reducing cooling load by controlling opening area ratio and hybrid ventilation

Simulation studies on aperture ratio control and hybrid ventilation were conducted using the simulation program. The reduction in the cooling load due to natural ventilation is shown in Figure 7, while the natural ventilation time is shown in Figure 8. In the graph, "natural ventilation" is defined as a state in which the opening is fully open and mechanical air conditioning was not used. The graph of Figure 7 shows that the effect was low when the air supply opening area was 2–25 cm²/m² in the hybrid ventilation and the effect increased when the opening ratio control was 25 cm²/m² or more. This was similar to reducing the cooling load and natural ventilation time. When the opening ratio control and hybrid ventilation were combined, the processing load was 14–147 MJ/m² and largely fluctuating depending on the effective opening area of the air supply port, against a total room load of 179 MJ/m² in the intermediate period. In addition, for "natural ventilation" alone the processing load was 1–54 MJ/m².

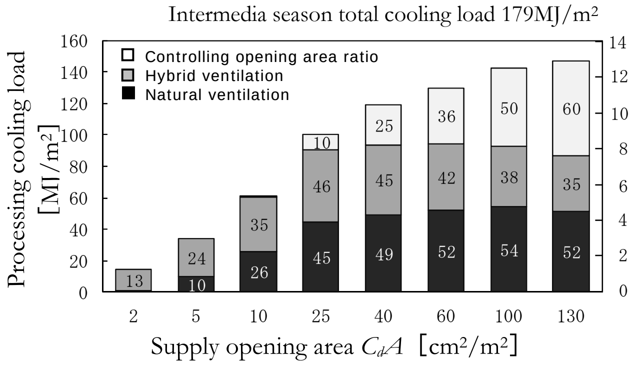


Figure7. Reducing cooling load by natural ventilation with opening area control and hybrid ventilation

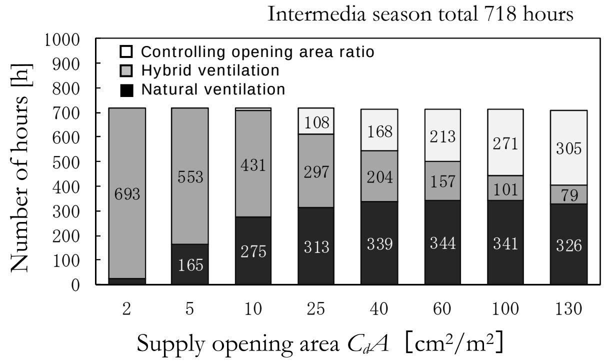


Figure8. Number of hours by natural ventilation with opening area control and hybrid ventilation

Energy Saving effect of Hybrid Ventilation

We evaluated the effect of reducing air conditioning energy consumption by hybrid ventilation in a building with a central heat source type air conditioning system installed. Figure 9 shows the evaluated air conditioning system model, while Table 5 lists equipment specifications of the air conditioning system. The heat source was an air-cooled heat pump chiller, and air handling unit was introduced to each of the interior and the perimeter. The minimum outside air volume was calculated as 630 m³/h (2 m³/(h·m²) per floor area) and the minimum air volume and the supply air flow rate of the air conditioner were calculated from the peak cooling load with a temperature difference of 10 °C. The lower limit value of the perimeter supply air flow rate was assumed to be 1,000 m³/h, assuming the lower limit of the VAV control to be 15%. The effective opening area C_dA of the natural ventilation opening of the perimeter was set to 40 cm²/m². Table 6 presents simulation case. The parameters of the simulation were the ventilation area and the fresh air lower limit temperature of trigger conditions for switching to natural ventilation. The evaluation period was from April to November when heating load did not occur.

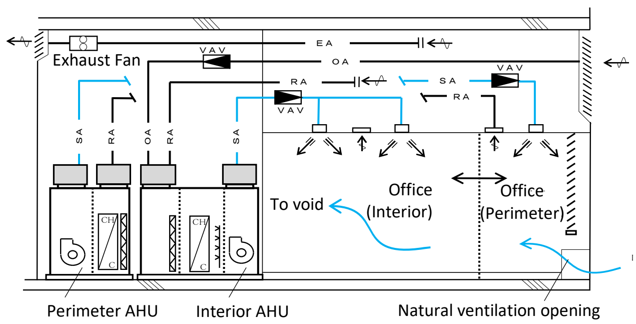


Figure 9. Diagram of air conditioning system

Table 5. Outline of air conditioning system

Component	Specification
Heat source	Air-cooled heat pump chiller, cooling/heating capacity 55 kW, Power consumption 13.5 kW
Interior AHU	Two pipe/VAV system, Water volume 23 L/min, Outdoor air volume 680 m³/h, Supply air volume 4,200 m³/h (Minimum 630 m³/h)
Perimeter AHU	Four pipe/VAV system, Water volume 32 L/min, Supply air volume 6,400 m³/h (Minimum 1,000 m³/h)

Figure 10 shows the cooling load reduction effect by natural ventilation in each case. "Natural ventilation" of the reference case was 23.4% reduction in the cooling load compared with air conditioning. In the case where the opening area was double (80 cm²/m²), the cooling load reduction rate was 25.7%, and there was no significant difference compared with the reference case. However, when the opening area was half (20 cm²/m²), the reduction rate significantly decreased. In addition, the reduction rate decreased by 2.1% when the lower limit outdoor temperature was lowered to 13 °C, and decreased by 4.6% when this temperature increased to 18 °C.

Table 6. Simulation case

Case	Outline
AC	Cooling is performed with only AHU
NV (Reference)	Hybrid ventilation, Supply opening area: 40 cm²/m², Lower limit of outdoor temperature: 15 °C
Double open	Hybrid ventilation, Supply opening area: 80 cm²/m², Lower limit of outdoor temperature: 15 °C
Half open	Hybrid ventilation, Supply opening area: 20 cm²/m², Lower limit of outdoor temperature: 15 °C
Limit 18 °C	Hybrid ventilation, Supply opening area: 40 cm²/m², Lower limit of outdoor temperature: 18 °C
Limit 13 °C	Hybrid ventilation, Supply opening area: 40 cm²/m², Lower limit of outdoor temperature: 13 °C

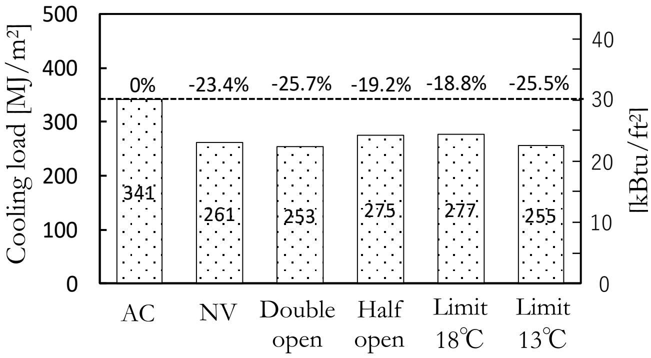


Figure 10. Cooling load reduction effect

Figure 11 shows the air conditioning primary energy consumption of the hybrid ventilation from April to November. The primary energy is obtained by multiplying the electric power by 9.76 MJ/kwh. Based on the air conditioning case, the energy saving effect was 10.7–14.2% when natural ventilation was used in combination with the air conditioning system. Compared with the cooling load reduction effect of Figure 10, the reduction rate of the cooling primary energy consumption was decreased by approximately 10% even for the same case. We examined the influence of partial load characteristics of the air conditioning system on energy saving effect on the standard case. Figure 12(a) shows the results when the lower limit value of the VAV air volume was changed from 15% to 30%. Figure 12(b) shows the result when the heat source capacity was twice the peak load and the power consumption of the heat source partial load of 25% or less was made constant. Compared with an energy consumption reduction rate of 13% in the reference case, the energy saving effect by natural ventilation was greatly reduced in air conditioning systems with low partial load efficiency. The main reason for this difference appears to be the low efficiency of the air conditioning system at partial cooling heat load. Therefore, it was found that in order to achieve further energy saving, the air conditioning system can be used with a higher partial load efficiency, or to stop the air conditioning system using appropriate control during natural ventilation. Furthermore, to improve partial load efficiency, improvements in the outer skin performance seems to be effective.

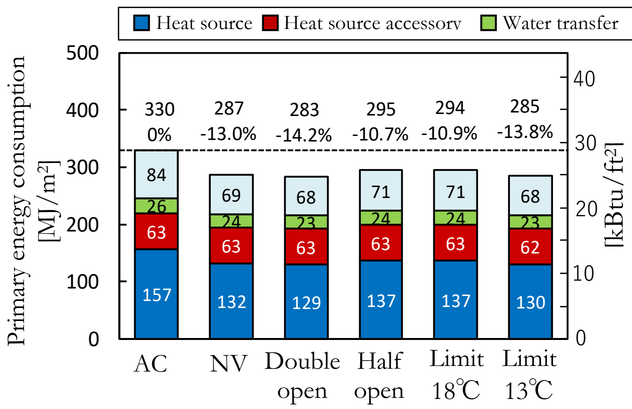


Figure 11. Primary energy consumption

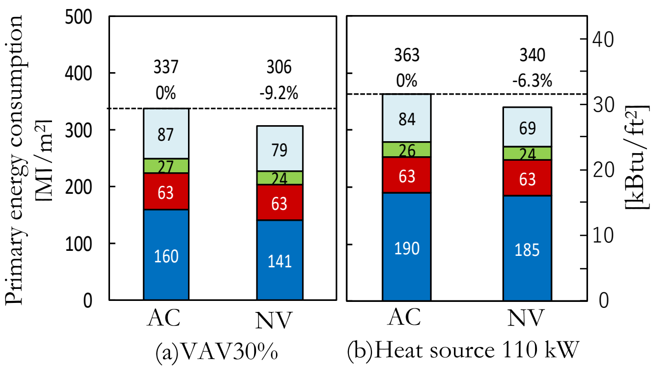


Figure 12. Influence of partial load characteristics of air conditioning system on energy saving

CONCLUSION

In this study, we investigated the actual state of a natural ventilation system in Japan and showed energy conservation effect in buoyancy-driven natural ventilation using "The BEST Program." Results indicate that in a standard office building where the central heat source type air conditioning was implemented, the cooling energy consumption reduction was 13% for a ventilation area of 40 cm^2/m^2. In order to secure this energy saving effect in an actual building, in addition to the construction of an air conditioning system with high partial load efficiency, suppression of peak load due to high outer skin performance, securing adequate ventilation port area, aperture ratio control, and hybrid air conditioning were introduced.

ACKNOWLEDGMENTS

The fact-finding survey on the existing naturally ventilated buildings is the collaborated study by M. Kuboki, H. Suzuki and Prof. S. Tanabe, Waseda University. The authors would like to thank all the members of the program consortium and Institute for Building Environment and Energy Conservation for their contribution.

NOMENCLATURE

H_{cool}	=	Internal heat generation, heat transmission and solar heat gain
Q_{vent_cool}	=	heat extraction at the buoyancy-driven natural ventilation
$\Delta\theta$	=	temperature difference between indoor and outdoor
C_p	=	specific heat of air
ρ	=	density of air
V	=	ventilation volume
C_d	=	discharge coefficient
θ_i	=	room temperature
h_i	=	height from ground to ventilation opening
h_{NPL}	=	height from ground to neutral pressure plane

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