Performance Evaluation of Energy-Efficient Hybrid Ventilation Systems for Office Buildings

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ABSTRACT

The present paper evaluates the thermal load reduction of air-handling equipment achieved by energy-efficient hybrid ventilation systems for office buildings through simulations, using the program Building Energy Simulation Tool (BEST), a transient solver developed in Japan. The target ventilation systems are automatic control systems that integrate natural ventilation and mechanical ventilation, including air-side economizer control, demand control, and heat recovery control. In advance of the simulation analysis, a thermal load simulation method was proposed for the evaluation of energy-efficient hybrid ventilation systems. Simulations throughout the year for 836 cities in Japan and eight cities in the US were then performed, and the regional features of ventilation operation and the equipment load reduction achieved by energy-efficient hybrid ventilation systems were evaluated.

INTRODUCTION

Buildings have been improved to have high-performance facades for space thermal comfort and reduction of space heating and cooling load. Energy-efficient hybrid ventilation systems that include natural ventilation control and mechanical ventilation control, such as air-side economizer control, demand control, and heat recovery control, have become more important for buildings in attempting to achieve net-zero energy. Recently, based on a survey of natural ventilation and hybrid ventilation systems switching between natural ventilation and mechanical simple ventilation (Y. Yamamoto et al. 2017), the number of office buildings capable of natural ventilation has been increasing. Methods by which to design and control energy-efficient hybrid ventilation systems suitable for the climates of different regions and building thermal performance remain unclear.

The present study introduces a thermal load simulation method that can predict the equipment load for heating, cooling, and energy-efficient hybrid ventilation and evaluates the regional performance of ventilation operations and the thermal load reduction achieved by energy-efficient hybrid ventilation systems through simulations. Although the impacts of ventilation systems on productivity, air quality, and air age are interesting subjects, they are not considered in the present study.

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TARGET VENTILATION CONTROL TECHNIQUES

The target ventilation systems are automatic control systems that integrate natural ventilation control (hereafter " NV ") and mechanical ventilation control, including air-side economizer control (hereafter " EC "), demand control (hereafter " DC "), and heat recovery control (hereafter " HR "). Both EC and NV use the cooling effects of outdoor air. In contrast, DC and HR suppress these effects. Almost ideal energy-efficient control is assumed in the simulations. Each zone is also assumed to have an individual system for heating, cooling, and ventilation.

Several conditions are necessary for switching between the four ventilation control modes. Table 1 shows an example of the conditions. Switching to the NV mode requires the perimeter zone air conditions, in addition to the outdoor air conditions, to be satisfied. The openings for natural ventilation are automatically regulated to adjust zone air temperature to be close to the lower limit temperature. Whether natural ventilation can be carried out in parallel with cooling is selectable. If both NV and EC are enabled, then NV is turned on in preference to EC. In EC and NV, the lower limit of the zone air temperature can be set lower than the cooling set point temperature. Note that DC can operate only if EC is not in operation, even if DC operation causes an increase in thermal load. Moreover, HR is basically enabled only during heating or cooling operation, and heat recovery efficiency may be regulated in order to avoid heating in winter. The upper limit of the ventilation rate under EC and the lower limit of the ventilation rate under DC can be given as constant values.

Table 1. Example of the conditions necessary for switching between ventilation control modes

Natural ventilation control (NV)	Economizer control (EC)
● $t_O > 18^\circ\mathrm{C}\ (64^\circ\mathrm{F})$ during occupied hours $t_O > 15^\circ\mathrm{C}\ (59^\circ\mathrm{F})$ outside of occupied hours ● $t_{DP} < 19^\circ\mathrm{C}\ (66^\circ\mathrm{F})$ and $\varphi < 90\%$ ● $v < 10\ m/s\ (33\ ft/s)$ ● $t_Z > 24^\circ\mathrm{C}\ (75^\circ\mathrm{F})$, $t_Z > t_O$ and $h_Z > h_O$	● $t_O > 10^\circ\mathrm{C}\ (50^\circ\mathrm{F})$ ● $5^\circ\mathrm{C}\ (41^\circ\mathrm{F}) < t_{DP} < 19^\circ\mathrm{C}\ (66^\circ\mathrm{F})$ ● $t_Z > 24^\circ\mathrm{C}\ (75^\circ\mathrm{F})$, $t_Z > t_O$ and $h_Z > h_O$
Demand control (DC)	Heat recover control (HR)
● Economizer control is not performed.	● Airflow rate through a heat exchanger > 50% of the design rate ● $t_Z > t_O$ and $h_Z > h_O$ during heating operation ● $t_Z < t_O$ and $h_Z < h_O$ during cooling operation

*1 t_O, h_O, t_{DP}, φ, and v are the temperature, enthalpy, dew point temperature, relative humidity and wind velocity of outdoor air, respectively. t_Z and h_Z are the temperature and enthalpy of indoor air, respectively.

*2 In operation, the conditions are checked in the order listed in the table for each control mode.

*3 For NV, in addition to the above conditions, the condition that avoids NV during cooling operation can be set.

THERMAL LOAD SIMULATION METHOD

The present study proposes a simulation method that was developed by improving the existing thermal load simulation method (H. Ishino et al. 2017) in order to simulate the operation of energy-efficient hybrid ventilation systems and their effects on the indoor thermal environment and the thermal load of air-handling equipment. The calculation of natural ventilation is very simple. The airflow balance in a building need not be solved. The airflow resistances of inner partitions are ignored, and the height of the neutral pressure level is assumed to be 2/3 the building height. The pressure difference across a natural ventilation opening is estimated using the target zone air temperature at the previous time step. In the present study, the effect of wind is neglected. In the calculation of DC, the required ventilation rate is assumed to be proportional to the occupant presence ratio.

Simultaneous heat balance equations for zone air are solved by an implicit technique using the assumed ventilation rates. The balance between heat and ventilation is solved iteratively using the following procedure.

1. Judge which ventilation modes are allowed to be enabled based on the schedules and the outdoor conditions.
2. Assume the ventilation rate for each zone to be the minimum value that can be true. If the HR mode is allowed to be enabled, the equivalent ventilation rate is assumed, into which the effect of heat recovery efficiency is converted. Each of the sensible and latent heat balances between zones is solved.

3. Judge which ventilation modes are allowed to be enabled for each zone based on the indoor conditions, such as the lower limit of the zone air temperature and the difference between indoor and outdoor air enthalpies. If the ventilation control modes are fixed and the true ventilation rates are obtained for all zones, then finish the procedure.
4. Perform iteration. Assume the ventilation control mode and assume the ventilation rate according to the ventilation mode for each zone. The sensible heat balance between zones is then solved. If the true ventilation rates are obtained for all zones, then proceed to Step 5. In order to reduce the number of iterations, regulation of the ventilation rate in EC or NV is replaced regulation by a virtual heater with the maximum ventilation rate.
5. Solve the latent heat balance between zones using the obtained true ventilation rates.

The proposed thermal load simulation method enables simulations that require easy input conditions and is appropriate for examination of the control methods of energy-efficient hybrid ventilation systems.

PERFORMANCE OF ENERGY-EFFICIENT HYBRID VENTILATION SYSTEMS

Details of an Office Building and Ventilation Systems for Simulations

Simulations were conducted for the office floor shown in Figure 1. Each of the south and north rooms consists of three perimeter zones and one interior zone, and each zone is individually air conditioned. In the simulations, the spaces between two rooms are assumed to be a single core zone. The heat balance is solved between eight conditioned office zones and an unconditioned core zone. A total of 836 cities in Japan and eight cities in the US are selected as building locations, and Japanese typical weather data (H. Akasaka et al. 2003) and the US typical weather data (U. S. Department of Energy 2013) throughout the year are used for the simulations. Table 2 shows the conditions for the simulations. Five types of ventilation systems are assumed for the simulations. One is the base system, which constantly supplies the design outdoor airflow rate without any energy-efficient technique. The others, the EC, EC+NV, EC+NV+DC, and EC+NV+DC+HR systems, include one or more energy-efficient ventilation technique from among EC, NV, DC, and HR.

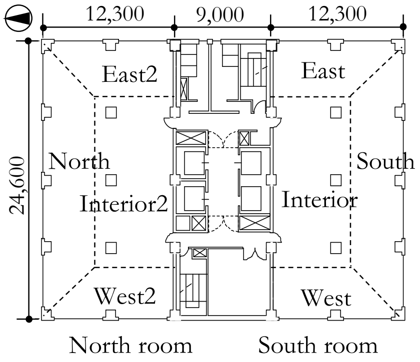


Figure 1 Floor plan of the subject office building. The second floor of a 10-story building

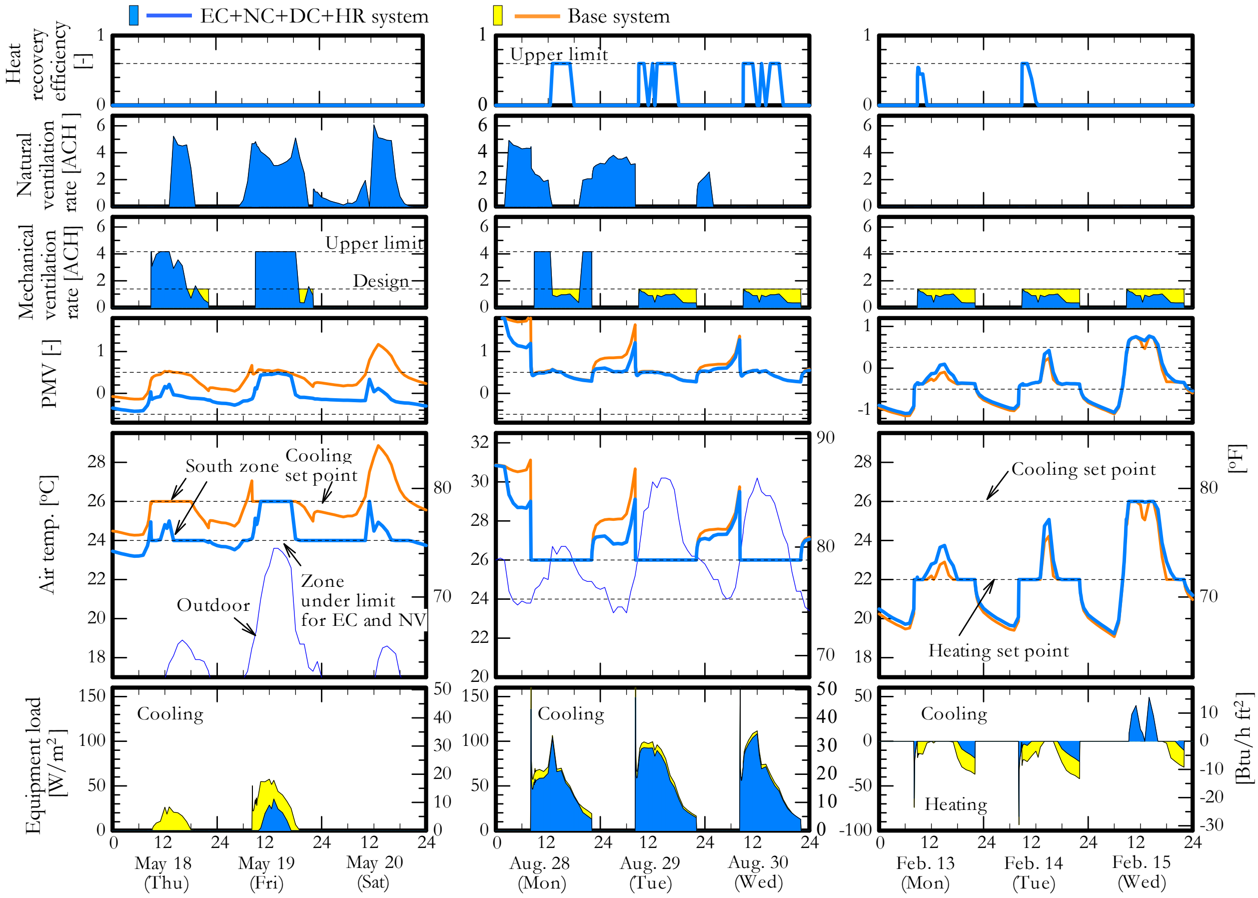
Table 2. Conditions for simulations

Wall U-value	0.9 W/m^{2}K (0.16 Btu/h ft^2 °F)
Window*1 U-value	1.5 W/m^{2}K (0.26 Btu/h ft^2 °F)
Window SHGC	0.3
Effective opening area for NV	0.005m^2/m (0.016 ft^2/ft)*2
Occupancy	0.15 persons/m^2 (0.014 persons/ft^2)
Lighting and equipment	30 W/m^2 (10 Btu/h ft^2)
Design ventilation rate	1.0 L/s m^2 (12 ft^3/h ft^2)
Set point temperature and humidity ratio	22°C (72°F) and 0.0082 g/g (lb/lb) for heating and humidification 26°C (79°F) and 0.0127 g/g (lb/lb) for cooling and dehumidification
Heating/cooling hours (ventilation hours)	8:00-22:00 (8:50-22:00) for weekdays
Ventilation control conditions	See Table 1.
Upper limit of ventilation rate for EC	300% of the design rate
Under limit of ventilation rate for DC	25% of the design rate
Heat recovery efficiency for HR	60%

*1 Low-E double glazing with inner blinds. The window-to-wall ratio is 1.3.
*2 Opening area per unit façade width.

Features of Operation of Energy-efficient Hybrid Systems

Figure 2 shows the changes in thermal environment and equipment load for the south zone in a building located in Tokyo, and the cases of the base system and the EC+NV+DC+HR system can be compared. For the results shown in this and subsequent figures, the equipment load includes the sensible and latent loads for heating, cooling, and ventilation. The lower limit of the zone air temperature for EC and NV was set at 24°C (75°F), which is lower than the cooling set point 26°C (79°F). On the intermediate days shown in Figure 2, the NV mode is switched on if the outdoor conditions are satisfied and the maximum natural ventilation rate during occupied hours is 5 ACH, based on the space volume in the south zone. Here, NV, and EC which is allowed to operate if the cooling power of natural ventilation is insufficient, lower the zone air temperature to approach the lower limit value. By using EC and NV, an improvement of the thermal environment as well as a reduction in the equipment load can be expected. On mid-summer days, DC and HR can slightly reduce the equipment load and have no effect on the thermal environment. In this case, the airflow rate through the heat exchanger in HR must be more than 50% of the design ventilation rate, and this condition is satisfied for around 70% of ventilation hours. On winter days, the south zone does not always require heating, and sometimes requires cooling. In this case, DC can considerably reduce the heating load and slightly increase the cooling load.



(a) (b) (c)

Figure 2 Changes in thermal environment and equipment load affected by ventilation operation (south zone, Tokyo). (a) Intermediate season. (b) Summer. (c) Winter.

The monthly results of ventilation operation in the EC+NV+DC+HR system are shown in Figure 3. Note that NV and EC are effectively used during intermediate seasons. In particular, in May and October, the operating ratio of NV during occupied hours is 60 to 70%, and that of EC is around 80%. The main reason for prohibiting operation of a control mode during intermediate seasons is low outdoor air temperature in the case of NV and low dew point outdoor temperature or low zone air temperature in the case of EC. Here, HR, which is used in combination with DC, is effective for this zone almost exclusively during summer. HR doesn't work during winter because the daytime heating requirement is small.

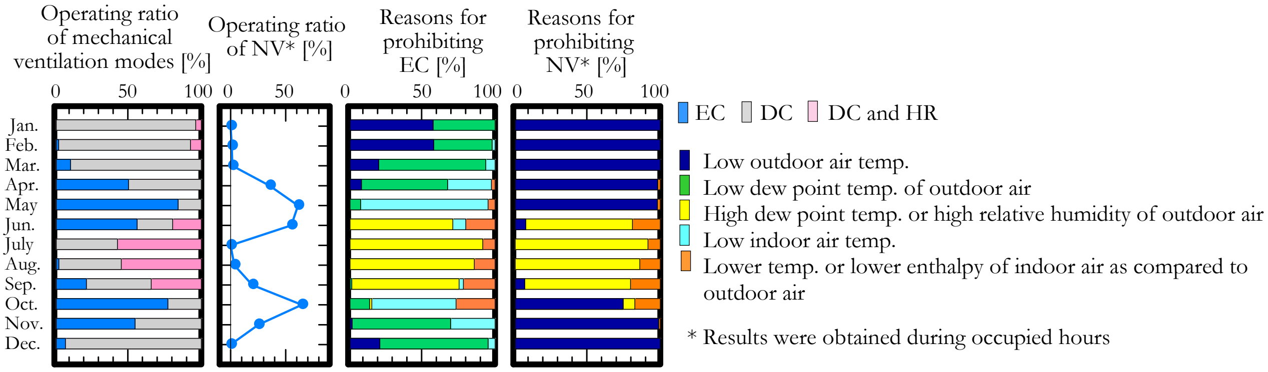


Figure 3 Monthly operating ratio of ventilation control modes and breakdown of the reasons for prohibiting switching between control modes in the EC+NV+DC+HR system (south zone, Tokyo).

The monthly equipment loads for the office floor, which includes eight office zones that use the EC+NV+DC+HR system, are shown in Figure 4. "Heating load" means equipment load for heating and humidification and "cooling load" means equipment load for cooling and dehumidification. When cooling and humidification are required, equipment load is calculated considering evaporative cooling effect of water spray. The load reduction rate achieved by EC and NE shown in Figure 4 is the load difference between the base system and the EC+NV system. The load reduction rate achieved by DC and HR is the load difference between the EC+NV system and the EC+NV+DC+HR system. Note that EC and NV can reduce the maximum rate of 20 MJ/m^2 (1.8 kBtu/ft^2) for the monthly cooling load in May. Moreover, DC and HR can reduce the maximum rate of 10 MJ/m^2 (0.9 kBtu/ft^2) for the monthly cooling load in August and can reduce the maximum rate of 15 MJ/m^2 (1.3 kBtu/ft^2) for the monthly heating load in January. Figure 5 shows the annual equipment loads for five ventilation systems. The load reduction ratio achieved by the EC+NV system is 17%, and that achieved by the EC+NV+DC+HR system reaches 34%. However, the load reduction effect of adding HR to the EC+NV+DC system is only 3%.

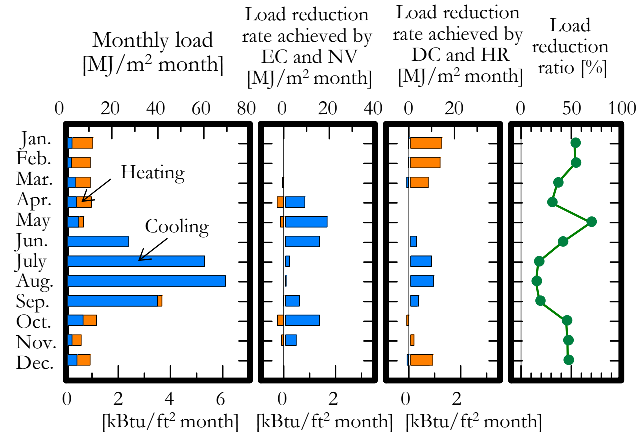


Figure 4 Monthly load for the office floor with the EC+NV+DC+HR system and its load reduction effects (Tokyo).

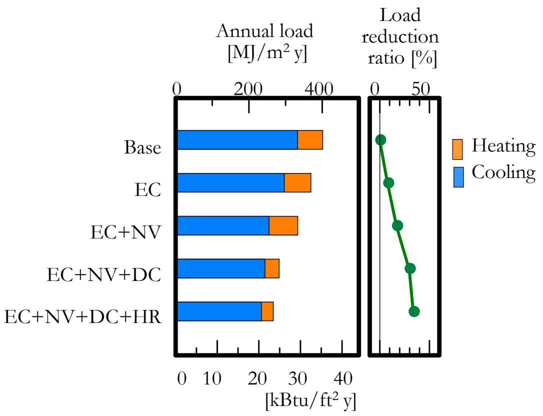
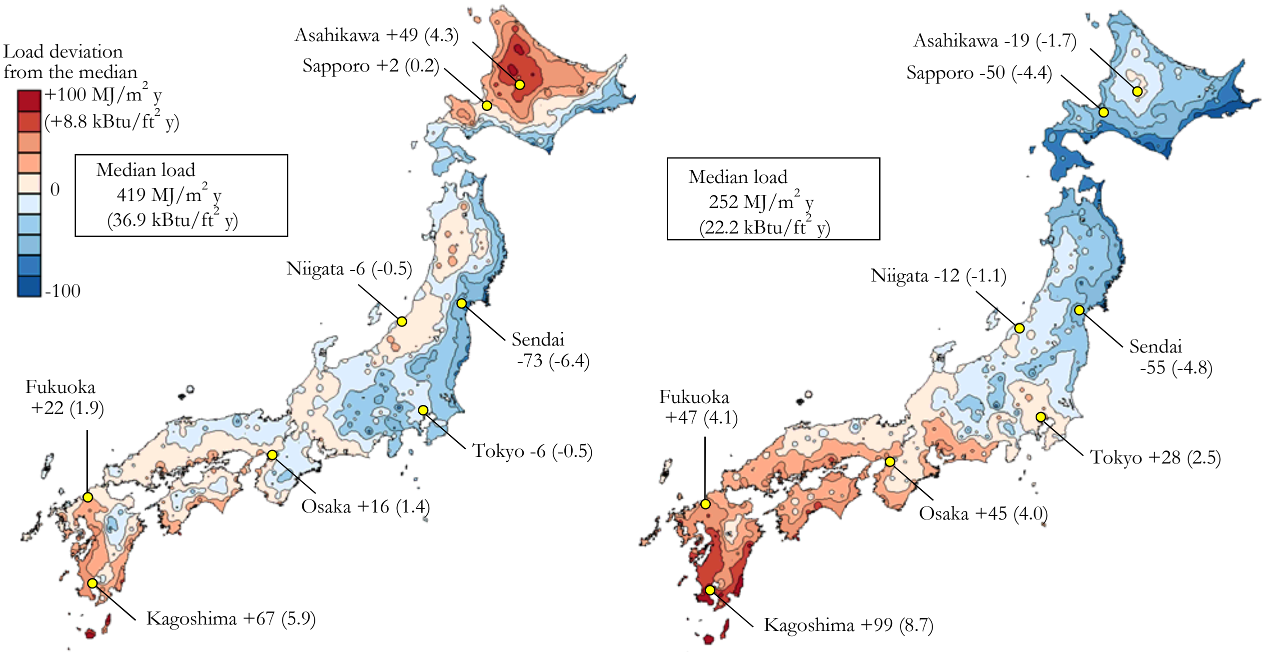


Figure 5 Annual load for the office floor and load reduction ratio achieved by energy-efficient ventilation systems (Tokyo).

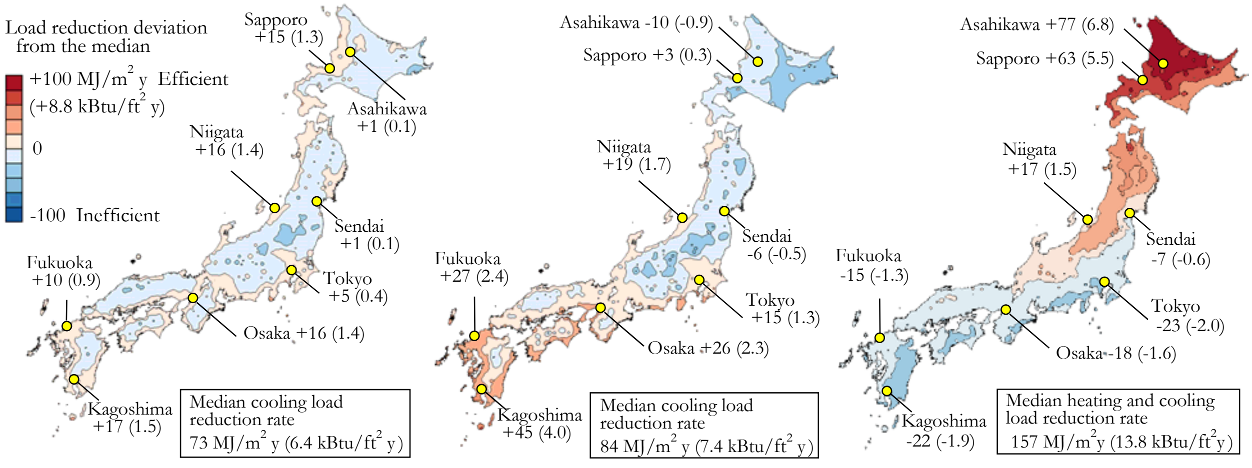
Color Maps of Annual Load Based on Simulations for 836 Locations in Japan

Thermal load simulations were conducted for a period of one year for 836 locations in Japan. The annual equipment loads for office floors at 836 locations were obtained, and the deviations from their median value were used to generate the color maps shown in Figure 6. Similarly, Figure 7 shows color maps of the deviation from the median value of the annul load reduction achieved by energy-efficient hybrid ventilation systems. The results for 22 locations, such as Naha, on remote southern islands are not shown in the figures. These color maps can be used for relative evaluation of the regional energy-efficiency.



(a) (b)

Figure 6 Color maps of the deviation from the median value of the annual load (including both heating and cooling loads). (a) Base system. (b) EC+NV+DC+HR system



(a) (b) (c)

Figure 7 Color maps of the deviation from the median annual load reduction rates. (a) Cooling load reduction achieved by the EC+NV system. (b) Cooling load reduction achieved by the EC+NV+DC+HR system. (c) Heating and cooling load reduction achieved by the EC+NV+DC+HR system.

As shown in Figure 6, the median value of the annual load for the EC+NV+DC+HR system is 40% less than that for the base system. In the case of the base system, regions of conspicuously large loads are located inland to the north of Asahikawa and on the islands south of Kagoshima. The small-load region is the Pacific coast of north of Tokyo. The features of the color map for the EC+NV+DC+HR system are different from those for the base system. The load is small in the north of Japan and is greater at lower altitudes. As shown in Figure 7(a), the median value of the cooling load reduction rate, 73 MJ/m^2 (6.4 kBtu/ft^2) achieved by the EC+NV system, is 17% of the median value of the heating and cooling load in the base system, and regional differences in cooling load reduction are small. Figure 7(b) indicates that the cooling load reduction achieved by the EC+NV+DC+HR system in comparison with the EC+NV system increases in the south of Japan. However, the difference in their median values is small. As shown in Figure 7(c), the heating and cooling load reduction appears to be larger in high-altitude regions than in low-altitude region, as well as larger on the Japan Sea coast than on the Pacific coast. The reason for this tendency is that the heating load reduction achieved by DC and HR is significantly larger in cold climates.

Comparison between Several Cities in the US and Japan

Regional differences were also examined between cities in the US and Japan. Seven cities in the US were selected from each zone in the Köppen climate classification, and New York was added as a major city. Five cities in Japan were selected based on climate. The annual loads for the EC+NV+DC+HR system were obtained through simulations. For three cities, San Francisco, Miami, and Naha, where little heating is required, simulations were also performed for a building having clear single-glazed windows with louvers. The results for annual load for the office floor are shown in Figure 8, and the results for ventilation operation for the south zone are shown in Figure 9.

The annual cooling loads for the EC+NV+DC+HR system are in a wide range of 60 to 640 MJ/m^2 (5 to 60 kBtu/ft^2). However, the cooling load reduction rates achieved by EC and NV are around 100 MJ/m^2 (9 kBtu/ft^2) for any city if the building has low-E double-glazed windows. By replacing the windows with single-glazed windows with louvers, which leads to a reduced cooling requirement during cooler seasons, the cooling load reduction rate becomes half or less. In Las Vegas and Denver, EC and NV operation increases the latent heating load. This indicates that the lower limit of the outdoor dew point temperature for switching to NV is necessary for these cities. For many cities, the load reduction achieved by DC and HR is observed almost exclusively in heating. The load reduction ratio achieved by the EC+NV+DC+HR system is approximately 40% for Denver, Chicago, New York, Tokyo, and Sendai, and is greater than 50% for Seattle, San Francisco, and Asahikawa, where the cooling requirement is small. The smallest load reduction ratio achieved by the EC+NV+DC+HR system was 15% for Las Vegas, where the cooling requirement is large and the climate is dry.

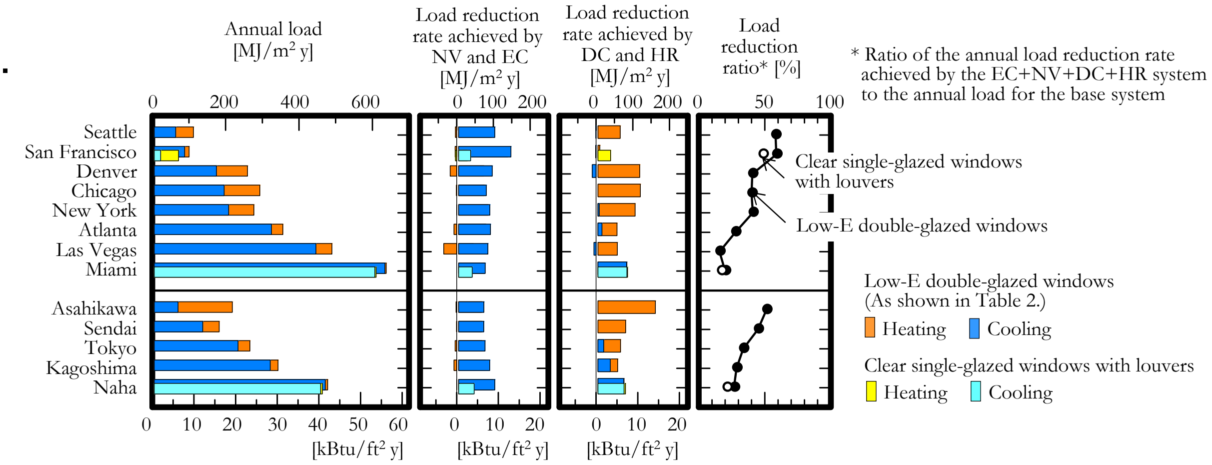


Figure 8 Annual load for the office floor with the EC+NV+DC+HR system and its load reduction effects.

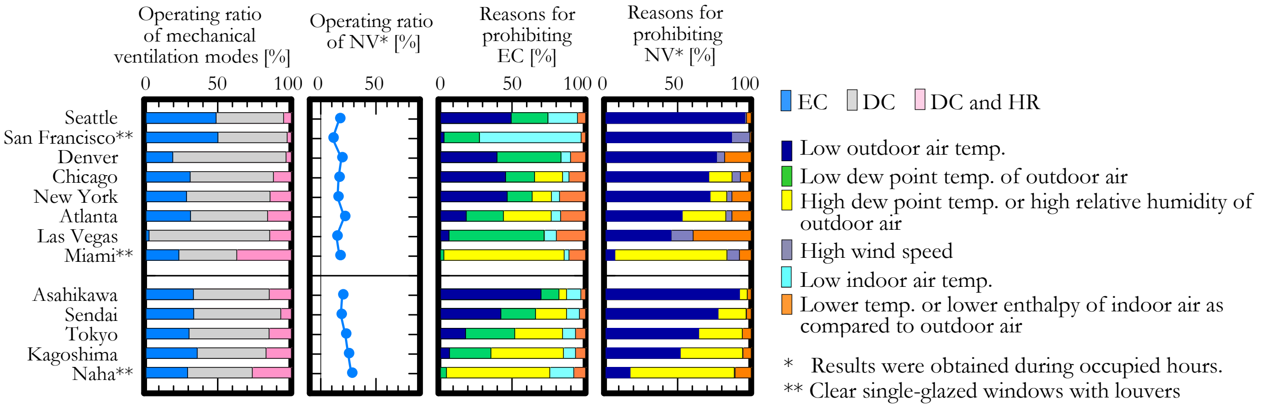


Figure 9 Annual operating ratio of ventilation control modes and breakdown of the reasons for prohibiting switching between control modes in the EC+NV+DC+HR system (south zone)

As shown in Figure 9, the operating ratio of NV is 10 to 20% for the US cities and 20 to 30% for Japanese cities. The upper limit of the outdoor air humidity is effective for Japanese cities but unnecessary for several cities in the US. Whereas the operating ratio of EC is approximately 30% for many cities, it is 50% for Seattle and San Francisco. Furthermore, EC may be much more profitable than NV for these two cities. Note that EC does not work in Las Vegas, where the outdoor air humidity is low during intermediate seasons. The operating ratio of the simultaneous operation of DC and HR is large for hot cities, such as Miami and Naha, where the annual load reduction rate achieved by DC and HR is not so large.

CONCLUSION

The present study developed a thermal load simulation method for evaluation of energy-efficient hybrid ventilation systems, which are assumed to achieve almost ideal energy-efficient control, and analyzed the regional features of ventilation operation and the equipment load reduction. The simulation results indicate that regional differences in annual load reduction rates achieved by EC and NV are small and that the annual load reduction rates achieved by DC and HR are larger for colder regions. In Tokyo, the annual load reduction ratio achieved by EC and NV is approximately 15% and that achieved by all four control techniques is approximately 35%. Based on the results for several cities in the US and Japan, the annual load reduction ratio achieved by all four control techniques was found to be approximately 40% for Denver, Chicago, New York, Tokyo, and Sendai, and the annual load reduction ratio was found to be smaller in hot cities than in cold cities.

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