# Experimental Study on the Combined Effect of Outdoor Thermal-Environment and Ventilation Patterns on Indoor Thermal-Environment Control for Summer

K. Tokunaga, Y.Fukai, and M. Shukuya
*Guraduate School of Envionment and Information Studies,*
*Musashi Institute of Technology, Japan*
K. Izawa
*Rui Corporation, Japan*

ABSTRACT

If thermal insulation and solar control of building envelopes are appropriately made for indoor thermal environment control, then the moderate air current becomes relatively effective for thermal comfort especially in residentional buildings in summer seasons.

To clarify the ways of natural ventilation with sufficient thermal insulation and solar control, we examined four cases of natural ventilation. We use an experimental house designed with the concept of symbiosis in Tsukuba for ten days in August, 2007. There are three rooms on the ground floor; the outdoor space in front of these rooms was equipped with shading devices for solar control. We examined the case of no ventilation, nighttime ventilation only, the nighttime and daytime ventilation with upper opening, and the nighttime ventilation with upper opening and daytime ventilation with horizontal openings. The transmitted vertical solar irradiance in the rooms was smaller than incident vertical solar irradiance. To describe the thermal environment provided by the cases of ventilation, we used exergy concept.

Cool exergy contained by the room air during daytime in the case of the nighttime ventilation only was the largest, but wet exergy was also available in the large amount. In the case of both nighttime and daytime ventilation with upper opening, cool exergy contained by the room air was larger than that in the case of nighttime ventilation with upper opening and daytime cross ventilation. Cool exergy contained by the room air decreased as the rate of air change increased. The average of the rate of air change was 7 times/h in the case of both nighttime and daytime ventilation with upper opening, and 13 times/h in the case of nighttime ventilation with upper opening and daytime cross ventilation. The air current velocity in the rooms during the nighttime was larger than that of daytime even if the wind velocity outdoors during nighttime was smaller than that during daytime. This is considered to be caused by buoyancy due to the difference in air temperature between indoors and outdoors. It is important to control the rate of air change during daytime ventilation to keep the coolness stored by nighttime ventilation by buoyancy.

## 1. INTRODUCTION

Ground surface have been covered by artificial materials such as asphalt and others especially in urban areas in the last few decades. This causes a change in thermal environment of these areas especially in summer. Exhaust heat from convective-cooling systems installed in a lot of buildings worsens the thermal environment condition. It has been clarified that, if a combination of thermal insulation and solar control of building envelopes is made for indoor thermal environment control, the moderate air current becomes effective for thermal comfort in residentional buildings even for hot and humid summer.

The purpose of this research is to clarify the way of natural ventilation for the indoor thermal environment control with sufficient thermal insulation and solar control.

## 2. EXPERIMENTAL SET-UP

We used an experimental wooden house designed with much of symbiotic strategies in Tsukuba. Overall heat-loss coefficient of this house is 2.54 W/㎡・K. *Photo 1* shows the appearance of this house from the south. *Figure 1* shows the floor plan. The ground floor has three rooms: “Tatami” room, living room and dining room.

There are different amounts of vegetation in each front of these rooms. There is also shading net with solar transmittance of 30 % in front of the Tatami room and the exterior Venetian blinds in front of the living room. *Figure 2* shows the percentage of configuration factors viewed from the south-facing window of each room. The outdoor space of the living room is best solar controlled and Tatami room follows.

Four cases of natural ventilation shown in Figure 3 were examined. The first is no ventilation for the whole of the following three days, 13$^{th}$, 19$^{th}$, and 20$^{th}$ of August. The second is natural ventilation during nighttime from 18:00 to 8:00 in the following morning and the windows closed during daytime from 10:00 to 18:00, namely no ventilation. This was done on 16$^{th}$ of August. The third is natural ventilation for nighttime mainly with buoyancy and for daytime with wind force in the horizontal direction. This was done for two days, 17$^{th}$ and 18$^{th}$ of August. The fourth is natural ventilation mainly with buoyancy both for nighttime and daytime. This was done on 14$^{th}$, 15th, and 21$^{st}$ of August.

Photo 1: An experimental house used

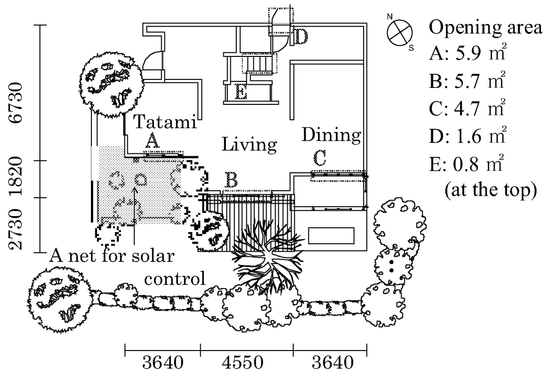


Figure 1: Floor plan of the house

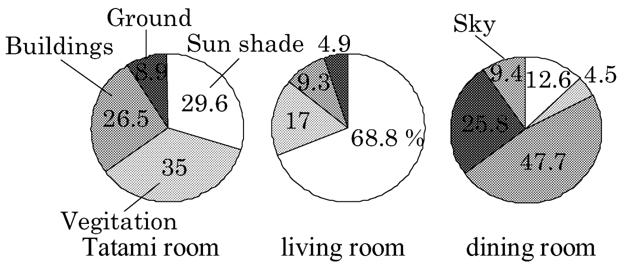


Figure 2: The Configuration factors in front of the three rooms. In Tatami and living room, no sky in veiewed

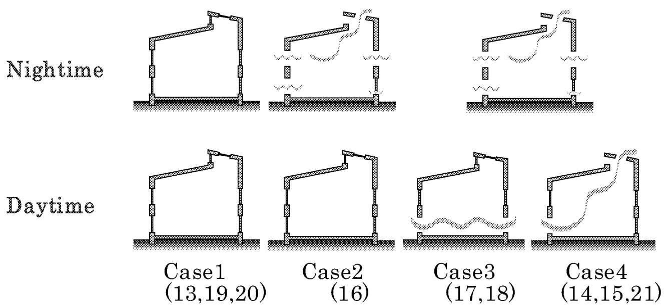


Figure 3: Four cases of natural ventilation examined

We measured physical quantities such as air current velocity, air temperature, relative humidity, and transmitted solar rradiance inside of the rooms. We mesureard the corresponding quantities of the outdoor space in front of those rooms. The outdoorair temperature, humidity, the horizontal solar irradiance and the wind velicity for the whole of this house were also measured in the places 10 to 20 m away from this house. In this experinment, the air-current velocity was measured with three-dimentional supersonic anemometers.

## 3. EXPERIMENTAL RESULTS

*Figure 4* shows the relationship between incident vertical solar irradiance and transmitted vertical solar irradiance. Transmitted vertical solar irradiance of the living room is the smallest and that of the dining room is largest. This difference is caused by the difference in configuration factors shown in Figure 2. Even if the case of the largest transmitted vertical solar irradiance, about one fifth of the incident vertical solar irradiance is transmitted. Therefore all of south-facing windows of three rooms are generally speaking well shaded by the shading devices and others.

*Figure 5* shows the relationship between outdoor air temperature and room air temperature during daytime. Room air temperature of the three rooms were usually lower than outdoor air temperature. Air temperature of the dining room is 1 to 2℃ higher than that of the two other rooms .There is no partition on the ground floor so that the air in these rooms must be mixed more or less. Therefore we use the average air temperature of the three rooms as the air temperature of the ground floor for the present investigation.

*Figure 6* shows the relative occurrence of outdoor wind velocity in the horizontal direction. The wind velocity from 0 to 2 m/s is available mainly during the nighttime. During the daytime, on the other hand, the velocity is 2 to 5 m/s. It shows that it is easier to bring in the outdoor air into the room space by making the use of wind during daytime than nighttime.

## 4. DESCRIPTION OF THERMAL ENVIRONMENT BY EXERGY CONCEPT

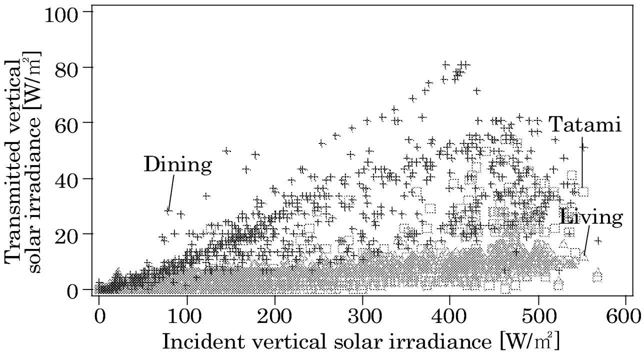


Figure 4: The relationship between incident and transmitted solar irradiances

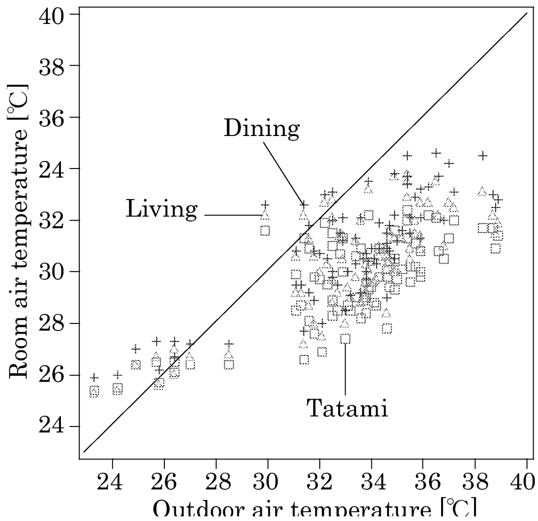


Figure 5: The relationship between outdoor air temperature and room air temperature

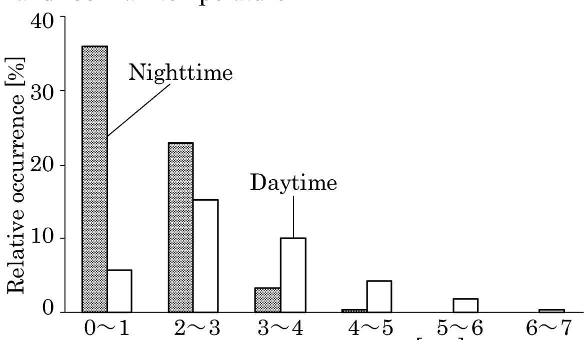


Figure 6: The relative occurrence of the outdoor wind velocity in the horizontal direction

The room air whose temperature and humidity are different from those of outdoor air contains warm or cool exergy and wet or dry exergy. In terms of warm/cool exergy, if the room air temperature is higher than the outdoor air temperature, the room air contains “warm” exergy, otherwise “cool” exergy. In terms of wet/dry exergy, if the water vapor pressure of the room air is higher than that of outdoor air, the room air contains "wet" exergy, otherwise, "dry" exergy. One of the merits of exergy concept is that it allows us to quantify the ability of dispersion of energy and matter on equal basis. Since warm/cool exergy and wet/dry exergy have the same unit, they can be compared directly, though the units of energy and matter themselves are different from each other; e.g., the former is expressed in Joule and the latter in kilogram.

Warm or cool exergy contained by a cubic meter of room air is calculated from the following equation.

$$X_h = (C_{pa}m_a + C_{pw}m_w)\left\{(T_r - T_o) - T_o \ln\frac{T_r}{T_o}\right\}, \quad (1)$$

where $C_{pa}$ is specific heat of dry air (=1.005) [J/(g·K)]; $C_{pw}$ is specific heat of water vapor (=1.846) [J/(g·K)]; $m_a$ is mass of dry air [g/m$^3$]; $m_w$ is mass of water vapor [g/m$^3$]; and $T_r$ is room air temperature [K].

Wet or dry exergy contained by a cubic meter of room air is calculated from the following equation.

$$X_d = T_o\left(\frac{m_a}{M_a}R\ln\frac{p_a}{p_{ao}} + \frac{m_w}{M_w}R\ln\frac{p_v}{p_{vo}}\right), \quad (2)$$

where $p_a$ is partial pressure of dry air indoors [Pa]; $p_v$ is partial pressure of water vapor indoors [Pa]; $p_{ao}$ is partial pressure of dry air outdoors [Pa]; $p_{vo}$ is partial pressure of water vapor outdoors [Pa]; $M_a$ is molar mass of air (=28.97) [g/mol]; $M_w$ is molar mass of water (=18) [g/mol] and $R$ is gas constant (=8.314) [J/(mol K)].

*Figure 7* shows the relationship between warm/cool exergy and wet/dry exergy contained by room air for daytime, from 10:00 to 18:00, of each case of experiment. In the horizontal axis, the plots in the left from the origin show warm exergy and those in the right cool exergy. In the vertical axis, the plots appearing in the space upper of the origin show wet exergy and those below dry exergy.

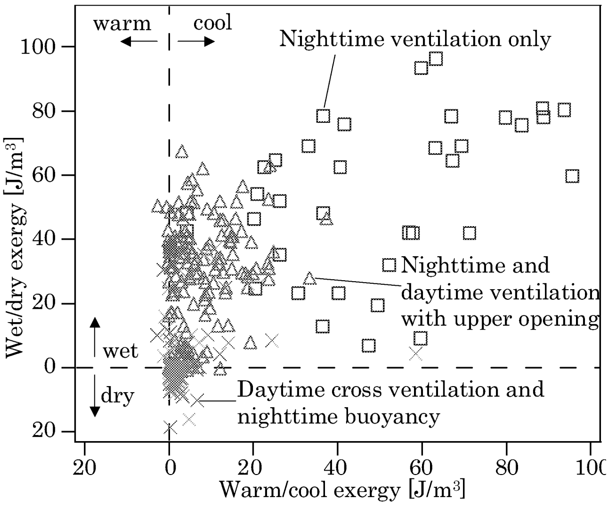


Figure 7: The relationship between warm/cool exergy and wet/dry exergy

Cool exergy contained by the room air in the second case of the experiment for nighttime ventilation only ( □ ) is larger than that in other cases. This is because the difference in air temperature between room and outdoor during the daytime is larger than that in other cases. On the other hand, wet exergy contained by the room air in this case is also much larger than that in other cases. The reason is that there is water vapour generation inside the house.

There are two other kinds of plots, the triangles ( △ ), and the cross ( ×), ; the formers denote the case of nighttime and daytime ventilation with the upper opening and the latters the case of nighttime ventilation with upper opening and daytime cross ventilation in horizontal direction. The cool exegy contained by the room air in the case that the upper opening is used is much larger than the other case with daytime horizontal cross ventilation. There are even warm exergy in this case, while on the other hand, there are little warm exergy in the case with the use of the upper opening.

In a building with thermally well-insulated walls with appropriate amounts of heat capacity, the room air can contain a good amount of cool exergy during daytime for the effect of nighttime ventilation, but it also contains wet exergy, which should be disposed of. It is necessary to exhaust moisture from the room space to outside while keeping the moderate amount of cool exergy contained by the room space especially by the walls, the ceiling and the floor.

*Figure 8* shows the rate of air change during daytime. The rate of air change was estimated by the following procedure: measured air current indoors near the opened window at one-minute intervals was multiplied by the opening area of the window and the results were summed up for each one-hour period and then they were divided by the volume of room space. The rate of air change in the case of ventilation with upper opening ranges turned out to be from 4 to 11 times/h, but that in the case of horizontal cross ventilation from 11 to 18 times/h. The average of the air change rate is 7 times/h in the case with upper opening, and 13 times/h in the case of cross ventilation. They are rough estimates so that the actual values of air change must be 70 to 80 % of the values we calculated.

*Figure 9* shows the relationship between warm/cool exergy and transmitted vertical solar irradiance and the rate of air change by natural ventilation while the daytime ventilation was made. Transmitted vertical solar irradiance is the average of that of three rooms on the ground floor. The warm exergy appears when the transmitted solar irradiance is small. On the other hand, as the rate of air change by ventilation increases, cool exergy tends to decrease. Generally speaking, during daytime, outdoor air temperature increases as the solar irradiance increases, and it usually becomes higher than room air temperature in the afternoon period. Therefore, the amount of cool exergy grows as the vertical solar irradiance increases. The reason that the large rates of air change with smaller cool exergy or ever with warm exergy is that room air temperature rises easily as the rate of air change in the room space increases.

In a building with effective solar control like this experimental house, the control of air change rate of natural ventilation during daytime is much important to keep the coolness harnessed during the nighttime.

*Figure 10* shows the relationship between the wind velocity near the opened window inside the room and that outdoors, which was measured about 20 m away from the window.

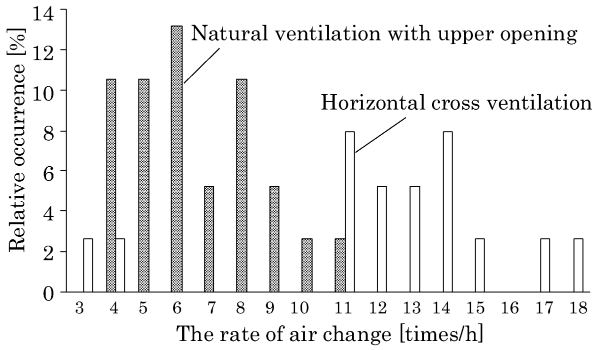

Figure 8: The times of rate of air change

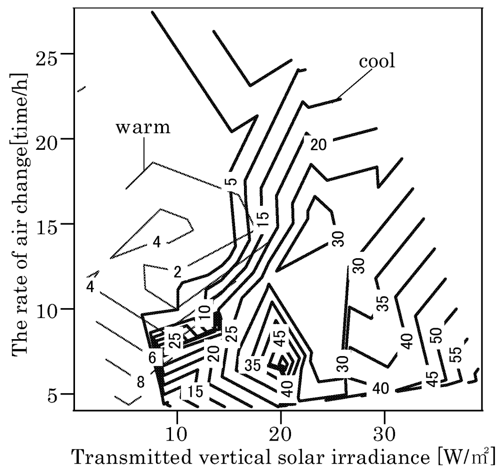

Figure 9:The relationship between warm/cool exergy and solar irradiance and the rate of air change by natural ventilation

The vertical axis indicates the air-current velocity near the upper opening or that in horizontal direction near the window opened on the ground floor. The former is denoted by triangles plots (▲ or △) and the latter by circular plots(● or ○). The closed plots represent nighttime and the open plots daytime. The plots above the horizontal axis in the middle represent the air flowing out and the plots below the air flowing into the room. During the nighttime, outdoor wind velocity tends to be smaller than that of daytime as already shown in Figure 6, but the absolute values of air-current velocity in the room is more or less the same or a little larger than those during the daytime.

*Figure 11* shows the relationship between the indoor-outdoor temperature difference and air-current velocity indoors. The plots used are the same as those in Figure 10. The horizontal axis indicates the indoor-outdoor air temperature difference; ther positive values imply that the indoor air temperature is higher than outdoors. During nighttime, room air temperature is about 1 to 3℃ higher than outdoors. This must have caused buoyancy. Warm air indoors tends to go out by buoyancy from the openings in higher places and let in the outdoor air through the openings in lower places. This is the reason of the air-current velocity in the room was large even if the outdoor wind velocity was small as shown Figure10.

The nighitime ventilation caused by buoyancy is a very effective way of the use of natural potentials to be able to dispose of the exhaust heat, namely the warm exergy, while at the same, to store the coolness, namely cool exergy to emerge in the following daytime.

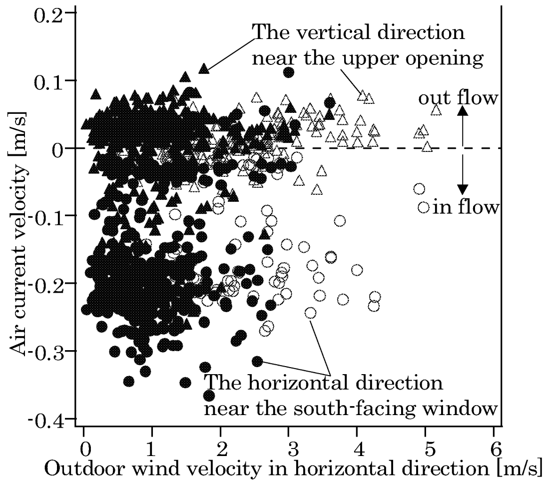


Figure 10: The relationship between indoor and outdoor air-current velocities

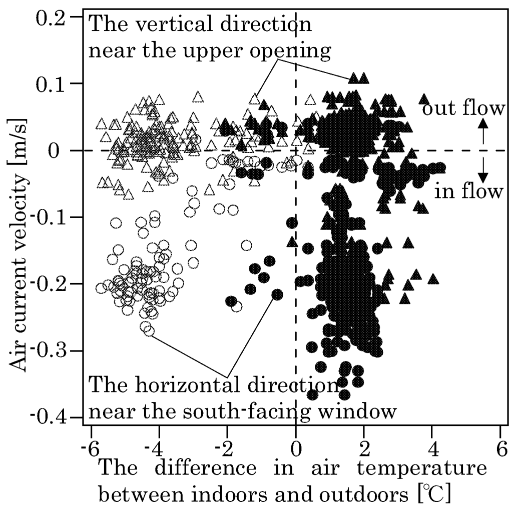


Figure 11: The relationship between the indoor-outdoor temperature difference and indoor air-current velocity

## 5. CONCLUSION

We conducted an experiment on the effect of natural ventilation using an experimental house with thermally-well insulated walls and effective solar control over the windows.

In the case of nighttime ventilation only, a large amount of cool exergy contained by room air was available, but wet exergy was also available. Cool exergy in the case of nighttime and daytime ventilation with upper opening is larger than that in the case of nighttime and daytime horizontal cross ventilation. Cool exergy contained by the room air decreases as the rate of air change by natural ventilation increases.

It is important to control the rate of air change for natural ventilation to exhaust the moisture to keep the coolness harnessed by nighttime ventilation. During the nighttime, air-current near the upper opening and the south-facing window of the ground floor was large even if the outdoor wind velocity was very small. This is caused by buoyancy due to the difference in air temperature between indoor and outdoors.

ACKnowlegdement

We are very grateful to Mr.I.Ishizaki, Mr T.Kakegami, Mr.H.Nishizaki, Mr.H.Yamada and Ms.S.Oshida, Sumitomo Forestry Co., Ltd. for their constant support for conducting the whole of this experiment and investigation. We are also very greatful to Ms.N.Kurosawa, Mr.S.Nishizawa, Mr.S.Hattori and Ms.Y. Yamaguchi, as then 4th grade under graduate students of Musashi Institute of Technology, for their involuvment in the experiment.

## REFERENCES

Mitobe, M., Fukai, Y., Izawa, K., Iwamatsu, T., Ohkuma, T., Fukuda, H., Asada. H. and Shukuya, M. and (2007), Experimental study on thermal comfort provided by high-temperature radiant cooling and low-temperature radiant heating system, *Proceedings of annual meeting, building science section,* Architectural Institute of Japan, pp.581-590.