CONTROL OF THE HUMIDITY AND TEMPERATURE IN AN ATRIUM BY COOLING THE SURFACE OF A POND IN THE ATRIUM

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ABSTRACT

This paper presents a method for dynamic numerical analysis of the thermal environment in an atrium.
In this study, the quantity of condensation on and the quantity of evaporation from the surface of water in a small pool (water surface area, 1m^2) were experimentally measured, and changes in the vertical distributions of humidity and temperature in an atrium were numerically calculated by using the Successive Integration Method. The analysis was carried out using BASIC language software. The atrium used as the model for this study was 360 m^2 in floor area, 11.78 m in height, and had a pond with a surface area of 50 m^2. The airflow between the atrium and outdoor is naturally ventilated in summer. If the temperature of the surface of the pond is maintained at less than 20 degrees Celsius, the estimated rate of vapor condensation in summer is 6 kg/h. This would allow the cool and low humidity air to be circulated to other parts of the building. A cooled surface of a pond in an atrium would therefore function as a type of dehumidifier, like an air-conditioning system.

INTRODUCTION

Many institutions for the elderly have recently been built in Japan due to the aging society. In Hokkaido, the northernmost island of Japan, approximately ten new institutions for the aged are currently being constructed every year. In winter, it is difficult for the residents of institutions for the aged in Hokkaido to go outdoors because of the large amount of snow and the frozen sidewalks. In such cold and snowy regions, a glass-covered space like atriums could provide ideal places for aged people to exercise in winter[3)]. For example, such a space in a building can provide several benefits for the occupants of the building, especially if the building is a residential facility for aged people. For one, a high level of ventilation is required to eliminate the unpleasant odor caused by wards annexed for aged people, and such a ventilated environment would be beneficial for the health of aged people. Moreover, cold fresh air infiltrating into the atrium in winter can be heated by solar radiation penetrating through the glazed roof, and this warmed air can be circulated to other parts such as the wards. On the other hand, one disadvantage of an atrium is that the temperature of the air heated by solar radiation penetrating through the glazed roof in summer is too high for the air to be used as ventilation for other parts of the building. There is, however, one relatively easy way to solve this problem. Since many atriums have artificial ponds built inside them, the water in the pond could be prevented from evaporating by keeping the water surface temperature lower than dew-point temperature, and this would lead to vapor condensation, which would cool the fresh air coming into the atrium from outside. This idea[4)] would enable both the humidity and temperature in an atrium to be controlled. It would also reduce the cooling load of the building in summer and the problem of condensation on the glazed roof in winter.

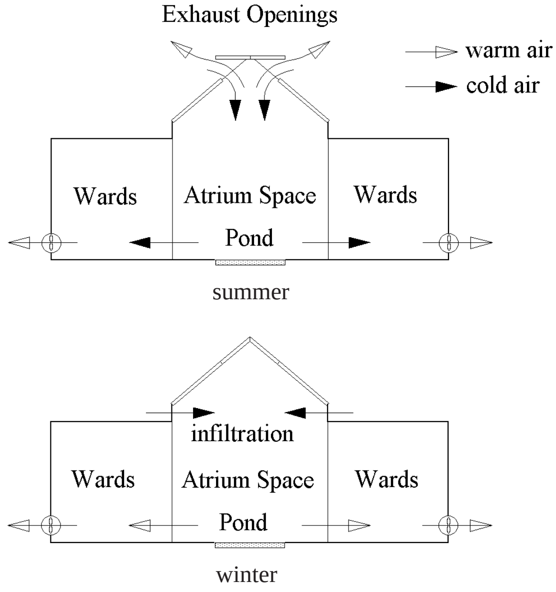

Fig. 1 System of ventilation for the building

Specification for numerical simulation:

・Convective heat transfer coefficient

Ceiling	: α_C=0.0495H_c+4.74 (upward)
Wall	: α_C=0.0411H_c+2.51
Floor	: α_C=0.0113H_c+4.02 (upward)
	: α_C=0.0103H_c+1.43 (downward)

α_C: convective heat transfer coefficient [W/m^{2}K]

H_C: convective heat flux [W/m^2]

・In this simulation, wind effect and air leakage of the atrium is negligible.

・Constitutions of each wall as follows

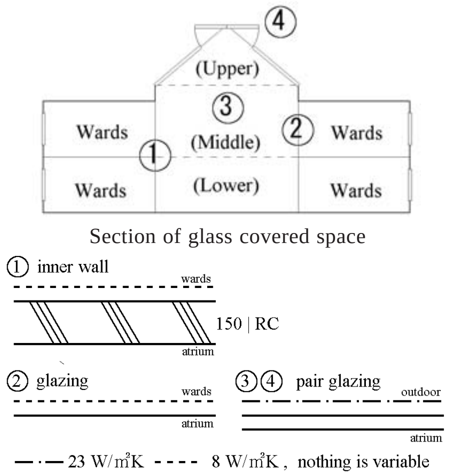

Fig. 2 Constitutions of each wall in the Atrium

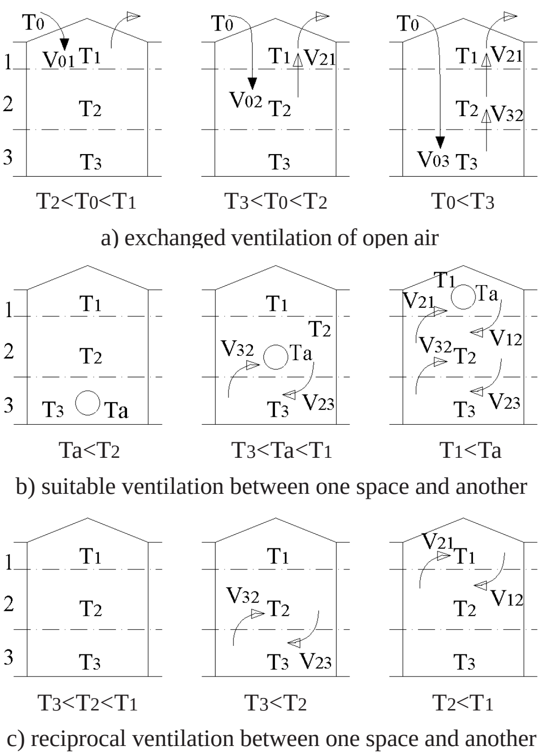

Fig. 3 Modeling of airflow paths between imaginary divisions in the atrium

Heat balance equations:

(i) Imaginary zones

$$c\gamma_i V_i \frac{d\theta_i}{dt} = \sum_{SW} \alpha_{cl} A_l (\theta_l - \theta_i) + \sum_{NS} c\gamma Q_{ji} (\theta_j - \theta_i) + W_i$$

(ii) Wall surfaces

$$A_k (H_m - H_k) + \alpha_{ck} A_k (\theta_j - \theta_k) + \varepsilon_k \sum_{SW} \beta_{lk} \alpha_{rk} (\theta_l - \theta_k) + W_k = 0$$

(iii) Pond

$$c_w \gamma_w V_p \frac{d\theta_w}{dt} = c_w \gamma_w q_w (\theta_c - \theta_w) + A_p (H_m - H_k)$$
$$+ \alpha_{cp} A_p (\theta_j - \theta_p) + \varepsilon_p \sum_{SW} \beta_{lp} \alpha_{rp} (\theta_l - \theta_p) - A_p r Z + W_p$$

Moisture balance equations:

Imaginary zones

$$\gamma_i V_i \frac{dx_i}{dt} = \sum_{NS} \gamma Q_{ji} (x_j - x_i) + Y_i$$

c : specific heat [Wh/kgK]

γ : density [kg/m^3]

V : volume of a room, zone, pond [m^3]

θ : temperature of air, wall surface, water [℃]

α_r : radiative heat transfer coefficient [W/m^{2}K]

Q_{ji} : quantity of ventilation from space j to i [m^3/h]

W : heat gain (solar radiation, human body, etc.) [W]

Y_i : moisture gain (human body) [g/h]

Z : quantity of condensation or of evaporation [g/m^{2}h]

x : humidity ratio of air [g/kg']

A : area of wall surface, pond [m^2]

H_k : loss of heat flux through the surrounding walls [W/m^2]

H_m : inflow of heat flux from the wall surface [W/m^2]

ε_k : absorbtivity of wall surface

β_{lk} : incident factor to radiation

q_w : quantity of circulated through the water pond [m^3/h]

r : latent heat of vaporization [Wh/g]

j : neighboring space number of space i, space to which wall surface k faces, outdoor

l : number of wall surface faced to space i and wall surface k

p : pond w : water c : cooling water

NS : neighboring spaces SW : surrounding walls

In this study, the thermal environment of an atrium in an institution for the aged was numerically calculated[3]. These results were used to determine the best ways (1) to improve the thermal environment of an atrium when the roof is opened for buoyant convection and to cool the atrium space by natural ventilation in summer, and (2) to circulate air that has been cooled and dehumidified by a pond in an atrium to other parts of the building and thereby reduce energy costs.

ANALSIS METHOD

The Successive Integration Method[1] was used for the analysis, BASIC language software was used for the numerical calculation. An illustration of the ventilation system used in the institution is shown in Figure 1, and the modeling airflow paths in the atrium is shown in Figure 3. Dry-bulb temperature is horizontally contoured in some actual measurements in a space with a high ceiling, such as an atrium, and the space is divided into the imaginary divisions of upper zone, middle zone and lower zones (i.e., occupied space) such as Block Model[2]. The heat transfer with respect to the constituent walls in the space is divided into convection and radiation components[2]. The imaginary walls between three zones are transparent to the radiation component, each zone has heat and airflow balances, respectively. The wall surfaces do not emit or absorb vapor. The temperature in each ward is maintained at 27 degrees Celsius, keeping RH 60 %. Fresh air into each ward is ventilated through the atrium by the forced ventilation system (2 ac/h) throughout the year. The polluted air is always exhausted from the wards to outside.

Figure 4 shows the floor plan and a cross section of the subject building used as the model for this study. The building is a residential institution for elderly people (current number of residents, 90 in both the East and West wards). There is an artificial pond containing cooled water on the floor level of the atrium. The roof of the atrium has openings (i.e., exhaust openings for fire smoke) to allow warm air near the roof level to be exhausted and fresh air from outside to enter the atrium by the buoyant ventilation[2]. When using the weather data in Sapporo (i.e., outdoor air temperature, dew point temperature, solar radiation [including the beamed component on a normal face and the diffuse component] of HASP standard data), hourly data in summer as shown in Figure 5 is made up an average value of the same time during 2-week of the hottest period. Awning cloths under the glazed roof absorb about 50 % of solar radiation penetrating through the glazed roof, and the air warmed by the absorbed heat of the cloths accelerates the buoyant ventilation through the exhaust opening in the roof. Changes in the area of sunshine on each wall were calculated before the dynamic numerical analysis of the thermal environments in the atrium is started, the solar radiation on each wall surface is estimated by the above changes in the area of sunshine.

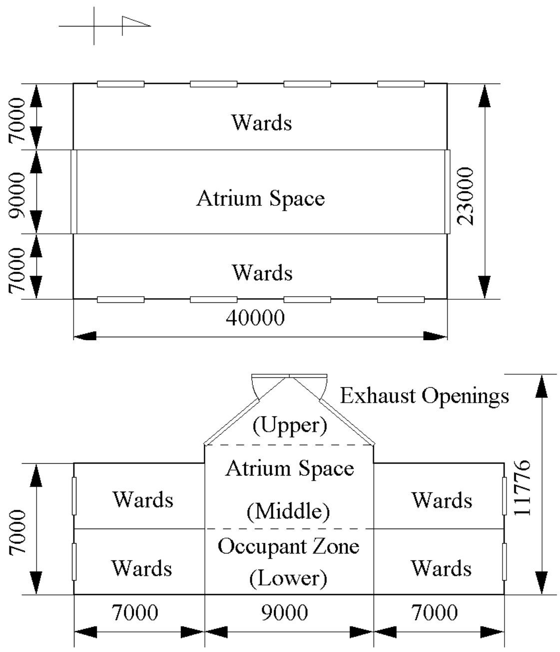

Fig. 4 Floor plan and a cross section of the building

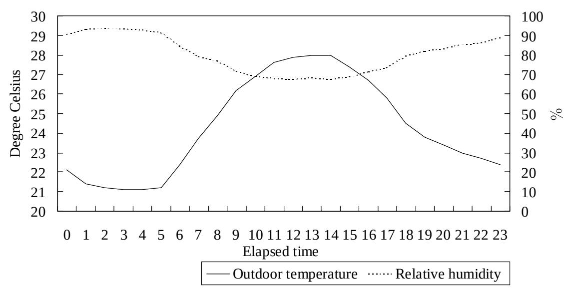

Fig. 5 Fluctuations in outdoor temperature and relative humidity in summer in Sapporo

The quantity of condensation on and quantity of evaporation from the water surface were experimentally measured by using a small pool containing water with a surface area of 1 m^2. The vapor transfer on the surface of a pond was calculated from the measurement results by using the following approximated equations[4].

Condensation:

$$Z=(134.8*v+45.5)\{df+0.0068(100-R_H)\}$$

Maeda-Enai

$$\alpha_C=3.6*v+4.1$$

Evaporation:

$$Z=(169.4*v+41.0)\{df+0.0054(100-R_H)\}$$

Kawaguchi-Enai

$$\alpha_C=5.4*v+7.4$$

where

Z: quantity of condensation or of evaporation [$g/(m^2h)$]

v: air velocity on the water surface [m/s]

df: difference between vapor pressure in room air and on the water surface [kPa]

R_H: relative humidity [%]

Changes in the distributions of temperature and humidity in the atrium space and changes in the thermal load for the wards can easily be calculated by the above BASIC language software.

SETTING CONDITIONS

We examined 17 cases in which the penetration coefficient, water surface area, air velocity and water temperature were varied (Table 1). In case 0, the wards are directly ventilated from outdoor.

Effect of water surface temperature: The effect of maintaining water surface temperature at between 10 and 20 degrees Celsius , of exhausting warm air by buoyant convection and on energy costs and amenity performance in the occupied zone of the atrium and in the wards were examined.

Effect of shield cloths: If the awning cloths are not used, the penetration coefficient of the glazed roof is 0. One merit of an atrium is to make the occupants feel as if they are in an outdoor space, which would not be possible if the awning cloths shielded too much of the glazed roof. The penetration coefficient was therefore controlled at the value of 0.5.

Effect of air velocity: Air velocity strongly affects the quantity of condensation on and the quantity of evaporation from the water surface. The air velocity at the water surface level was maintained in the range of 0.25 to 1.0 m/s.

RESULTS & DISCUSSION

Table 1 Setting conditions

	Penetration coefficient	Water surface area [m^2]	Air velocity [m/s]	Water temperature [Degree Celsius]
Case0	0.5	0		
Case1	0	0		
Case2	0.2	0		
Case3	0.5	0		
Case4	0	50	0.5	10
Case5	0	50	0.5	15
Case6	0	50	0.5	20
Case7	0	50	0.25	no control
Case8	0.5	50	0.5	10
Case9	0.5	50	0.5	15
Case10	0.5	50	0.5	20
Case11	0.5	50	0.25	no control
Case12	0.5	50	0.25	10
Case13	0.5	50	0.75	10
Case14	0.5	50	1	10
Case15	0.5	25	0.5	10
Case16	0.5	75	0.5	10

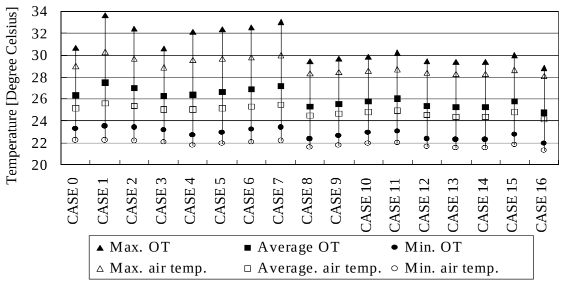

Fig. 6 Thermal environments in the occupant zones

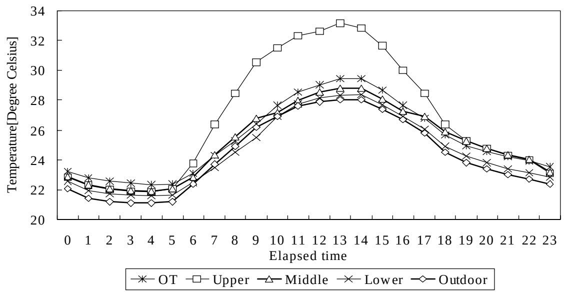

Fig. 7 Fluctuations in temperature in each of the three zones of the atrium

Figure 6 shows the thermal environment of the occupant zone in each of the 17 cases listed in Table 1. The results for cases 1 to case 3, which are without ponds, are bases for discussing the effect of a cooled surface of a pond in an atrium. In case 1, the operative temperature (OT) in the occupant zone rose as high as 33.6 degrees, a temperature which is not comfortable for occupants. When the penetration coefficient of awning cloths to solar radiation was set to 0.5, the temperature of the lower zone was less than 29 degree Celsius. Even in case 7, where there is a pond in the atrium, the water surface temperature rose to more than 30 degrees Celsius due to the air temperature in the atrium. On the other hand, in case 8, where awning cloths were used, thermal amenity could be maintained due to the decrease

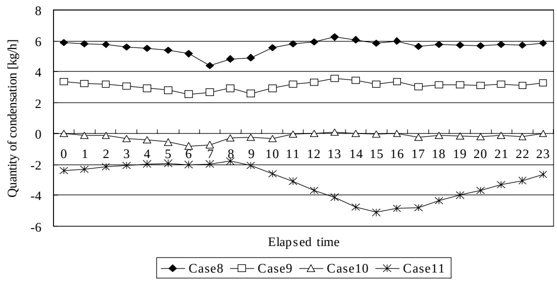

Fig. 8 Fluctuations in quantity of condensation

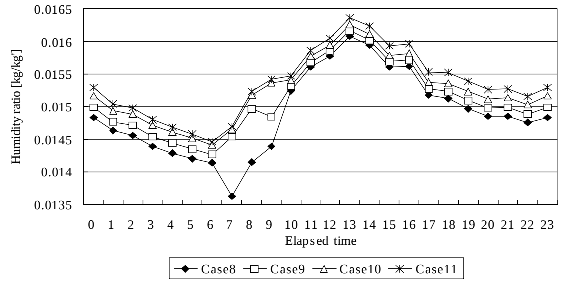

Fig. 9 Fluctuations in humidity ratio in the lower zone

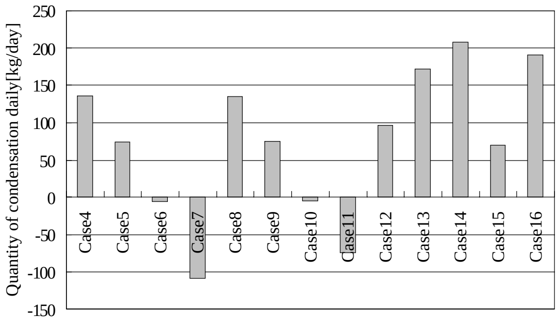

Fig. 10 Comparison of the quantities of condensation

in the air temperature of the lower zone, as shown in Figure 7.

Figure 8 shows the quantity of vapor condensation on the water surface, Negative values indicate the quantity of vapor evaporation. Figure 9 shows the changes in humidity ratio in the lower zone. The humidity ratio in the lower zone decreases with decrease in the water surface temperature. Thus, water surface temperature affects the humidity in the lower zone.

Figure 10 shows the quantity of vapor condensation throughout the day under various conditions. If the water in the ponds is not cooled, it constantly evaporates. Condensation is greatly affected by the water surface area and air velocity at water surface level.

Figure 11 and Figure 12 show the sum of radiation heat, convection heat and latent heat absorbed on the water surface if the pond was cooled. Each is illustrated as the value per the floor area. The water temperature af-

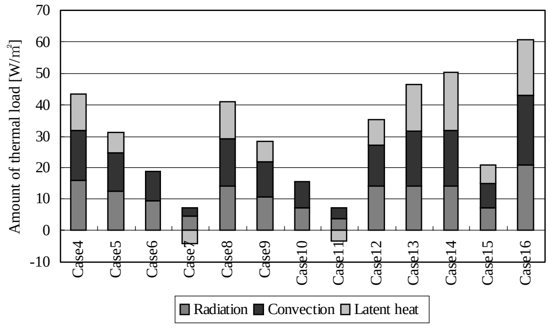

Fig.11 Thermal load reduced with cool water surface at peak time

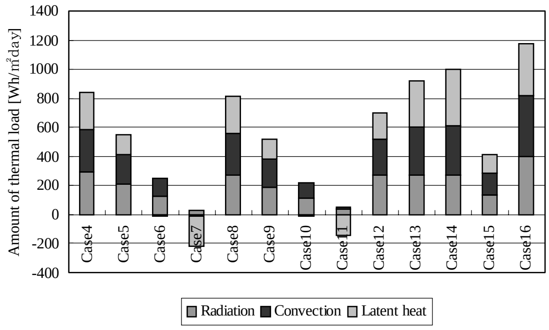

Fig. 12 Integral thermal load reduced daily with cool water surface

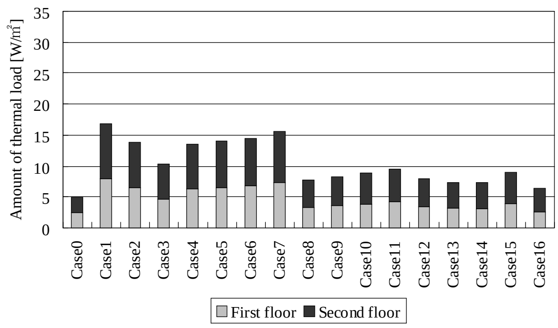

Fig. 13 Sensible thermal load provided by ventilation through atrium space at peak time

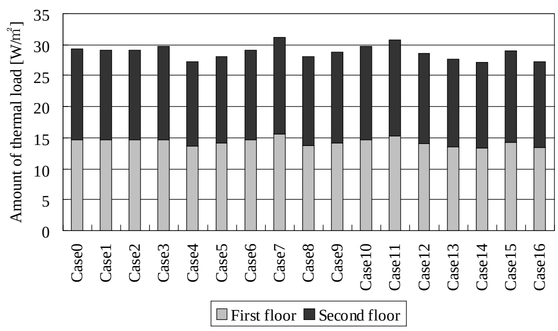

Fig. 14 Latent thermal load provided by ventilation through atrium space at peak time

fects the amount of condensation or evaporation. If the water temperature will not be kept lower than the dew point temperature in the lower zone, the latent heat to evaporate from the water surface becomes the thermal load to the wards which are air-conditioned. The maximum thermal load in case 8 is 10-times greater than that in case 11.

Figure 13 and Figure 14 show the thermal loads in each case when ventilating into the wards through the atrium. The thermal loads were expressed as the values per the floor area of wards. If awning cloths are not used, the peak load rises to about 40 W/m^2 as the total heat. The thermal load is greatly affected by solar radiation penetrating through the glazed roof.

In comparison with case 3 which is the atrium without a pond and case 8 which is the atrium with a pond, the effects of a pond can be discussed, and also in the same way from case 9 to case 16, the effects of the pond can be evaluated. The cooled pond can decrease the total heat of 6.4 W/m^2 to the maximum of thermal load.

Artificial ponds, which are often built in atriums for esthetic purpose, can become a source of high humidity if there is no control of the water temperature. On the other hand, if the water temperature is kept lower than the dew point temperature, the cool water surface can act as a type of dehumidifier by causing vapor to condense.

CONCLUSIONS

In this study, we investigated the effect on amenity and energy conservation in an atrium of (1) shielding solar radiation by the use of awning cloths under the glazed roof of an atrium, (2) using openings in the roof of an atrium as a mean to provide fresh air to other parts of the building and to exhaust warm air from the atrium in summer, (3) cooling the surface of a pond in an atrium.

The merits of an atrium as part of a building used for elderly people are as follows: (1) the high level of ventilation needed to eliminate the unpleasant odor caused by wards is beneficial for the health of aged people, and (2) air that cool and of low humidity can be circulated throughout the building if the surface of a pond in the atrium is cooled.

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