Simulation of the Maximum Heating and Cooling Loads for an Atrium Space

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ABSTRACT

This paper reports the simulation results of the maximum heating and cooling load of an atrium. Two different methods were used: One method was the so-called "manual" maximum heating and cooling load calculation, proposed by the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan. The other was "TEA" (Simulation Software of the Thermal Environment of an Atrium) which we have developed.

The heating and cooling loads between the "manual" calculation and "TEA" were compared. The results of the heating and cooling loads using "manual" calculation were twice as much as those using "TEA".

Next, we made predictions using "TEA" changing the ventilation route, the opening ratio of the solar shading panels, the angle between the floor and the walls constructed by clear glazing, and the zone conditioned by HVAC system. As a result, the best route was one in which the room air was exhausted through the attic space. The cooling load increased in proportion to an increase in the opening ratio of the solar shading panel, while the heating load did not vary so much. The cooling load was reduced and the heating load increased in proportion to the sharpness of the angle between the floor and the glazing walls.

INTRODUCTION

Because of recent developments in architecture, buildings tend to have various structures, functions and designs in Japan. Gymnasiums, in particular, have symbolic designs and a large space from necessity. Gymnasiums have not only straight lines but also many complicated curved lines. Furthermore, it is not a rare case to find that the gymnasium has glazed windows on all around it. These buildings are very different from general residences in their forms and this has a significant effect on the selection of air-conditioners.

It is important to make an accurate estimate of the inside thermal environment to decide the capacity and the number of air-conditioners before the new building is constructed.

In Japan, the so-called "manual" maximum heating and cooling load calculation, proposed by the Society of Japan, is often used to decide the air-conditioners. The biggest advantage of the "manual" calculation is ease of use. Computers and computer simulation are not needed to make the calculations. The other advantage is safety. Data for the worst days for air-conditioning (hottest summer day and coldest winter day) are used so the result is safe. The capacity and the number of air-conditioners must be enough. But this is also one of the most serious disadvantages. The "manual" calculation is sometimes very rough, because it is a static calculation, and so safe that it may let the building have surplus capacity and a surplus number of air-conditioners. A more realistic way should be considered to select the appropriate capacity and number of air-conditioners and thus save energy.

With the foregoing in mind, "TEA" (Simulation Software of the Thermal Environment of an Atrium) has been developed as a dynamic computer simulation with accurate calculation of heat transfer. For instance, "TEA" accurately simulates solar heat gain including multiple reflections of solar radiation between inside surfaces.

DESCRIPTION OF THE GYMNASIUM

Table 1 shows the outline of the gymnasium. The gymnasium was a two-story building and the total floor area was 9690.0m^2. As for the second floor, the area was 2715.4m^2 and the volume was 25263.8m^3. The floor plan of the gymnasium was elliptical and the major axis was from north to south. (See Figure 1)

The gymnasium was covered with glazed windows all around it. The angle between the floor and the windows was 99 degrees. (See Figure 2) "The Punching Metal", that is a metal board with many tiny holes (6mm in diameter), was installed inside 1.5m away from the glass over 2.5m from the second floor.

The opening ratio of the Punching Metal was 50%. The opening ratio is the ratio of the area occupied by hole to the total area of the Punching Metal. Also eaves with a width of 0.5m are installed around the glass. These structures obviously played an important role in reducing the sunshine coming into the room through the windows. The Punching Metal also created the air space between the metal layer and the glass layer. It made the relation between the outside and the room less. (See Figure 3)

Table 1 Some characteristics of the gymnasium

Purpose	: facility for sports
Structure	: mainly SRC, partly RC or S
Latitude	: 34.683 °N
Longitude	: 135.183 °E
Story	: 2 story
Total floor area	: 9690.0 m^2
Second floor area	: 2715.4 m^2
Second floor volume	: 25263.8 m^3

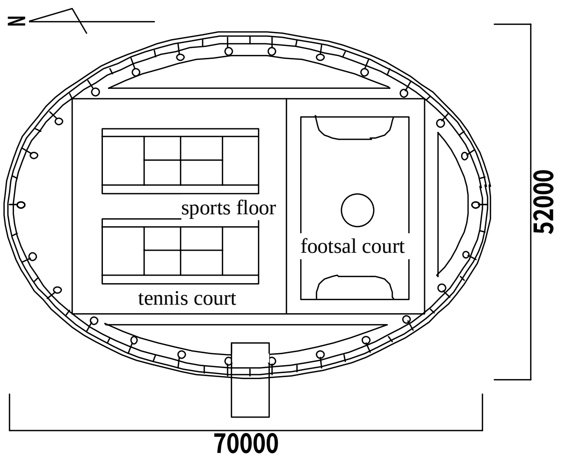


Figure 1 Floor plan of the second floor of the gym

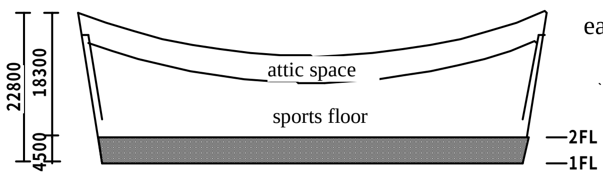


Figure 2 Vertical cross sectional diagram of the gym

"MANUAL" MAXIMUM HEATING AND COOLING LOAD CALCULATION

The so-called "manual" maximum heating and cooling load calculation has been proposed by the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan[1].

OUTLINE AND CONDITION OF CALCULATION

The "manual" maximum heating and cooling load calculation is one of the methods that are called cyclical steady calculation. Although it should be calculated with a computer to calculate it precisely, it is usually calculated without a computer to make it easier. In this method, some factors which don't affect or reduce the load of the air-conditioner are disregarded. For instance, solar heat, sunlight coming into the room through windows, generation of heat by machines, lighting and human beings are disregarded in winter. Table 2 shows the outside temperatures and target temperatures in summer and winter. In summer, it was calculated at 09:00, 12:00, 14:00 and 16:00 because the influence of the sun was considered. These times are local standard time of Japan.

Table 3 shows the direction coefficient and Table 4 shows the shading coefficient. The direction coefficient was settled for each direction on the calculation of the heating load instead of using solar heat gain. The loads are multiplied by the direction coefficients. For instance, the load for the north part is 1.10 times larger than that for the south part. For that reason, for instance, the heating load for SSE and NNE are slightly different in Table 5. On the other hand, as for the calculation of cooling load, solar heat gains were used in each direction in each time. The heat gain of the opposite side areas to solar direction becomes exactly same each other because of none of direct solar radiation. For instance, the cooling load for ENE and ESE are exactly same at 12:00, 14:00 and 16:00.

Only the second floor was calculated. The second floor was divided into eight parts. (See Figure 4)

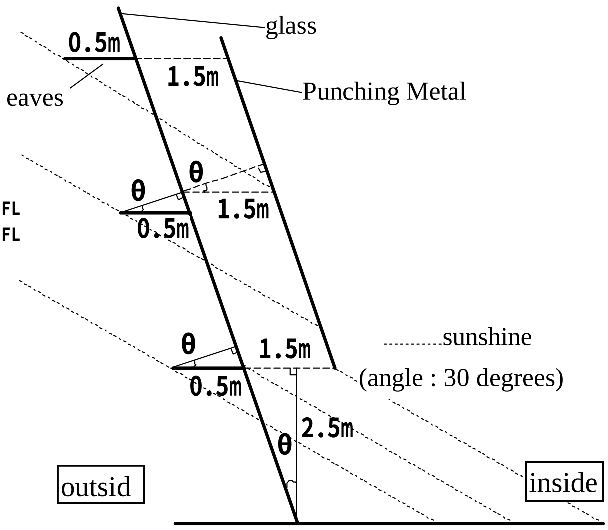


Figure 3 Details of the building envelope of the gym

Table 2 Assumed indoor and outdoor temperatures for the manual calculation method

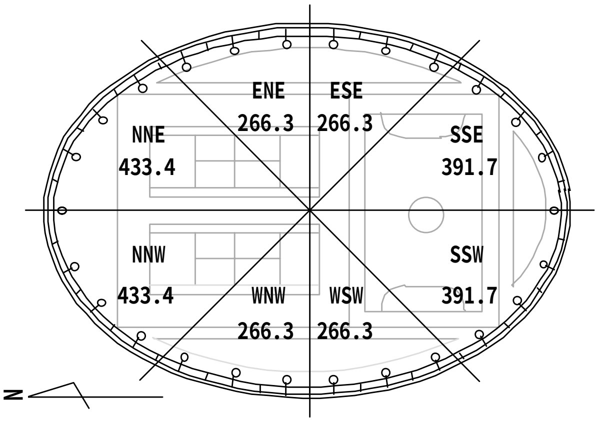
		Outside air temperature [°C]	Inside air temperature [°C]
Summer	09:00	31.4	28.0
	12:00	34.0	
	14:00	34.5	
	16:00	33.7	
Winter		1.3	20.0

Table 3 Direction coefficients based on "manual" calculation method

Flat roof, Floor on first story, Piloti	1.20
Outside wall (north, northeast, northwest, east, west)	1.10
Outside wall (southeast, southwest)	1.05
Outside wall (south)	1.00

Table 4 Shading coefficients based on "manual" calculation method

Without the Punching Metal (1st layer)	0.93
With the Punching Metal (2nd and 3rd layer)	0.56



Figures show each floor space [unit:m^2]

Figure 4 Zoning of the gymnasium for the "manual" calculation method

RESULTS OF THE "MANUAL" CALCULATION

Table 5 shows the heating and cooling load (sensible load) of each division and the whole second floor in summer and in winter. As for the cooling load, each division had its maximum load at a different time because the solar heat was considered in summer. The cooling load of the whole second floor was at a maximum at 16:00. As for the heating load, on the other hand, the differences of the load between other divisions depended on the differences in the area space (or volume) and on the direction coefficients instead of the solar heat.

Table 5 Cooling and Heating Loads in "Manual" Calculation

Division	Cooling load [W]				Heating load [W]
	09:00	12:00	14:00	16:00	
NNE	41643	54519	54690	45053	68452
NNW	39638	54519	54690	71037	68452
SSE	66336	58133	54461	44846	65765
SSW	39480	56234	78902	67605	65765
ENE	83329	40672	40589	33313	47365
ESE	93243	40672	40589	33313	47365
WSW	29751	40672	77024	108932	47365
WNW	29751	40672	57408	109668	47365
TOTAL	423171	386093	458353	513767	457894

*Underlined figures show the maximum load in each division.

MAXIMUM HEATING AND COOLING LOAD CALCULATION USING "TEA"

"TEA" (Simulation Software of the Thermal Environment of an Atrium) has been developed as a dynamic computer simulation with accurate calculation of heat transfer. Temperatures (air temperatures and surface temperatures) and heating and cooling loads of plural rooms (or zones) can be calculated using "TEA". "TEA" basically has the same solution as "THERB*" (Simulation Software of the Thermal Environment of Residential Buildings) which has been developed as a dynamic computer simulation with accurate calculation of heat transfer for residential buildings[2]. As with "TEA", all of the spaces can be divided into rooms (attic space, under floor space and the space between the floors) and air spaces (the space should be put between parallel flat boards) at will. The ways to calculate the convective heat transfer coefficient and radiative heat transfer coefficient in rooms are different from those in air spaces.

By default the convective and radiative heat transfer coefficients in "TEA" are fixed on exterior, interior and cavity surfaces. They can be recalculated at every time steps dimensionless equations which are derived from either the profile method for boundary layer (based on the energy equation, the momentum equation and the fluid friction) or defined from the experimental findings according to natural or forced convection. In this paper, 17.8W/m^{2}K was applied to the exterior convective heat transfer coefficient and 4.3W/m^{2}K was applied to the interior. These values are given in the "TEA" method.

On the exterior surfaces of the buildings, the standard method of using the radiant heat transfer coefficients and net terrestrial radiation is applied. On the interior of buildings, instead of the general method (that is, the calculation of heat transfer by over-all coefficient), the use of the long-wave absorption coefficient makes it possible to simulate a net absorption among interior surfaces. Mutual radiation between the surfaces of cavities in walls and windows can be also simulated[3]. The radiative heat transfer coefficients are calculated using Equation (1). In this paper, 0.9 was applied for the long-wave emissivity of the floor, ceiling and the interior surface of the roof, 0.4 for that of the exterior surface of the roof and the Punching Metal and 0.85 for that of the window.

$$\alpha_r \equiv 0.04\varepsilon_1\varepsilon_2 C_b \left(\frac{T_m}{100}\right)^3 \qquad (1)$$

ε is the long-wave emissivity of the surface and C_b is radiation constant of the black body. T_m should be the average of the temperatures of surface 1 and surface 2.

Incident solar radiation on the exterior and into the interior of buildings is divided into direct and diffuse solar radiation. And they are calculated for all parts of the building in all directions using accurate geometric calculations of shaded and unshaded portions of the building by considering the influence of overhangs and wings. Although the isotropic model is applied by default, the anisotropic model can be chosen.

The solar transmittance and the solar absorptance consider multiplex reflection (depending on the incident angle of solar radiation and the thickness of the glass) between not only the glazing layers but also between the window and interior shade. The multiplex reflection of both direct and diffuse solar radiation among interior surfaces including re-transmission of solar radiation from the inside to the outside through the windows is simulated by using the short-wave absorption coefficient.

In this paper, the solar transmittance and the solar absorptance considering multiplex reflection between the window and the Punching Metal were calculated using Equation (2), (3), (4) and (5). The solar absorptances of window and Punching Metal were α_1 and α_2, the solar reflectances were ρ_1 and ρ_2 and the solar transmittances were τ_1 and τ_2. Granted that the step incidence comes from outside, the net solar transmittance was the sum of the infinite series of transmitted ingredient after the many times of solar absorptions, reflections and permeations between the windows and the Punching Metals[2].

$$\tau_{12} = \tau_1\tau_2 + \tau_1\tau_2\rho_1\rho_2 + \tau_1\tau_2\rho_1^2\rho_2^2 + \cdots = \frac{\tau_1\tau_2}{1-\rho_1\rho_2} \qquad (2)$$

The total solar absorptance of the window and the Punching Metal was also calculated as the sum of the infinite series.

$$\alpha_{\bar{1}2} = \alpha_1\left(1+\tau_1\rho_2+\tau_1\rho_1\rho_2^2+\cdots\right) = \alpha_1\left(1+\frac{\tau_1\rho_2}{1-\rho_1\rho_2}\right) \qquad (3)$$

$$\alpha_{1\bar{2}} = \alpha_2\tau_1\left(1+\rho_1\rho_2+\rho_1^2\rho_1^2+\cdots\right) = \frac{\alpha_2\tau_1}{1-\rho_1\rho_2} \qquad (4)$$

The net reflectance was calculated using Equation (5).

$$\rho_{12} = \rho_1 + \tau_1^2\rho_2 + \tau_1^2\rho_1\rho_2^2 + \cdots = \rho_1 + \frac{\tau_1^2\rho_1}{1-\rho_1\rho_2} \qquad (5)$$

OUTLINE AND CONDITION OF CALCULATION

Calculations were only made for the second floor. Firstly, the floor was divided along the height into three layers. (See Figure 5) Next, the first layer was divided into 16 zones and the second and the third layers were divided into 30 divisions because the second and the third layers had spaces between the Punching Metals and windows. (See Figure 6) In the following section, the heating and cooling loads were calculated in each division (NORTH, SOUTH, EAST and WEST) which consisted of four zones on the first layer, and seven or eight zones on the second and third layers.

Table 6 shows the conditions for simulation. The Standard Weather Data for Osaka were used as the weather data in the calculation. The target temperature of cooling and heating were the same as the ones in the "manual" maximum heating and cooling load calculation. As for the lower four lines in Table 6, the existence of ventilation, the opening ratio of the Punching Metal, the air-conditioning system and the angle between the floor and the windows show the original values. Those have been changed in the following section to verify that the original values are appropriate.

Table 6 The Conditions for Simulation

Weather data	: Standard Weather Data (Osaka)
Calculation periods	: June – September (Summer) December – March (Winter)
Simulation interval	: 1 hour
Target temperatures	: 28 degrees C (cooling) 20 degrees C (heating)
Air-conditioning time	: 10:00 – 20:00
Ventilation	: no*
Opening ratio of the Punching Metal	: 50%*
Angle between floor and windows	: 99 degrees*
Air-conditioning system (area)	: central*

*Lower four lines are changed in calculation

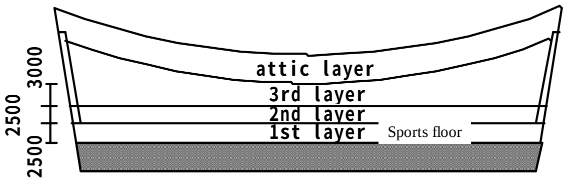
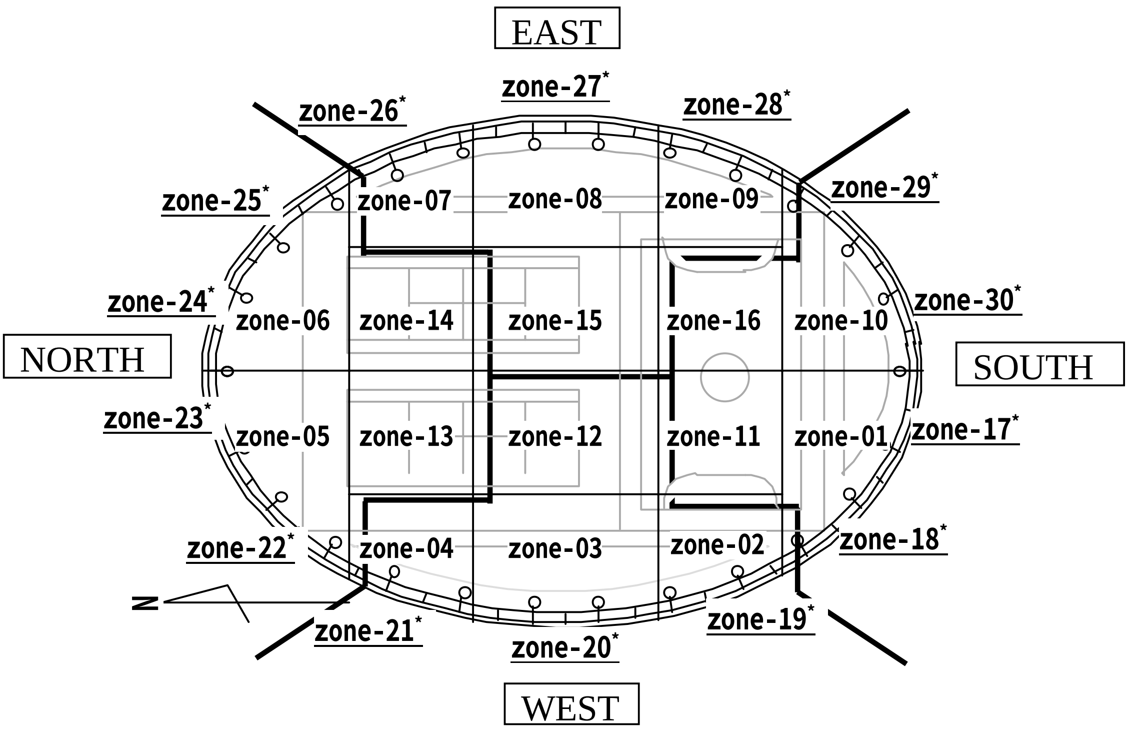


Figure 5 Divisions in "TEA" (**s**ection)



*The figures with underline are for air space between windows and the Punching Metals only on the second and the third layers.

Figure 6 Divisions in "TEA" (plane)

RESULTS OF THE "TEA"

Table 7 shows the outdoor temperature of Osaka. Table 8 shows the heating and cooling load (sensible load) of each division and the whole second floor in summer and winter that were calculated using "TEA". The cooling loads were the simulation results for August 11th and the heating loads were for January 28th. As for the total load, the cooling load reached its maximum (a little lower than 250kW) at 16:00 and the heating load became a little higher than 263kW at 10:00. Both of these loads were much lower than those calculated using the "manual" calculation. Figure 7 shows the accumulative time distribution of the heating and cooling load. The percentage of time that the load was more than 250kW were 1.11% for cooling load, and 1.07% for heating load. As for the heating load, it showed 0W in 275 hours out of 1331 hours. (20.66%)

Table 7 Assumed indoor and outdoor temperatures on the maximum load days in Osaka

		Outside air temperature [°C]	Inside air temperature [°C]
Summer (Aug. 11)	14:00	34.0	28.0
	15:00	33.9	
	16:00	33.4	
	17:00	32.5	
Winter (Jan. 28)		2.6	20.0

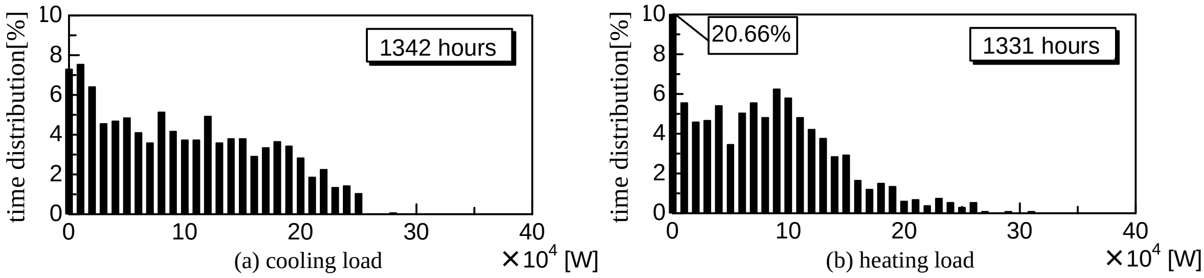


Figure 7 Accumulative Time Distribution of the Heat Load

Table 8 Cooling and Heating Load in "TEA"

Division	Cooling load [W]				Heating load [W]
	14:00	15:00	16:00	17:00	10:00
NORTH	<u>64072</u>	62887	61536	59088	81048
SOUTH	65683	<u>67219</u>	64355	57453	64245
EAST	<u>49842</u>	49063	45534	39465	53084
WEST	56774	68700	78566	<u>83107</u>	64959
TOTAL	236371	247869	<u>249991</u>	239113	263336

*Underlined figures show the maximum heat load in each division.

PARAMETER SENSITIVE ANALYSIS OF "TEA"

The parameters, shown in the lower four lines in Table 6, were changed to clarify their influences on the heating and cooling loads, the indoor air temperatures and the solar transmittances. All of the cooling loads were calculated for August 11th and the heating loads were calculated for January 28th.

INFLUENCE OF THE VENTILATION ROUTE

Although, in the previous section, ventilation was disregarded in "TEA" to compare it with the "manual" calculation, ventilation by using air-conditioning equipment should really be considered. Figure 8 shows the three routes of ventilation. The inside air went out from the top of the windows in Case 1. The air exhausted through the attic space in Case 2 and through the airspace between the windows and the Punching Metals in Case 3.

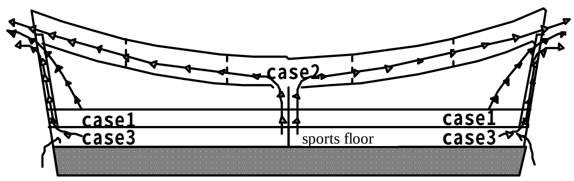


Figure 8 Routes of Ventilation

Table 9 shows the influence of the ventilation routes upon the cooling and the heating loads. Case 0, with no ventilation, was also calculated to compare with the others. The air change rate per hour was 0.5 except in Case 0. The temperature of the supplied air was the setting temperature of the air-conditioning equipment. Both the cooling load and the heating load were at their lowest in Case 2. The air temperature in the attic space tended to be affected by the outside air temperature. In Case 2, the exhaust air from the second floor was drawn into the attic space and reduced the influence of the radiation from the ceiling by making the attic space air temperature closer to the room air temperature.

INFLUENCE OF THE OPENING RATIO OF THE PUNCHING METAL

The opening ratio of the punching metal was originally 50%. In this section, the heating and cooling loads and the solar transmittances were calculated for four types of opening ratio, 30%, 50%, 70% and 100%. There is no Punching Metal when the opening ratio is 100%. Table 10 shows the results of the simulation. To get rid of the Punching Metal led to two consequences. One was an increase in the solar radiation and the other was the removal of the air space between the windows and the Punching Metals. In summer, the cooling load without the Punching Metal (an opening ratio of 100%) was much higher than the others because both of the consequences acted as disadvantages. In winter, compared with the cooling load, the heating load without the Punching Metal was not much higher than the others because, although the removal of the air space between the windows and the Punching Metals acted as a disadvantage, the increase in solar radiation became an advantage.

Figure 9 shows the influence of the opening ratio of the Punching Metal on the net direct solar transmittances considering the glass and the Punching Metals. The direct solar transmittances were in proportion to the opening ratio of the Punching Metal except on the north side, which did not get sunshine in winter.

INFLUENCE OF THE ANGLE BETWEEN THE FLOOR AND THE WINDOWS

The heating and cooling loads were calculated for different angles between the floor and the windows the original angle of 99° was changed to 90°, 110° and 120°. Table 11 shows the result. To enlarge the angle between the floor and the windows decreased the sunlight through the windows into the room. That was an advantage to cooling loads and a disadvantage to heating loads. The amount of increase of the heating load for angles over 99° was larger than that for below 99°. On the other hand, the amount of decrease of the cooling load for angle over 110° was much smaller than that for below 110°.

Table 9 Influence of the Ventilation Routes

Route	Cooling load [W]	Heating load [W]
Case0 (no ventilation)	249991	263336
Case1	249668	218984
Case2	230372	197317
Case3	241404	224395

Table 10 Influence of the Opening Ratio of the Punching Metal

Opening ratio of Punching Metal	Cooling load [W]	Heating load [W]
30%	245376	262130
50%	249991	263336
70%	254535	266169
100%*	391559	277686

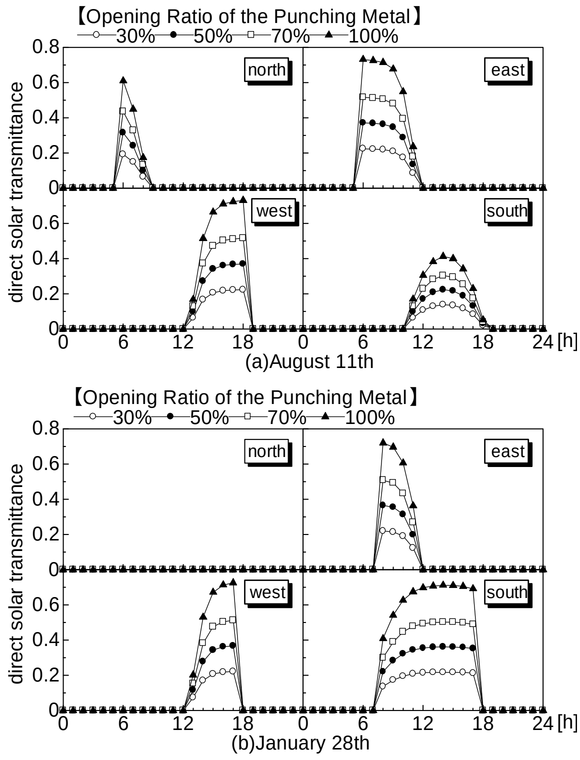


Figure 9 Direct Solar Transmittance

INFLUENCE OF THE AIR-CONDITIONING AREA

Although, so far in this paper the air-conditioning area was considered as the whole area of the second floor, only the lower areas for activities are air-conditioned (particularly air-cooled) in most cases. Table 12 shows the results of simulation changing the air-conditioning area. The ventilation route was also changed. In all routes, the cooling load for only the first layer was less than half of that for the whole area. The cooling load for only the first layer, the same as that for the whole area, showed the lowest load with the Case2 route. Figure 10 shows the temperatures in the second floor with the air-cooling for only the first layer. The temperatures in the figure were the average of the zone temperatures in each layer. Above the second layer, the temperatures with the Case1 and Case2 route were slightly lower than those for the other routes.

CONCLUSIONS

1) The "manual" calculation was so rough that the heating and cooling loads were more than twice those obtained from calculations using "TEA". Using the "manual" calculation may let the building have surplus capacity and a surplus number of air-conditioners.
2) A dynamic simulation is better than a steady calculation to calculate accurate heating and cooling loads.
3) It is important to simulate heating and cooling loads with a parameter sensitive analysis before starting construction. For instance, the following are the conclusions of the parameter sensitive analysis in this paper.
   i) Different ventilation routes have variable influence on the heating and cooling load. In this paper, the exhaust air should be drawn into the attic space.
   ii) Although the Punching Metal has more influence on the cooling load than on the heating load, it works well even in winter.
   iii) To incline the windows a little, with the top to the outside, makes the heating and cooling load smaller.
   iv) The load, particularly the cooling load, should be calculated using the actual cooling area to make accurate more calculations.

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Table 11 Influence of the Angle between the floor and the windows

Angle between floor and windows	Cooling load [W]		Heating load [W]	
90°	263020		257854	
99°	249991	-13029	263336	+5482
110°	235553	-14438	270826	+7490
120°	232118	- 3435	278715	+7889

Table 12 Influence of the Air-conditioning Area

Air-conditioning area	Cooling load[W]			
	case0	case1	case2	case3
Whole area	249991	249668	230372	241404
1st layer	102428	98610	96477	102190

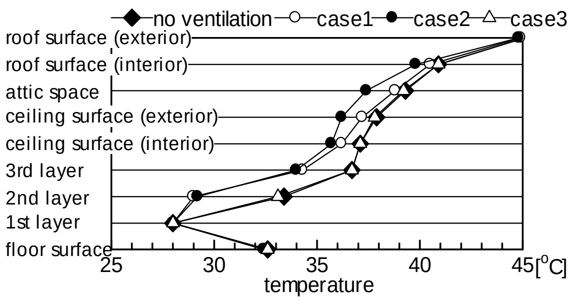

Figure 10 Temperatures (Vertical Distribution)

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*THERB has been approved as the method to calculate annual heat loads by Ministry of Land, Infrastructure and Transport, Japan. (The approval number : 141)