COMPARATIVE SUMMER THERMAL AND COOLING LOAD PERFORMANCE OF NATURAL VENTILATION OF CAVITY ROOF UNDER THREE DIFFERENT CLIMATE ZONES

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ABSTRACT
This paper presents the benefit of natural ventilation of a roof cavity to reduce summer thermal loads of a factory and, therefore, the cooling load due to air-conditioning systems with respect to various climate zones in Japan. A simulation program was developed to analyze the impact of cavity ventilation on the operative temperatures of the occupied zones in a factory. Three climate zones in Japan: cold region (Sapporo), temperate hot-humid region (Tokyo), and subtropical region (Naha) were selected for comparison. In an air-conditioning mode, two calculations of cooling loads were made. In one of the calculations, the factories were supposed to be air-conditioned whenever the operative temperature was higher than 26°C. In the other calculation, the air-conditioning was operated only during the working hours. Results show that the cavity roof factory was superior to the single roof factory in lowering operative temperature. In a cold region, the presence of natural ventilation of a cavity roof allowed the factory operated under natural ventilation in most of summer time while in the hotter regions, the application of cavity roof showed an excellent potential for reducing energy cooling loads.

KEYWORDS
Cavity roof, Factory building, Climate zone, Cooling load, Energy savings

INTRODUCTION
The necessity to improve thermal environment and to reduce the energy demand of the HVAC system in buildings is pushing designers into application of new options for the ventilation system. With the rapid industrial development period since several decades ago, many factories exist in South-East Asia which, were built with corrugated asbestos cement boards. The typical structure involves a single roof, which spreads widely and has a relatively low inclination. In such a building, the heat transfer characteristics of the roof have strong influence on the thermal environment and thermal load beneath it. In particular, the solar irradiation of the roof out-weighs the cooling load substantially, making the work space below unbearably hot, causing a reduction in work efficiency and precision. In terms of improving the thermal environment of building and reducing cooling power consumption, it is more viable to prevent heat transfer through building claddings than to evacuate the heated air by way of cooling installations. This holds true concerning the initial investment and is also favorable considering the long-term expense. As a result of the recent warming of the global atmosphere, industrial buildings which require cooling in summer are beginning to appear in areas of higher latitude.

Since the factories have become aged and require expensive maintenance and repair work, the idea of

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covering the old single roofs totally with folded thin metal plates was pointed out in this study. When an old single roof is covered, a cavity is formed between the old roof and the new cover. If this cavity was to be ventilated, it would favorably stop the penetration of solar radiation and thus reduce the heat in the work space.

The present authors had previously undertaken a study on the impact of natural ventilation of a roof cavity on improvement of the thermal environment and reduction of cooling load of a factory building (Susanti et al, 2007). A simulation program was developed to discuss the effect of cavity ventilation on the operative temperature of the occupied zone in a factory under the climate of Toyohashi city, Japan (Latitude of 37°43’N). The study concluded that a factory with a cavity roof system was superior to a conventional single roof factory in lowering operative temperature by about 4.4°C. When the factory was air conditioned, the cooling load reduction reached to about 50% during the summer to keep an operative temperature of 26°C.

Base on those findings then the authors considered the possible influences of the climatic variations existed in Japan due to large north-south extension, as shown in Figure 1, on the thermal performance of a factory building. In this study, the climate condition of Japan was divided into three climate zones; cold region (Sapporo), temperate hot-humid region (Tokyo), and subtropical region (Naha). Figure 2 shows mean temperature and horizontal solar radiation during the year of 2006 for those representative cities. It can be seen that outdoor temperature of Sapporo was the lowest among three cities indicating cool summer was allowed in this city. But it is interesting to see that horizontal solar radiation of Sapporo, particularly during the summer period was considerable stronger than that of Tokyo. It is supported by a well-known fact that Tokyo’s environment is more polluted than that of Sapporo hence diffused radiation in Tokyo is greater than the portion of its direct solar radiation. It is presumed that these variations in climate condition will contribute significantly to the heat gain in the factory. Indeed, since the building envelopes of a factory due to its working purpose and efficiency are normally constructed with the similar building materials throughout Japan, the climate impact on the thermal environment of the factory will be profound. Therefore, it is important to evaluate the benefit of implementation of the cavity roof system with respect to various climate zones in Japan.
METHODOLOGY

The Factory

The factory was modeled as a one-story building occupying a total floor area of 5000 m$^2$ (100 m x 50 m). The ridged roof tilted at 20$^\circ$ facing east and west and the gable end walls faced north and south. Figure 3 shows the schematic representation of the cavity roof. The upper layer of the roof consisted of a folded metal plate of a thickness of 0.6 mm separated from the lower structure by an air cavity of a thickness of 78 mm. The lower structure was composed of a corrugated asbestos cement board of a thickness of 8 mm and an insulation board of a thickness of 20 mm made from wood fiber and cement mixture. The subsequent cavity was left open to the air at the top and bottom of the roof inclination. Slits of various sizes were considered at the openings to substitute the flow resistances of rain cover, insect net and structural members in a real cavity.

Other geometries of the factory were as follows: the eave height was 6 m; the ridge height was 14.1 m; the roof length was 26.6 m; the ridge length was 100 m, and the volume was 47750 m$^3$. The doors were placed at both northern and southern walls, respectively, and accounted for 10% of each wall area. The walls consisted of a corrugated asbestos cement board of a thickness of 8 mm, an air space of 50 mm, which had a thermal resistance of 0.04 m$^2$K/W, and a wood fiber cement insulation board of a thickness of 25 mm, from the outermost to the innermost layers. Corrugated transparent plastic sheets were arranged along both eastern and western walls for day lighting, respectively accounting for 14.7% of total area of the each wall. The thermal properties of the materials used were procured from the ASHRAE Handbook of Fundamentals 2005, and elsewhere, and presented in Table 1. The reference single roof factory was considered to have the same geometry as the cavity roof factory, but without the upper plate on the roof. An air change of 5 times per hour was supposed in both of the conditions. In the natural ventilation mode, this air change was supposed to be caused by natural wind through the opened doors. In the air-conditioned mode, this air change was kept by mechanical ventilation. This structure was used for calculation for all cities considered.

Weather Data of Investigated Cities

The typical meteorological year weather data of the Expanded AMeDAS (Automated Meteorological Data Acquisition System) developed by the Japan Meteorological Agency (JMA) was used to generate the weather data on an hourly basis for each day. Direct and diffused solar radiations on a horizontal
surface and ambient temperatures were included in the data. For prediction of insolation on non-horizontal surfaces, the formulations described in Chapter 31 of ASHRAE Handbook of Fundamentals 2005, were used. Radiation from the ground was estimated from ambient temperature where ground reflectivity was taken to be 0.2 for a typical mixture of ground surfaces.

Simulation Model

Modeling of heat and air transfers in the cavity roof was developed by steady state energy balance equations. Mathematical model of the factory simulation was formulated in details by Susanti et al. in the other article that is not presented in this paper. In a naturally ventilated mode factory three parameters of indoor thermal environment; indoor air temperature, mean radiant temperature and operative temperature were discussed. Three days in August which showed similar pattern of incident solar radiation in three cities were chosen as representative days of strongest solar radiation during the summer months for detailed performance discussion.

When the factory was operated under an air-conditioning mode two calculations of cooling loads were made. In one of the calculations, the thermostat of air-conditioning was set 24 hours and the factories were supposed to be air-conditioned whenever the operative temperature was higher than 26°C. In the other calculation, the air-conditioning was operated only during the working hours of between 8 a.m. and 6 p.m. The simulation was used to estimate total cooling load during the summer period (Approximately July through September).

RESULTS AND DISCUSSIONS

Comparisons of thermal environment in a naturally ventilated factory

Indoor air temperatures

Comparison of indoor air temperatures between factories with a cavity roof and a single roof in three climate zones is displayed in Figure 4. As revealed by the graph, factory with a cavity roof was superior to the single roof factory in lowering the peak indoor temperatures of 3.9°C, 3.9°C and 4.1°C, respectively for Sapporo, Tokyo and Naha. As the factory buildings were identical to both cavity and the single roof factories, except their roof structures, the difference in indoor air temperatures was mainly the result of the difference in the heat transferred from the roofs. It can be seen that there was a high improvement of indoor air temperatures inside the factory with the help of the cavity roof.

Mean radiant temperatures

Figure 5 shows comparison of mean radiant temperatures for both cavity and single roof factories in three investigated cities. Mean radiant temperature is a measure used to indicate the effects of radiant heat of a surface on an occupant’s thermal comfort. The larger the surface area, and the higher the temperature, the stronger the effect of the surface is on the thermal comfort in a space. In this study, the surface area of the roof accounted for a considerable part of the total area of the envelopes, hence the surface temperature of the roof significantly influenced on thermal comfort. As indicated in the

<table>
<thead>
<tr>
<th>Materials</th>
<th>Thickness (mm)</th>
<th>Specific Heat (J/kg.K)</th>
<th>Specific mass (kg/m3)</th>
<th>Thermal conductivity (W/m.K)</th>
<th>Thermal Transmittance</th>
<th>Emissivity</th>
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<tbody>
<tr>
<td>Corrugated metal plate</td>
<td>0.6</td>
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<td>7830</td>
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<tr>
<td>Corrugated asbestos cement board</td>
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<td>2400</td>
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<tr>
<td>Wood cement board</td>
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<td>Glass wall</td>
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</table>
graphs, mean radiant temperatures for a single roof factory were considerably high compared to those of a cavity roof factory in all cities presumed causing discomfort to occupants. However, the presence of the air cavity in the roof decreased the peak mean radiant temperatures by about 7.1 °C, 7.1 °C and 7.5 °C, for Sapporo, Tokyo, and Naha, respectively.

Operative temperatures
The operative temperature takes both radiation and convection into account and is therefore a much better indicator of thermal comfort in a built space rather than a single indoor air temperature. Figure 6 shows comparison of operative temperatures between the two roofing systems for three different climate zones. Average operative temperatures during the working hours for the cavity roof factory were 28.6 °C, 32.0 °C and 31.6 °C while for the single roof factory were 32.5 °C, 35.5 °C and 35.8 °C, for Sapporo, Tokyo and Naha, respectively. Thus the operative temperatures of the factory could be
lowered 3.9°C, 3.5°C and 4.2°C, respectively by the presence of the cavity roof. This improvement is perceived as being valuable in effecting working efficiency.

From the thermal point of view the cavity roof factory may successfully competed with the conventional single roof factory. Natural ventilation of a cavity roof was a crucial component for reduction operative temperatures inside the factory. However, in a period of excessive heat gain the natural ventilation solely might bring disadvantages to the thermal environment of the factory. In this condition, therefore, the use of air-conditioning was unavoidable to ensure the occupant’s comfort.

Comparison of cooling load in an air-conditioning factory

Figure 7 to Figure 9 show comparisons of total summer cooling loads for both single roof and cavity roof factories for the three cities. In each city, comparison of cooling loads was made between the factory operated under air-conditioning mode during the working hours and during 24 hours. Cooling consumptions of the factory for Naha were the highest among the three cities indicated that this city had longer hours of the summer period compared to other two cities resulting in increasing the energy consumption of air-conditioning. A single roof factory in Naha consumed energy for cooling 13MW/day when the air-conditioning was operated during the working hours and 17MW/day when the air-conditioning was operated during 24 hours. But these consumptions were reduced with the help of the cavity roof. The savings were predicted 46.4% and 39.3% for both two operating time of air-conditioning, respectively. Table 2, moreover, shows detailed performance of this outcome.

In Tokyo, the cavity roof factory reduced cooling load of 42.8 % and 31.0% for the two operating time of air-conditioning, respectively. The largest saving was promoted by the cavity roof in Sapporo. The cooling loads decreased 49.4% during the working hours of operating system and 70.6% during 24-hours of operating system. From these results it can be concluded that the implementation of the cavity roof system in three different climate zones has potential benefit in reducing cooling loads in a factory. This makes significant contribution to energy savings.

Table 3 exhibits the effectiveness of the use of air-conditioning in two operating time. In Naha and Tokyo, the use of air-conditioning system during the working hours was recommended compared to that of during the 24-hours. The cooling loads reduced 33.9% and 35.1%, respectively for the cavity roof factory and 25.1% and 21.8%, respectively for the single roof factory. However, the results were in reverse for Sapporo. When the air-conditioning was operated continuously during the working hours it increased the cooling loads by 53.1% and 19.1% for the cavity roof factory and the single roof factory, respectively. This result indicated that cool summer in Sapporo allowed the factory operated under natural ventilation. The thermal environment inside the factory was most in a comfortable range for the occupants hence there was time during the working hours that were not necessary for the use of air-conditioning. Therefore, if the air-conditioning was turn on only when the operative temperatures exceeded 26°C, it would give higher potential savings compared to if the air-conditioning was operated at all working times.

CONCLUSIONS

The presence of natural ventilation of the cavity roof in a factory showed major advantages in term of improvement thermal environment in the occupied zone and reduction of summer cooling energy consumption. Its application in cold region (Sapporo) would bring benefits on allowing the factory operated in a naturally ventilated mode at most of summer time. The use of air conditioning non-stop during the working hours in this region was not recommended. Instead, it would give larger savings if the air-conditioning was operated only if the operative temperatures exceeded 26°C.

In hotter region like Tokyo and Naha the reverse was true. During the working hours of the entire summer period, thermal environment inside the factory was beyond the occupant’s comfort hence the utilization of air-conditioning during the working hours would provide good indoor thermal environment for the occupants and save larger energy cooling consumption.
REFERENCES


Table 2 Comparison of reduction of cooling load of factories in three cities for two roofing system

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<tr>
<td></td>
<td>Naha</td>
<td>Tokyo</td>
</tr>
<tr>
<td>Single roof</td>
<td>100%</td>
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<tr>
<td>Cavity roof</td>
<td>46.4%</td>
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Table 3 Comparison of reduction of cooling load of factories in three cities for two operating time of air conditioning

<table>
<thead>
<tr>
<th></th>
<th>Cavity roof</th>
<th>Single roof</th>
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<tr>
<td></td>
<td>Naha</td>
<td>Tokyo</td>
</tr>
<tr>
<td>24 hours</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Working hours</td>
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<td>35.1%</td>
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