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Measurement and evaluation of the indoor thermal environment in a large domed stadium

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Abstract

This paper describes the measurements and evaluation of the indoor thermal environments in a large domed stadium. This stadium was built mainly for professional baseball games, but it has a lot of other purposes. It will be used not only for many sport games but also for various entertainment events. To satisfy such purposes, various intelligent mechanical systems were equipped to control and create a suitable space and environment without consuming excessive energy. A multi-zonal air-conditioning system with an under-seat supply of conditioned air and displacement ventilation is one of these. Measurements, including temperature distribution, humidity, air flow and outdoor weather conditions, were carried out for three seasons, with each measurement period lasting for a week. In this paper, the results during the summer are discussed. The results show that the horizontal temperature distribution indicates that the air-conditioning system separates the space effectively and that each zone can run well separately. The vertical temperature distribution also indicates that the under-seat supply air-conditioning system provides air-conditioning to a limited area, or to the occupant zone only.

Keywords: A large domed stadium; Under-seat supply air-conditioning; Displacement ventilation

1. Introduction

An indoor stadium or roofed field can bring the moderate indoor climate by shutting out rain, strong wind and direct sunshine. Inside, players may do their best and spectators can enjoy the game comfortably. A large indoor stadium can provide any kind of sport that needs a wide field in all kinds of weather. Professional baseball is one such sport. In Japan, the rather long rainy season often disturbs baseball games and makes the schedule very tight. A desire and necessity to solve these difficulties has led to the construction of large indoor stadiums [1]. They are called domes because generally they are circular and have a rotunda. Their primary purpose is to provide space for professional baseball games and other sports that need a large area. These activities having in huge numbers of spectators, and the domes are like an amphitheaters. They may also be used for many other kinds of events, such as musical concerts, exhibits and ceremonies. To satisfy so many requirements, the dome must have a variety of technical installations. At the same time, a huge amount of energy will be consumed to control the environment of such a large space, even if adequate precautions have been taken [2]. It is very interesting to know how indoor climate conditions are controlled and what kind of technology are adopted to various outdoor conditions. This paper describes the summer measurement and evaluation of the indoor climate of the stadium built in April, 1997, in Osaka [3,4]. This commercial facility needs to satisfy many functions as well as to save energy. The former need is provided for with a mechanical system used to adjust or modify the spacing, the lighting and the sound. For example, a huge movable wall and suspended ring ceilings can divide the space both horizontally and vertically [5]. The

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latter need is dealt with by a multi-zonal air-conditioning system limited to the occupant area and a system of natural displacement ventilation. In this paper, we mainly discuss the latter items.

2. Description of dome and technical installations

Fig. 1 shows the dome used in this measurement. The roof of the dome is 166 m in diameter, is 42 m high, and is constructed of a steel lamella truss frame that is 7000 tons in weight. The inner part of the roof, which is 76 m in diameter, is made with translucent polycarbonate resin sheets and the rest with stainless steel sheets. The daylight through the translucent roof can be blocked off by the super-rings hanging from the roof. The arena is 150 m in diameter, is 72 m high, and has about 50,000 seats at a maximum. The circumference of the arena, which contains many shops, restaurants, luxury suites and game arcades acts as a good rigid frame, as well as a heat barrier. It has one story below, nine above ground, as well as a penthouse.

One of the most important requirements to air-condition such a huge space effectively is to minimize the air-conditioned space. This can be done by employing a seat air-conditioning system and multi-zoning. The conditioned air is discharged from the diffuser situated at the top of the

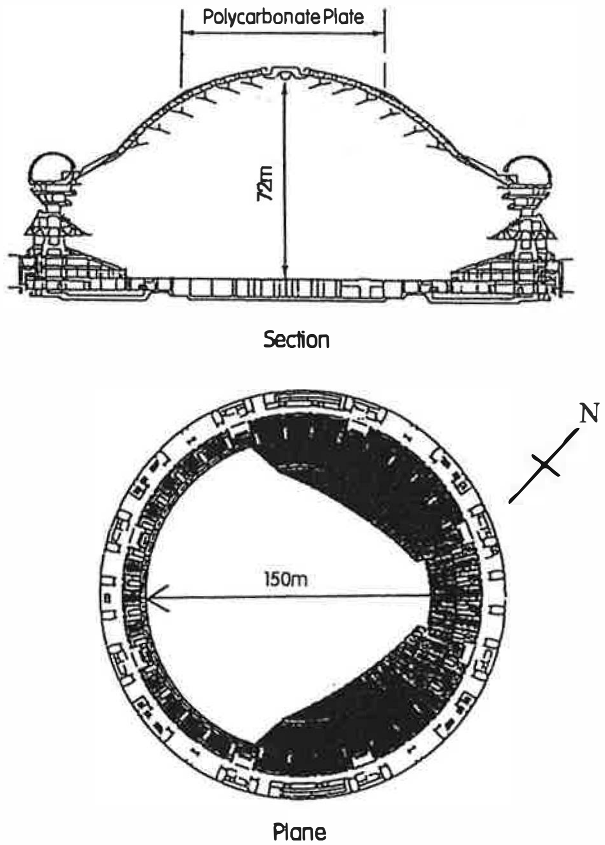

Fig. 1. Plane and section view of the domed stadium.

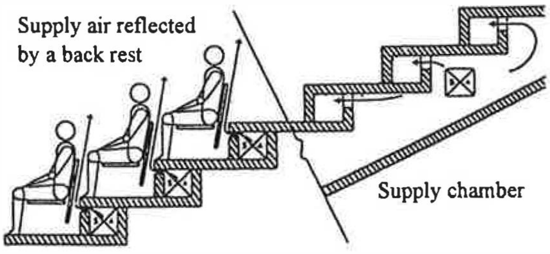

Fig. 2. Seat supply air conditioning system.

back rest and/or from under the seat at the rate of 33 m^3/h per each seat. The latter discharges the conditioned air from the diffuser situated under the seat and bends upward by the next front rest, as shown in Fig. 2. This seat air-conditioning system can limit the air-conditioned space within the zone of normal occupancy. In addition, these dispersed diffusers are divided into 29 zones; in each zone the air can be supplied with a different temperature and any rate of out door air. The heat load of each zone will be handled independently by the temperature and the amount of supplied air. The air discharged from the seats will go up by picking up the heat generated by occupants, lights and other equipment. The warmed and contaminated air will go out through the roof air-movers, and on the way will pick up the solar heat accumulating in the top light. This displacement ventilation, boosted by the blowing outside wind force, will be able to satisfy the required air change rate, at about 1.4 changes per hour at maximum occupancy. The amount of the extracted air is controlled by remotely adjusting the rate of the opening area of the air-mover to the direction and the power of the wind, which is one of many other computer controls. When neither cooling nor heating is required, natural ventilation is expected to satisfy the minimum acceptable rate of air changes.

3. Measurement

Measurements are taken both in intensive short-term periods and over a continuous long-term period. The for-

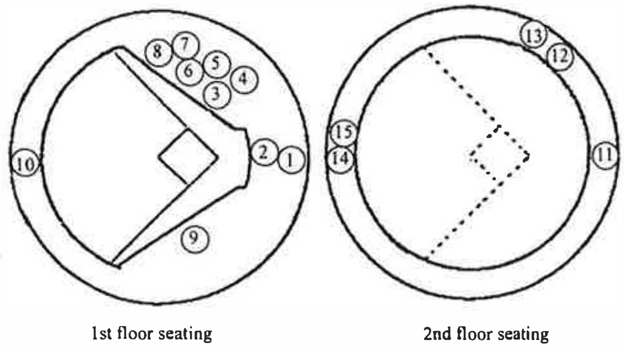

Fig. 3. Temperature and humidity measuring points at seating.

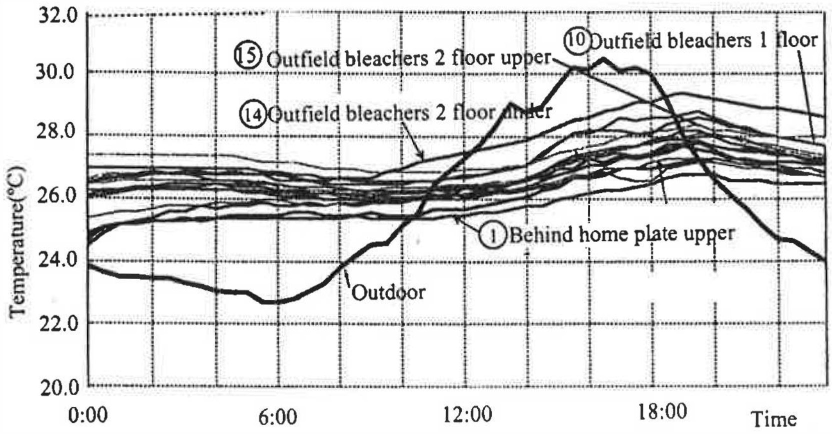

Fig. 4. Temperature (July 18; No use; No cooling).

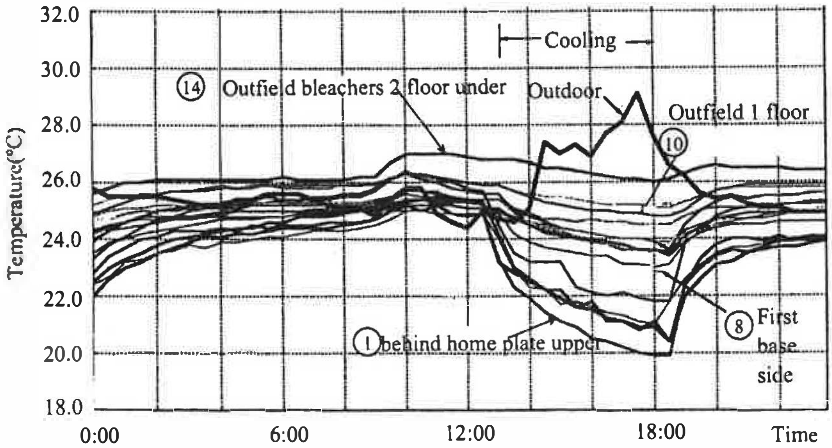

Fig. 5. Temperature (July 13; No use; Cooling).

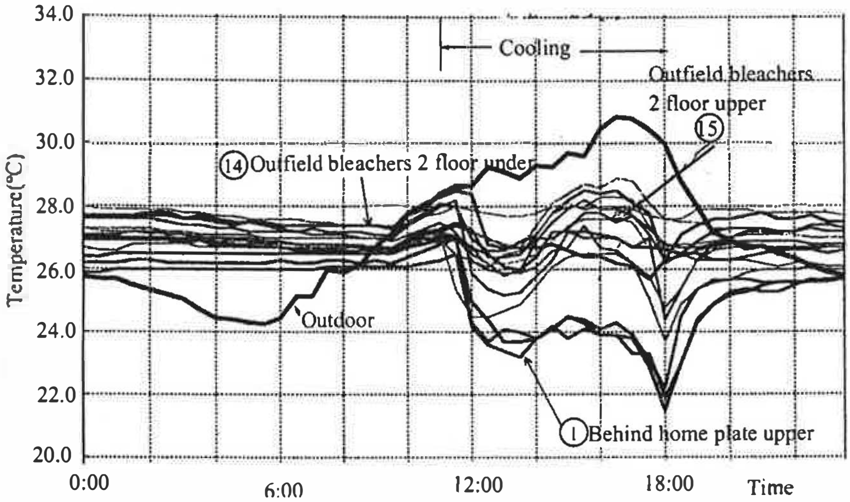

Fig. 6. Temperature (July 20; Professional Baseball; 40,000 people).

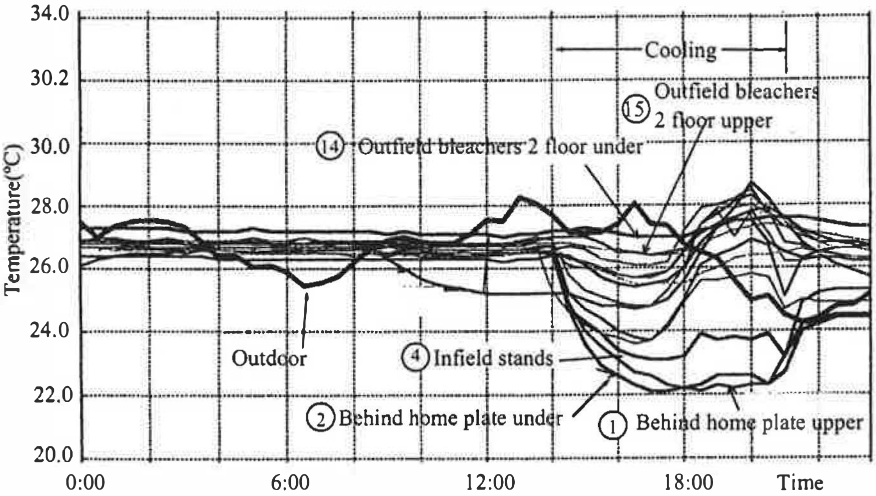

Fig. 7. Temperature (July 27; Concert; 55,000 people).

mer measures of the vertical temperature distribution, which cannot be done when the spectator events are taking place. The latter measures the horizontal distribution of temperature and humidity in the seats both while they are in use and not in use. The thermistor measuring temperature and humidity is connected to a small datalogger, which is contained in a metal-box to protect against burglars. The 15 datalogger units are distributed at the sampling spots shown in Fig. 3. The measuring accuracy of the thermistor is ± 0.3°C ($-20 \sim 80$°C) and $\pm 5\% \pm$ (at 25°C and 50%) average.

4. Results and discussion

To certify the efficiency of cooling system, temperature distributions in seating are discussed. Fig. 4 shows a temperature distribution, while the area is not in use and does not need cooling. A horizontal temperature variation among the sampling points is only within 2°C, and the daily temperature change is very small compared with the outside temperature. The time-lag between them is about 2 h. This shows that there is no remarkable temperature difference between seats. The lower seat has a lower temperature than te upper one. This shows the effect of natural temperature stratification.

To compare with this, a temperature distribution during a period when the structure is not in use but when it is being cooled is shown in Fig. 5. The temperature of supply air is 20°C. The temperature variation grows wider both horizontally and vertically. The reason of this variation is because the different path of the conditioned air. The air temperatures at the air-conditioner outlet are the same but those at the under seat diffuser differ from each other. In

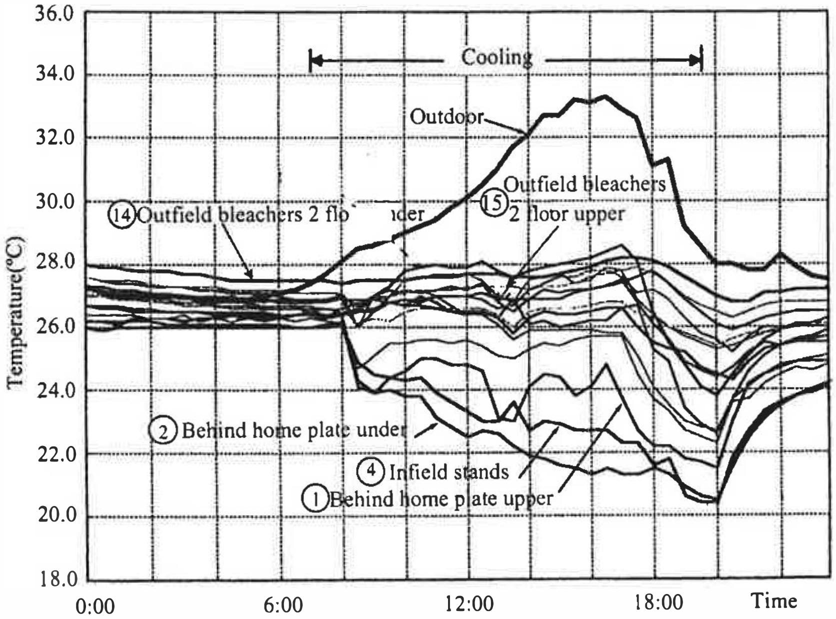

Fig. 8. Temperature (August 2; Ceremony; 23,000 people).

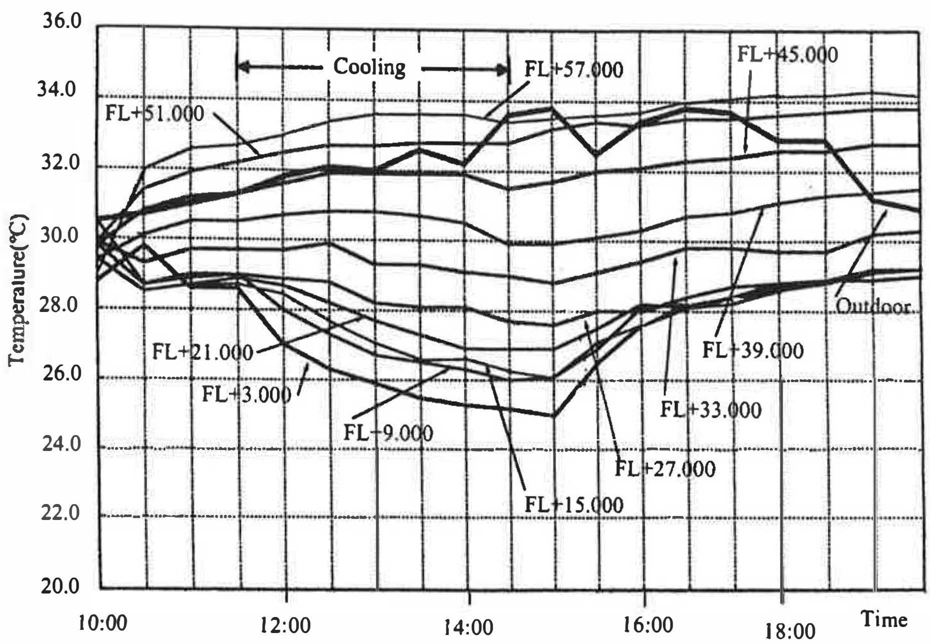

Fig. 9. Vertical temperature distribution above the field as time series (August 11).

this case, the air-conditioner supplying the zone expressed by Point No. 10 in Fig. 3 is only turned off. As shown in Fig. 5, Point 10 keeps at an even temperature and is 2°C higher than that of Point 8. This clearly shows the effect of zone control. Only a slight mixing of air in the adjoining zones occurs, and the heat load of each zone can be handled separately.

The results measured under occupancy are discussed, as follows. Fig. 6 shows the temperature changes measured during a professional baseball match, Fig. 7 shows them during a concert event, and Fig. 8 shows them during a religion ceremony. In Fig. 6, the indoor temperature fluctuates precisely as it follows the change of the load. When the air-conditioning kicks in at about 1100 h, the indoor air temperature dives quickly and rises with an increase of spectators at about 1300 h. The temperature again dives and rises more quickly after the spectators go away and the air-conditioning is turned off at 1800 h. In the cases of the concert and ceremony shown in Figs. 7 and 8, the indoor temperature changes like the baseball game but more moderately. The temperatures at Points 1, 2 and 4 during cooling are lower than the others, because these have fewest spectators. Also very slow stream of air from home plate to the backstand was observed.

Figs. 9 and 10 indicate the vertical temperature distribution during a period when the area is not in use but is being cooled. The temperatures of the height from 0 to 20 m sank and soar immediately after the air-conditioning was turned on and off. On the contrary, those above them change with a time-lag. Fig. 10 shows that the tempera-

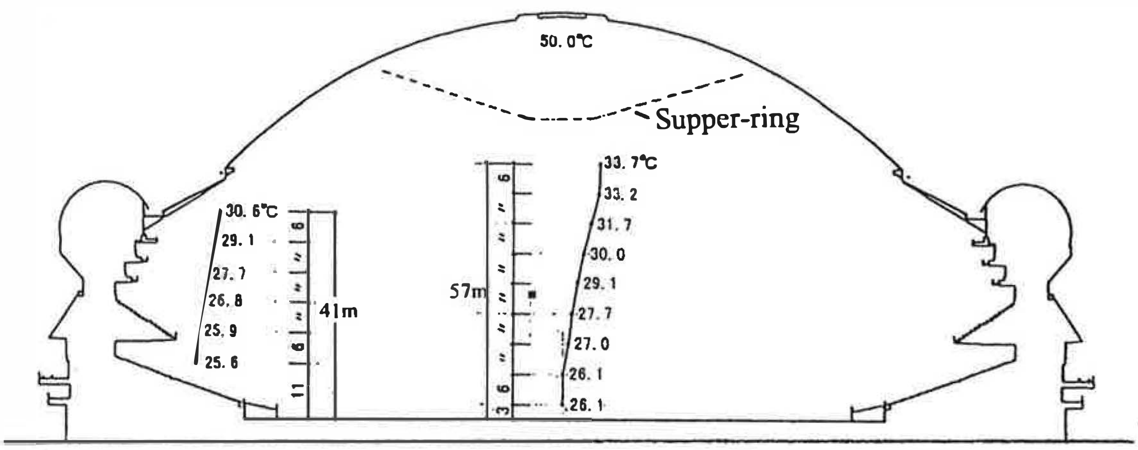

Fig. 10. Vertical temperature distribution (at 1500 same day as Fig. 9).

tures below 20 m are fairly uniform, while the temperatures above that rise with its height. This indicates that the air below 20 m is mixed completely and results in a uniform temperature distribution, and the air above forms the temperature gradient by displacement ventilation. This temperature gradient is steeper than other domes [6].

Fig. 11 shows the estimation of the exhausted heat from the roof air-movers by the displacement ventilation [7]. This data was obtained on the day when the professional baseball game took place in summer. Both the air temperature of the arena and the cooling load are also shown in the figure. The amount of heat was calculated as follows:

$$H_e = C_p \rho Q(\theta_c - \theta_a)$$

where H_e: the amount of heat exhausted from the roof air-mover (J/h), C_p: specific heat capacity of the air (J/kg°C), ρ: mass density of the air (kg/m^3), Q: volume air flow rate through the roof air-mover (m^3/h), θ_c: air temperature of the ceiling (the upper zone of the arena) (°C), and θ_a: air temperature of the occupied zone of the arena (∞C).

The air flow rate through the roof air-mover is able to estimate by subtracting the mechanically exhausted air flow rate from the supply air flow rate. The exhausted heat is equal to 40% of the cooling load of the arena and this indicates that the roof air-mover effectively removes the accumulated heat in the ceiling space of the arena.

Fig. 12 shows the monthly air-conditioning loads from April, 1997 till September, 1998 [8]. The annual cooling load of the whole building from October, 1997 till September, 1998 is about 45,242 GJ (69.1 Mcal/m^2) and that for heating is about 8644 GJ (13.2 Mcal/m^2). The arena part of that is very small, i.e. 5064 GJ (24.5 Mcal/m^2) and 888 GJ (4.3 Mcal/m^2), respectively. This is provided by both small flow and small temperature difference of supply air which are the strong points of the under-seat supply air-conditioning system. The hours of use of the arena is very small compared to the rest of the building and the energy consumption of it holds a little share in the whole building.

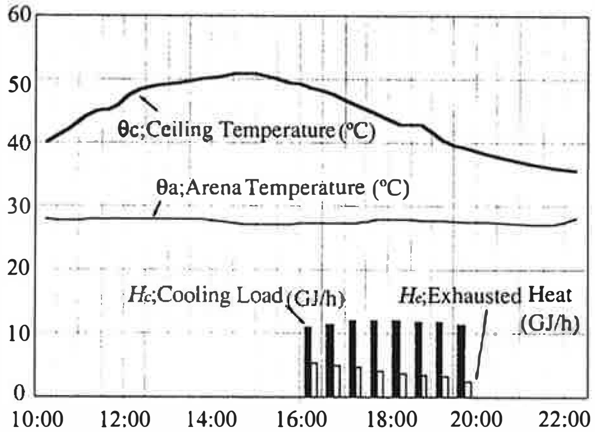

Fig. 11. Heat exhausted from air-mover.

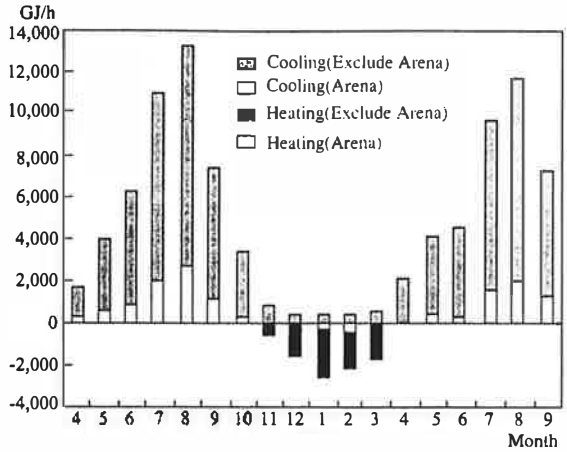

Fig. 12. Monthly air-conditioning load.

There is no available data to compare this with other domes, but this system will prove good energy conservation [9].

5. Conclusion

The temperature distribution measured during cooling in a large indoor stadium indicates that the seat supply air-conditioning system and multi-zoning technique are adequate to cool the limited space, namely the occupied zone, effectively. In addition, displacement and natural ventilation contribute to save excessive energy by preventing the cool air below from mixing with the warm air above. Measurements in other seasons should also be made. It is useful to know whether the natural ventilation rate is enough to make the indoor thermal conditions comfortable in the intermediate season and how the environment of the heating season is controlled.

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