DEVELOPMENT OF ICE CONTAINER SYSTEM FOR TEMPORARY SPACE COOLING

Y. Itoh[1†], Y. Hamada[1], H. Kubota[1], T. Nagata[2], T. Ono[2], and Y. Hashimoto[2]

[1]*Graduate School of Engineering, Hokkaido University,*
[2]*Kokusaku Corporation Co., Ltd.*

ABSTRACT

In 2000, the domestic greenhouse gas emission in Japan was 1332 million tons of CO_2, which increased by 8% in comparison with that of 1990. According to the Kyoto Protocol to the United Nations Framework Convention on Climate Change (COP3) held in December, 1997, Japan is obliged to reduce CO_2 by 6%, compared with 1990. As a result, Japan is required to reduce by 14% (172 million tons) on average during the period between 2008 and 2012. Particularly the emission in the residential/commercial sector in 2000 was on the increase by 21.3%, compared with that of 1990. More efforts of emission control for housing and buildings are demanded.

This paper aims to contribute to the introduction and promotion of the snow-and-ice cryogenic energy in cold and heavy snowfall regions in the future. To achieve this goal, we have developed a new concept for improvement of the performance of a snow-and-ice cryogenic energy system.

We propose an ice container system for the temporary space cooling. In 2006, space cooling was operated by using this ice container system. We evaluate the efficiency of space cooling.

KEYWORDS

Experiment, Renewable cryogenic energy, Space cooling

INTRODUCTION

The idea of storing snow and ice in winter for use as cooling sources for space cooling in summer has long existed in cold regions[1)]. Ice, in particular, has considerable cryogenic energy. The amount of latent heat per 1 kg of ice is 80,000 cal. If this cryogenic energy can be used for space cooling and the storage of agricultural products in summer, it will be possible to contribute to the reduction of carbon dioxide emission in addition to energy saving.

In this study, an ice container system for temporary air-conditioning was developed for the simple cooling of spaces, such as prefabricated buildings and tents used for events and at times of disaster, and analysis and experiments were conducted concerning the system. First, the concept of this system was established. Two types of cooling methods – natural and forced circulation – were adopted. Next, the cooling capacity was predicted by calculation. Measurement results were also presented concerning the cooling capacity of the forced circulation-type system in a temporary tent. Furthermore, the ice container system was actually tested on a temporary tent and a prefabricated building and demonstration experiments were conducted. The operation results were indicated and the cooling capacity was evaluated.

OVERVIEW OF THE ICE CONTAINER SYSTEM

The ice container system for temporary air-conditioning proposed by the authors uses ice placed in a cargo container. Cold air is brought in by circulating the air in the building to be cooled and the container. Two types of operation methods – natural and forced circulation – are used depending on the cooling demand. Figs. 1 and 2 display conceptual drawings of the natural and forced circulation-type systems. The natural circulation type uses natural convection caused by the difference in the air temperature of

† Corresponding Author: *E-mail address: hamada@eng.hokudai.ac.jp*

the container and the space to be cooled. This method is for facilities with relatively small cooling demands, and can provide cooling without a power supply. The forced circulation type circulates air by using fans or other power sources. It can be adopted for facilities with diverse cooling demands by changing the power and number of fans.

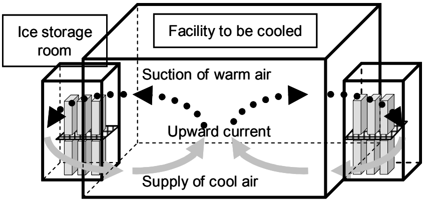

Fig. 1. Schematic diagram of the natural circulation-type system.

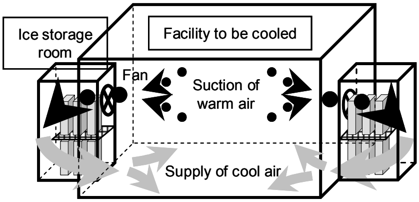

Fig. 2. Schematic diagram of the forced circulation-type system.

PREDICTION OF THE COOLING CAPACITY BY THEORETICAL CALCULATION

Equations for theoretical calculation

Equations to predict the cooling capacity are as shown below.

$$\gamma_{ice}\rho_{ice}\frac{\delta V_{ice}}{\delta\tau} = h_c A_{ice}(0 - t_s) \quad \text{...(1)}$$

$$c_p q(t_r - t_s) = K_r A_r(sat_r - t_r) + Q_{sun} + Q_{hum} \quad \text{...(2)}$$

$$N h_c A_{ice}(t_s - 0) = K_s A_s(sat_s - t_s) + c_p q(t_r - t_s) \quad \text{...(3)}$$

$$V_{ice} = xyL_{ice}^{\ 3}, \ A_{ice} = 2(x + xy + y)L_{ice}^{\ 2} \quad \text{...(4)}$$

$$q = q_f = const \ \ \text{(forced circulation type)} \quad \text{...(5)}$$

$$q = q_n = \frac{2}{3}\alpha B H^{\frac{2}{3}}\sqrt{2g\frac{t_r - t_s}{T_r}} \ \text{(Natural circulation type)} \quad \text{...(6)}$$

Equations (1), (2) and (3) are the heat balance equations of ice, the facility to be cooled and the ice storage room, respectively. The ice is approximately L_{ice} m in width, $x\ L_{ice}$ m in depth and $y\ L_{ice}$ m in height, and its volume and surface area are as expressed in Eq. (4). The amount of ventilation q is kept uniform by the airflow of the fan(s) in the case of the forced circulation type. In the case of the natural circulation type, the amount is changed depending on the temperature of the building and the ice storage room, using the ventilation algorithm for a vertically long opening [2].

Calculation conditions

The system is designed to use ice of a JIS standard size with a mass of 135 kg. Building A represents a prefabricated shed without transmitted solar radiation. Building B represents an event tent with a solar transmittance of 0.10. The ice storage room is equivalent to a 24-foot cargo container with 0.05-meter-thick insulation on its walls. The heat load of walls is for the case where the outdoor air temperature is 30°C and the preset indoor temperature is 26°C. The load of transmitted solar radiation was found from the design insolation for Sapporo [3]. The load of human body heat is 55 W per person for 40 and 100 persons in Buildings A and B, respectively. In Building B, half of the 3.5-kW cooling load is the load of transmitted solar radiation.

Overview of calculation

Table 1 lists the types of calculation. Calculation was conducted for the forced circulation type for both buildings and for the natural circulation type for Building A. In Calculation 1, 40 masses of ice were stored in a container and the amount of air circulation was 1.8 kg/sec (equivalent to a ventilating fan of 5400 m^3/h). In Calculation 2, two containers were used and the amount of air circulation was doubled to 3.6 kg/sec. Since Calculation 3 was the natural circulation type and the airflow was expected to be smaller than the forced circulation type, two containers containing 40 masses of ice each were used.

Table 1 Types of calculation

	Calculation 1	Calculation 2	Calculation 3
Circulation method	Forced circulation type		Natural circulation type
Target building	Building A	Building B	Building A
No. of containers	1	2	2
No. of pieces of ice (per container)	40	40	40
Total number of pieces of ice	40	80	80
Amount of air circulation	1.8 kg/sec	3.6 kg/sec	Temperature-dependent
Cooling load	8079 W	34900 W	8079 W

Calculation results

Fig. 3 shows the changes in temperature, cooling capacity and ice shape with the passage of time of the Calculation 1 (forced circulation-type, Building A). The temperature in the building was 28˚C or lower and satisfactory until 18 hours after the beginning of air conditioning. The surface area of the ice decreased to 75% of the initial value after a lapse of 24 hours, and was followed by a decline in cooling capacity.

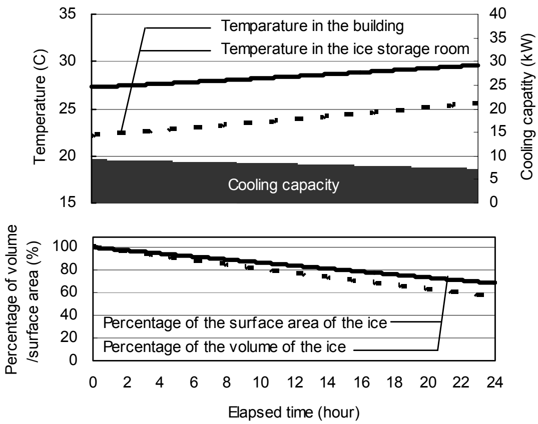

Fig. 3. Changes in temperature, cooling capacity and ice shape with the passage of time (Calculation 1).

EXPERIMENTS USING A FORCED CIRCULATION-TYPE SYSTEM

Overview of the experiment facility

Experiments were conducted using actual containers. The experiment facility consisted of a simple tent as the building to be cooled and a container on its side as the air-conditioning facility. The air-conditioning method was the forced circulation type using a pressure fan. Thirty pieces of JIS standard sized ice with a mass of 135 kg each were used. Beams were placed in the spaces between the masses of ice to prevent the ice from rolling sideways. This can prevent decrease in heat exchange effectiveness.

Overview of the experiments and measurement points

Table 2 shows the overview of the experiments. Experiments were conducted under two conditions, both of which were the forced circulation type and with 30 masses of ice. Experiments 1 and 2 were conducted using one and two fans, respectively, and the air-conditioning operation was carried out for a total of 12 hours during the daytime over two days.

The temperature was measured at six supply and suction openings and the wind velocity was measured regularly to estimate the cooling capacity. As outside conditions, the temperature, humidity and amount of solar radiation were measured.

Table 2 Overview of the experiments

	Experiment 1	Experiment 2
Period	July 13, 11:00 –July 14, 17:00 (stopped from 17:00 to 11:00 of the following day)	July 18, 11:00 – July 19, 17:00 (stopped from 17:00 to 11:00 of the following day)
Method	Forced circulation type	
No. of pieces of ice	30	
No. of fans	1 (5400 m^3/h)	2 (10800 m^3/h)

Experiment results

Fig. 4 displays the convective heat transfer coefficients estimated from the surface areas of ice in Experiments 1 and 2. The convective heat transfer coefficient was approximately 10 and 15 W/m^2 K for one and two fans, respectively.

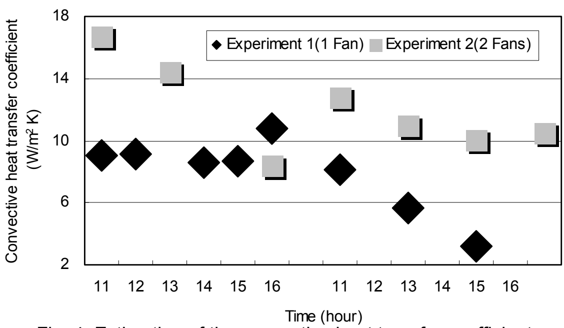

Fig. 4. Estimation of the convective heat transfer coefficient.

OVERVIEW OF THE DEMONSTRATION EXPERIMENT

The ice container system was adopted as a simple air-conditioning system for a summer event in Sapporo. The ice container system for temporary air-conditioning proposed by the authors uses ice placed in a cargo container. The air-conditioning method employed was the forced circulation type using a pressure fan. Table 3 presents the overview of the facilities to be cooled and the ice storage room. The opening of the container is 3.3 m^2 in area. In anticipation of an increase in cooling load, one and two fans were used for the prefabricated building and tent, respectively.

Table 3 Overview of the facilities to be cooled and the ice storage room

Facility to be cooled	Tent	Floor space	203.6 m^2
		Height	4.9 m
	Prefabricated building	Floor space	81 m^2
		Height	4.1 m
Ice storage room		Floor space	12.4 m^2
		Height	2.3 m

MESUREMENT ITEMS

The experiment period was from July 29 to August 20. Temperature and humidity were measured outside at one point each near the fan of the ice storage room and at the center of the container and at three points each in the vertical direction along the suction and supply openings. The wind velocity was also measured at nine suction and supply openings to find the amount of airflow. The wind direction distribution near the opening of the container was also measured using an ultrasonic anemometer (at 35 measurement points). To confirm the air-conditioning effect, the indoor temperature of the facility to be cooled was measured at two points. Temperature, humidity and wind velocity at five points in the vertical direction were also measured in nine sections to clarify the air-conditioning conditions. The ice shape was measured to find the amount of ice consumed.

EXPERIMENT RESULTS

Space cooling conditions

As outside conditions, Fig. 5 displays the measurement results of outdoor air temperature and humidity during the experiment period. The temperature was above 25°C almost every day during the period, and exceeded 30°C on nine days.

(1) Air-conditioning experiment of the prefabricated building

Table 4 shows the results of the air-conditioning experiment of the prefabricated building. The wind velocity was measured for seven days to find the cooling capacity. Two types of cooling operations with fan supply voltages of 100 and 50 V were conducted. As a result of the wind velocity measurements, the amounts of airflow were 1.4 and 1.0 m^3/s during 100- and 50-V operations, respectively. The experiment results revealed that the cooling capacity was approximately 9 kW during the 100-V operation and 7 kW during the 50-V operation. The cooling capacity decreased in the latter half of operation due to the shortage of ice supply.

Fig. 6 presents the operation conditions on August 6, as a representative day of the air-conditioning experiment of the prefabricated building. It was a very hot day with temperatures exceeding 30°C. The mean temperature during air-conditioning was 23.8°C at the center of the room and 25.5°C at the back of the room, indicating that a safe environment was maintained by air-conditioning.

Fig. 7 shows the changes in ice supply on the same day. The ice volume, which was approximately 2.5 m^3 at the beginning of air-conditioning, decreased by 80% to 0.5 m^3 at the end. This suggests that air-conditioning is possible by one supply of ice even on a day with a large cooling load.

(2) Air-conditioning experiment of the tent

Table 5 presents the results of the air-conditioning experiment of the tent. The wind velocity was measured for six days to find the cooling capacity. Two types of cooling operations were conducted with one and two fans respectively. As a result of wind velocity measurements, the amounts of airflow were 3.3 m^3/s with two fans and 1.4 m^3/s with one. The experiment result indicated that the cooling capacity during the operation with two fans was approximately 20 kW. The maximum cooling capacity was 30 kW on August 7.

Fig. 8 shows the operation conditions on August 7, as a representative day of the air-conditioning experiment of the tent. It was a very hot day with temperatures exceeding 30°C. The mean temperature during air-conditioning was 25.6˚C at the center and 29.1˚C at the back of the room. The temperature at the back was slightly higher because it was on the south side and was affected more by solar radiation. Fig. 9 displays the changes in ice supply on the same day. The ice volume, which was approximately 6.6 m^3 at a maximum, decreased by 65% to 2.3 m^3.

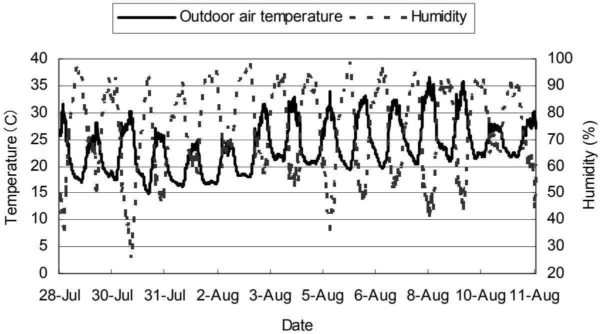

Fig. 5. Outdoor air temperature and humidity.

Table 4 Results of the air-conditioning experiment of the prefabricated building

Date	July 29	Aug. 3	Aug. 5	Aug. 6	Aug. 7	Aug. 8	Aug. 11
Fan supply voltage	50 V	50 V	50or100 V	100 V	100 V	100 V	50or100 V
Operating time	3.8 h	5.5 h	8.8 h	9.2 h	9.0 h	9.3 h	9.2 h
Temperature at the suction opening	20.0˚C	22.3˚C	25.2˚C	25.1˚C	26.7˚C	30.6˚C	25.8˚C
Heat supply	96.5 MJ	132.9 MJ	217.4 MJ	306.9 MJ	155.2 MJ	116.5 MJ	146.0 MJ
Cooling capacity	7.0 kW	6.7 kW	6.8 kW	9.3 kW	4.8 kW	3.5 kW	4.4 kW
Total ice supply				2.6 m^3	1.4 m^3	1.1 m^3	1.7 m^3

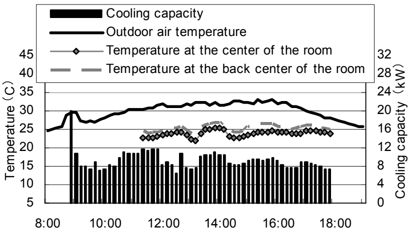

Fig. 6. Operating conditions on a representative day of air-conditioning of the prefabricated building.

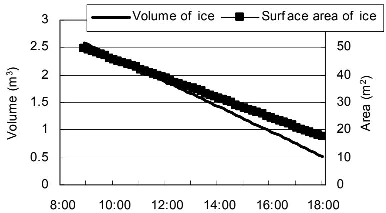

Fig. 7. Ice supply (prefabricated building, August 6).

Table 5 Results of the air-conditioning experiment of the tent

Date	3-Aug	5-Aug	6-Aug	7-Aug	8-Aug	11-Aug
No. of fans	2	2	2	2	2	1or2
Operating time	7.5 h	7.7 h	8.3 h	8.5 h	8.2 h	8.7 h
Temperature at the suction opening	24.4˚C	29.0˚C	29.1˚C	27.5˚C	31.4˚C	28.2˚C
Heat supply (MJ)	545.2	362.3	573.9	896.7	499.0	372.9
Cooling capacity (kW)	20.2	13.1	19.1	29.3	17.0	12.0
Total ice supply				6.9 m^3	3.8 m^3	2.1 m^3

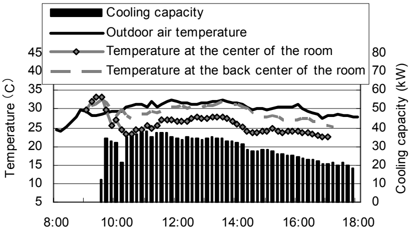

Fig. 8. Operating conditions on a representative day of air-conditioning of the tent.

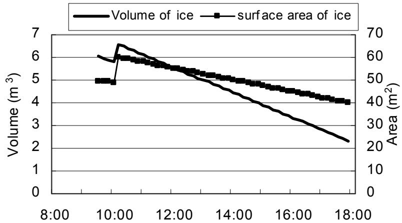

Fig. 9. Ice supply (tent, August 7).

Discussion on the cooling capacity

The convective heat transfer coefficient was estimated from the cooling capacity of the ice container system and the surface area of the ice. The coefficient was also estimated from the amount of dehumidification using Lewis' relation[4)]. Fig. 10 shows the estimated values found from the heat supply and Lewis' relation. The convective heat transfer coefficient was thought to be around 30 to 40 W/m^2 K during the operation of two fans although the estimated values from the relation rule were slightly lower. The value estimated from the ambient flow velocity was approximately 10 W/m^2 K[5)]. It was thought to be due mainly to the effect of combined convection on the ice surface.

Changes in the convective heat transfer coefficient on August 6 in the prefabricated building were also estimated. The fan supply voltage on this day was 100 V. The convective heat transfer coefficient estimated from the heat supply was 20 to 30 W/m^2 K. The value estimated from the ambient flow velocity was approximately 7 W/m^2 K. Further studies will be necessary in the future.

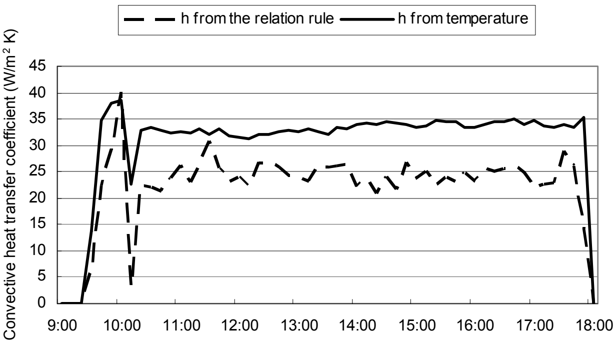

Fig. 10. Estimation of the convective heat transfer coefficient (tent).

CONCLUSION

1) An ice container system for temporary air-conditioning was developed for the purpose of the easy cooling of spaces, such as prefabricated buildings and tents used for events and at times of disaster. Two types of cooling methods – natural circulation type using temperature difference and forced circulation type using fans for power supply – were adopted depending on the demand for cryogenic energy.
2) Predictive calculation was conducted to estimate the cooling capacity. Two kinds of forced circulation-type and one kind of natural circulation-type calculation were made for two buildings with different cooling loads. It was found as a result that it would be appropriate to use the forced

circulation type for buildings with high cooling loads and the natural circulation type for those with low cooling loads.

3) Two kinds of experiments were conducted concerning predictive calculation for the forced circulation type. The cooling capacity estimated by predictive calculation was roughly confirmed in both experiments. The convective heat transfer coefficient of the ice container was also estimated from the measurement results.
4) Demonstration experiments of an ice container system for temporary air-conditioning were conducted for the purpose of providing simple air-conditioning for events and at times of disaster. The system was introduced for the air-conditioning of an event facility, and the forced circulation type was adopted as the cooling method.
5) Operating conditions were studied in the facilities to be cooled. The experiment results indicated that this system had potential to display sufficient cooling capacity for temporary prefabricated buildings. Its application to the air-conditioning of temporary tents was thought to be possible by taking anti-solar radiation and other measures.
6) The convective heat transfer coefficient was estimated to evaluate the cooling capacity. As a result, the coefficient was estimated to be 30 to 40 W/m^2 K during the operation of two fans.

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SYMBOLS

A_{ice}: surface area of ice (m^2), A_r: wall area of the building (m^2), A_s: wall area of the ice storage room (m^2), B: width of opening (m), C_p: specific heat of the air (J/kg K), g: acceleration of gravity (m/sec^2), H: height difference (m), h_c: convective heat transfer coefficient (W/m^2 K), K_r: overall heat transfer coefficient of the building (W/m^2 K), K_s: overall heat transfer coefficient of the ice storage room (W/m^2 K), L_{ice}: length of the ice (m), q: air volume (kg/sec), Q_{hum}: load of human body heat (W), Q_{sun}: load of transmitted solar radiation (W), sat_r: sol-air temperature of the building (°C), sat_s: sol-air temperature of the ice storage room (°C), t_{out}: outdoor air temperature (°C), t_r: air temperature in the building (°C) T_r: building temperature (K) t_s: air temperature in the ice storage room (°C), V_{ice}: ice volume (m^3), x: length ratio (-), y: length ratio (-), α: airflow coefficient (-), γ_{ice}: latent heat of ice (J/kg), ρ_{air}: air density (kg/m^3) ρ_{ice}: ice density (kg/m^3), τ: elapsed time (sec)