【*Technical Paper*】

PERFORMANCE VERIFICATION OF A SUB-COOLING SYSTEM FOR A REFRIGERATION SHOWCASE

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ABSTRACT

Owing to the concerns regarding global warming and ozone depletion, the development of high-performance energy-saving technologies and equipment for refrigeration systems has become increasingly crucial in international communities. In 2009, we developed a sub-cooling apparatus called the Eva-chilled unit for application in multi-type building air conditioners (PAC) and module chillers [1], [2], [3]. This unit resembles a small-scale cooling tower, and the sprinkling water cools the liquid refrigerant along the refrigerant pipes using the latent heat of vaporization of the water, thereby reducing the peak power consumption and overall energy consumption. Furthermore, it reduces the heat island effect. This energy-saving technology does not depend on the capacity of the air-cooled PAC and is effective only when installing PAC. In this study, with a focus on the refrigerant system of the grocery supermarket, we verified the cycle performance of the refrigerant systems in grocery supermarkets in Japan by adding experimental equipment to the developed unit and presented the results. The experiment was conducted using refrigerant R410A at a thermal load rate from 0.25–1.0 °C and outside air temperature ranging from 4.1–34 °C. We investigated the hourly electric power consumption and peak value. As a result, we confirmed that the system COP rate improved by 21% on adding the developed unit at an outside air temperature of 34 °C. Furthermore, we found that the pressure of the high-pressure side during the operation of the Eva-chilled unit was lower than that when the operation of the Eva-chilled unit had stopped, considering the refrigeration effect per unit flow rate improved due to the supercooling of the Eva-chilled unit.

1. INTRODUCTION

In 2019, as a measure to prevent global warming, the regular report of the revised energy saving law, Japan, suggested the food supermarket industries to prepare performance reports indicating whether the target benchmark indicator, obtained by dividing the amount of energy used in supermarkets by the specified value of an item (calculated from the total floor area, annual business hours, and the size of the cold equipment), was met. Refrigeration equipment consume in supermarkets account for approximately 56% of the total annual electric power consumption of the entire supermarket facility. Therefore, energy saving is an urgent problem that needs to be addressed. In 2005, we developed a sub-cooling system for multi-type building air conditioners using HCFC refrigerants as an energy-saving technology with a heat exchange function between the refrigerant and the cooling water from outside. In 2009, we developed an Eva-chilled unit comprising a small cooling unit in the outdoor unit for installation in small-scale properties. In this study, we conduct a performance verification test to evaluate the energy-saving performance of the Eva-chilled unit with a refrigerated showcase and report the results.

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2. 2. OUTLINE OF THE EVA-CHILLED UNIT

The Eva-chilled unit integrated heat exchanger and cooling tower were incorporated in the cold system of the vapor compression refrigeration cycle of HCFC refrigerants of the sub-cooling system, which further subcooled the refrigerant at the outlet condenser. Because the refrigerant temperature was higher than the outside air temperature, it would be possible to contribute to energy saving, reduce electricity charges, and improve the refrigeration capacity if tap water or well water were used as a water supply source. Figures 1 and 2 show the actual photograph and schematic representation of the Eva-chilled unit, respectively. Table 1 shows the specifications of the unit. This system connects to only one unit in the applicable range of 5–50 HP when applied to a multiple-air conditioner. The unit can be carried through a single door and easily transported by an elevator. Furthermore, it is easy to install owing to the small refrigerant (Φ22.2mm) and water supply (15 A) pipes. It also comprises a refrigerant pipe coil inside the unit, flowing in the liquid refrigerant condensed in the existing outdoor unit. The control operation of the Eva-chilled unit automatically sprinkles and ventilates when the pressure in the refrigerant pipe exceeds a predetermined level.

Table 1 Specifications of the Eva-chilled unit.

Equipment body	Outside dimension	500W × 650D × 1100H
	Weight	About 90 kg (includes water and refrigerant)
	Air volume	2,400 CMH
	water sprinkling volume	24 L/min
	Heat exchanger	CUP (C1220) Φ9.53 22 row × 5 stage × 480L
Power supply	Voltage	3Φ 200V
	Power consumption	250 / 295W (50 /60Hz)
Water supply	Amount of water consumption	Maximum continuous water consumption 0.25 L/min
	Pressure	0.01 ～ 0.5 MPa
	Quality	Follow guideline of water quality for refrigeration and air conditioning equipment(JSA-GL 02)
Pipe connection	Refrigerant liquid pipe	CUP Φ22.22 × 2 places
	Water supply pipe	15A female screw (brass)
	Drain pipe	VP15A single pipe

Fig. 1 Eva-chilled unit when installed in the PAC's outdoor unit.

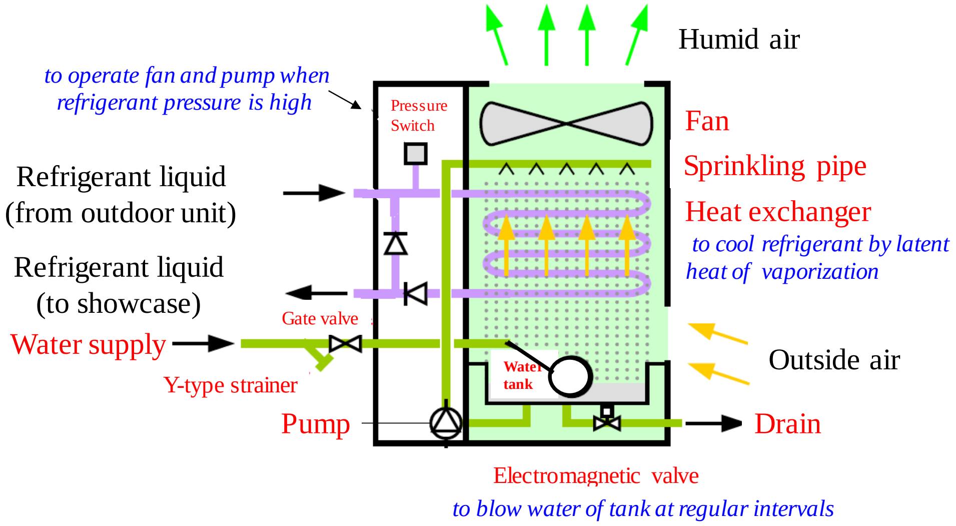


Fig. 2 Schematic of the Eva-chilled unit.

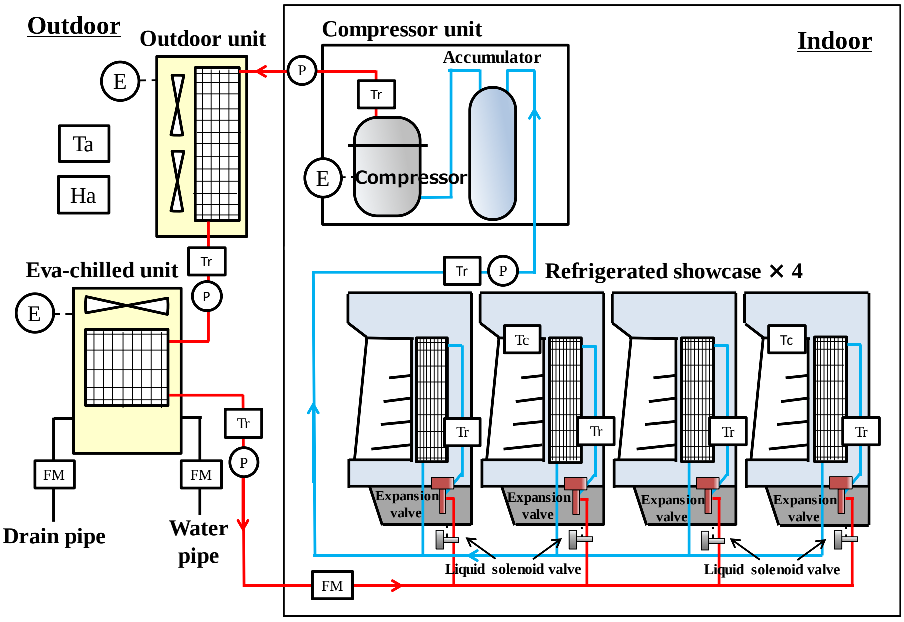


Fig. 3 Schematic of the experimental apparatus.

Table 2 Specifications of the Eva-chilled unit.

Experimental period		May 2019 to February 2020
Refrigerant		R410A
Equipment	Existing unit	Showcase, 4 units 2.51kW（@ 27℃ 70RH%） Inverter compressor unit, 1 unit 4HP（@ Evaporation temp. sets to -10^{o}C） Outdoor unit, 1 unit
	Additional unit	Eva-chilled unit, 1 unit
Condition of operation		No control start/stop of compressor and outdoor air temp.
Thermal load factor		25, 50, 75, 100%
Interval of measurement and calculation		Measurement time : 1 sec. Calculation : average of 1 hour
Water supply		Without temperature control Blow one time 5 hours

Table 3 Measurement item and measurement equipment

Symbol	Measurement item	Measuring equipment	Point
Ⓔ	Power consumption	Watt hour meter	3
Ta	Outside air temperature	Weather measurement device	1
Ha	Outside air relative humidity		1
Tw	Water supply temperature	Pipe insertion type RTD	1
Tr	Refrigerant temperature	Film-type RTD	8
Tc	Temperature in showcase	Film-type RTD	2
FM	Refrigerant flow rate	Coriolis flow meter	1
	Water supply / Drain flow rate	Electromagnetic flow meter	2
Ⓟ	Refrigerant pressure	Pressure gage	4

3. EXPERIMENTAL EQUIPMENT AND PERFORMANCE VERIFICATION

Figure 3 shows a schematic of the experimental apparatus, a vapor compression-type refrigeration cycle comprising four refrigerated showcases, a compressor unit, an outdoor unit, and the Eva-chilled unit. The refrigerated showcases and compressor units were installed indoors, whereas the outdoor and Eva-chilled units were installed outdoors. Owing to the workability of the piping connection of the Eva-chilled unit and the actual condition of the customer store, we installed a refrigeration system separately from the compressor and outdoor units. The refrigerant was discharged by the compressor at high temperature and pressure, and condensed by the outdoor unit. The refrigerant then enters the Eva-chilled unit and is further supercooled. Subsequently, it passes through the Coriolis flow meter and is decompressed by the expansion valve in the returns to the compressor. To prevent heat exchange with the indoor air, the thermal load of the refrigerated showcase was covered with heat-insulating material. Furthermore, a variable-simulated load heater was installed in the showcase. The temperature of the refrigeration showcase was set to 2 °C, whereas the evaporation temperature of the compressor unit was set to -10 °C. The refrigerant pressure control, compressor frequency control, and expansion valve opening control conform to the manufacturer's standards. As described in the previous section, the operation of the Eva-chilled unit was controlled in a way that it operated automatically when the refrigerant pressure exceeded a predetermined level.

Tables 2 and 3 show the experiment duration and conditions and the measurement items and equipment, respectively. We conducted a performance verification test from May 2019 to February 2020 and measured parameters such as the power consumption of the compressor, outdoor unit, and Eva-chilled unit during operation, the outside air temperature and air relative humidity, the temperature of the water supply, refrigerant, and in the showcase, the refrigerant flow rate, amount of water supply/drain, and the refrigerant pressure. The performance verification was performed using the data that was obtained by averaging the data measured for 1 h at 1 s intervals. Based on the experimental conditions, the thermal load rates of the variable heater in the refrigerated showcase were changed to 25, 50, 75, and 100%. The thermal load rate is the value obtained by dividing the refrigeration capacity by the rated capacity of the compressor under experimental conditions, which is a product of the refrigerant flow rate and difference in enthalpy from the inlet of the compressor to the outlet of the expansion valve. The outside air temperature, outside air relative humidity, and the water supply temperature to the Eva-chilled were not controlled. Furthermore, the cycle COP and system COP were stopped were examined during the operation of the Eva-chilled unit to verify the performance. The cycle COP is the value obtained by dividing the calculatedrefrigeration capacity by the compressor power consumption, whereas the system COP is the value obtained by dividing the refrigeration capacity by the total power consumption of the compressor, outdoor unit, and Eva-chilled unit. The refrigerant enthalpy was calculated using the REFPROP Ver. 10 [4].

4. RESULT AND DISCUSSION

4.1 Operation trend of each measurement value

Fig. 4 shows the time change of each measured value (inlet pressure of compressor Pin, the outlet pressure of compressor Pout, outside air temperature Ta, the representative temperature in showcase Tc, refrigerant flow rate Wr) on August 28, 2019, when the thermal load rate was 88% and during the operation of the Eva-chilled unit. The measurement time was 1 h, starting from 11:00. The representative temperature in the showcase was between 3 – -1 °C, and the refrigerant flow rate increased as the representative temperature increased. Moreover, due to an increase in the refrigerant flow rate, the inlet and outlet pressures of the compressor decreased and increased, respectively. In contrast, when the representative temperature approached the minimum value (-1°C), the refrigerant flow rate decreased. Therefore, we can conclude that the refrigerant flow rate was adjusted by the expansion valve opening control against the showcase temperature. At a low thermal load rate, the start and stop frequency increased owing to the rapid temperature change in the representative showcase. The changes in the flow rate with time were attributed to the capacity control of the inverter compressor based on the superheat at the compressor inlet. Moreover, by comparing the changes during and after operation of the Eva-chilled unit with time, it was confirmed that it had no influence on the operation control on the showcase side (evaporator side) during the operation of the Eva-chilled unit.

4.2 Comparison of the P-h cycle diagrams

Figures 5 (a), (b), and (c) compare the P-h cycle diagram during and after the operation of the Eva-chilled unit, respectively, at outside air temperatures of approximately 9.5, 23.5, and 33.5 °C and high thermal load rates ranging from 80–93%. P is the refrigerant pressure, and h is the enthalpy in the figures. Each section represents the operation of each piece of equipment, where the compressor is between a and b (A and B), the outdoor unit is between b and c (B and C), the Eva-chilled unit is between c and c', the expansion valve is between c'–d (C–D), the refrigerated showcase is between d and a (D and A) . Note that the lower-case and upper-case letters show each equipment section during and after the operation of the Eva-chilled unit, respectively. It can be confirmed that the supercooling effect (between c and c') was greater during the Eva-chilled unit operation compared to after the operation, at any outside air temperature. Furthermore, the

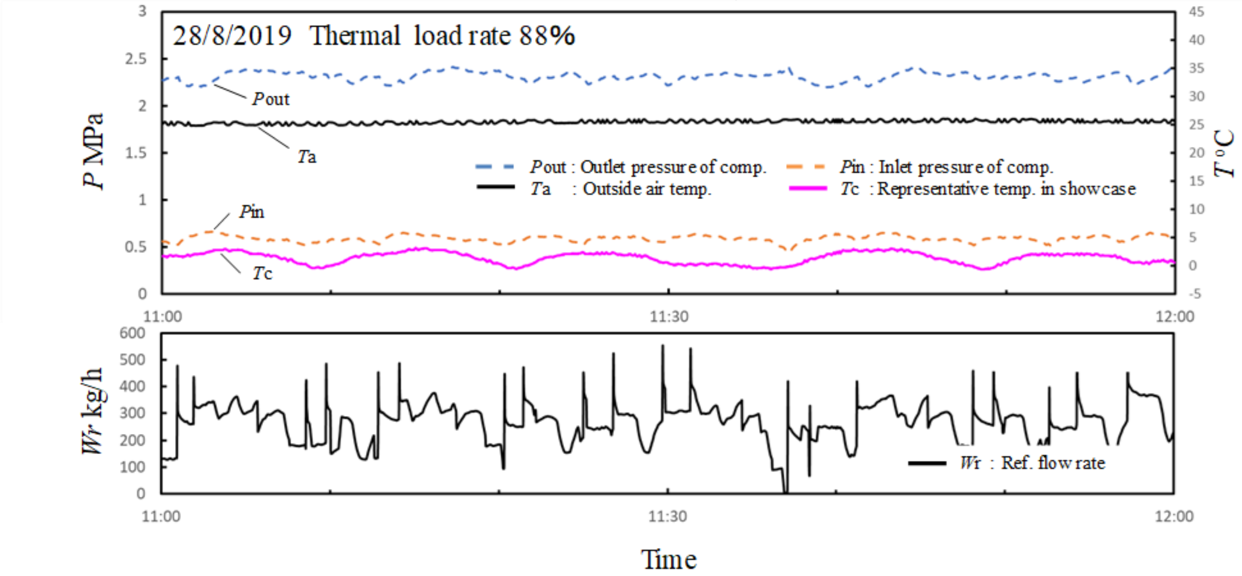
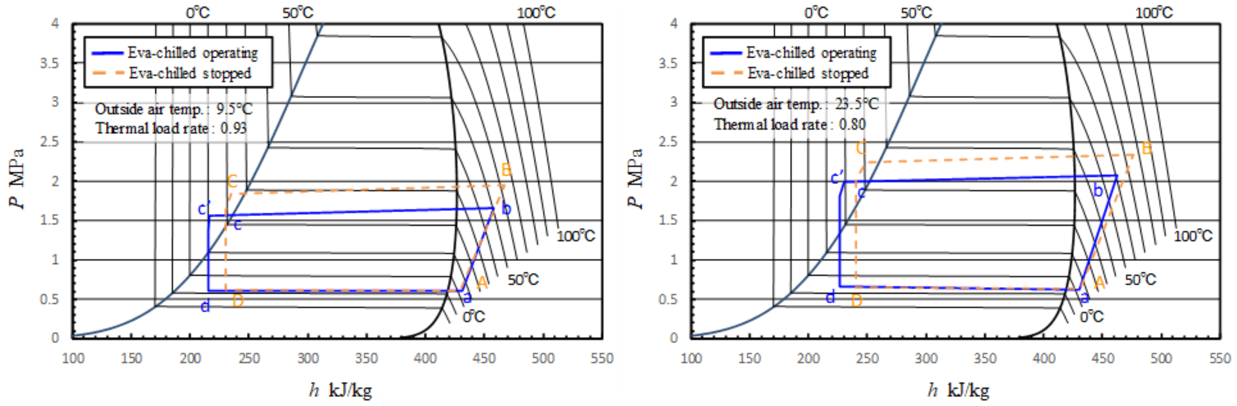
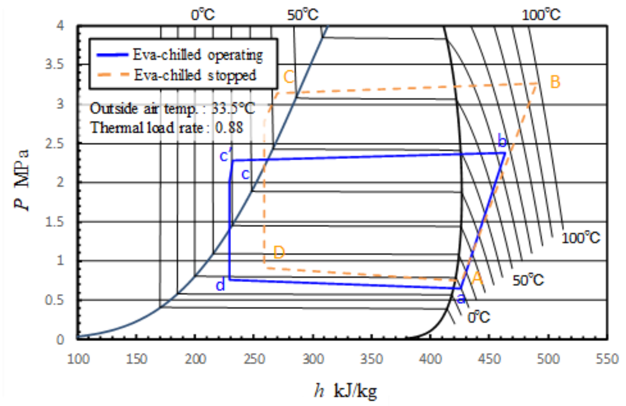


Fig. 4 System operation results during operation of the Eva-chilled unit.



(a) Outside air temperature: 9.5 ºC

(b) Outside air temperature: 23.5 ºC



(c) Outside air temperature: 33.5 ºC

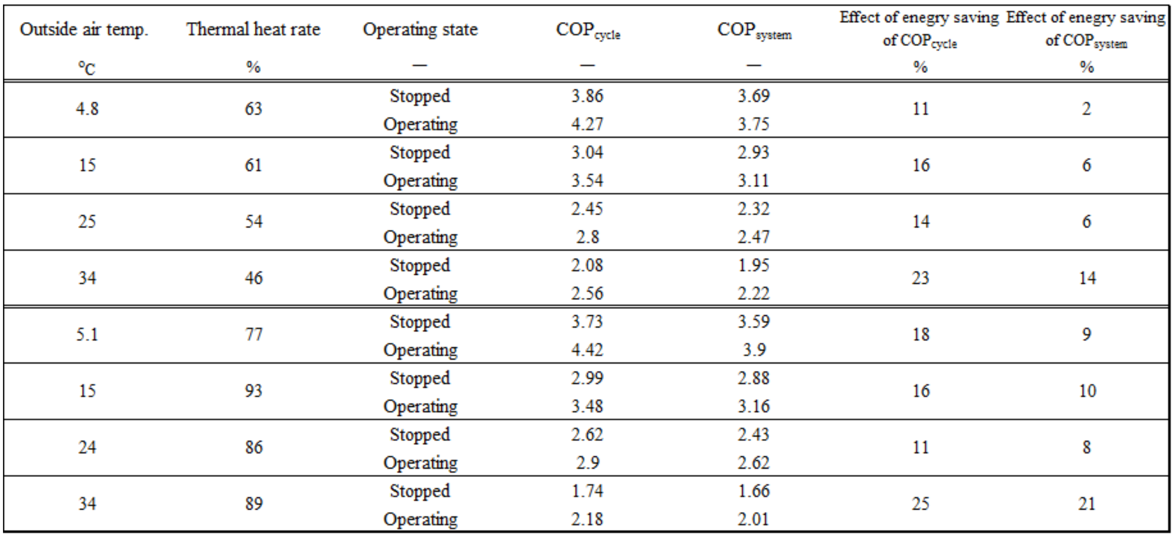
Fig. 5 Comparison of the P-h cycle diagrams during and after the operation of the Eva-chilled unit..

pressure on the high-pressure side was lower during the operation of the Eva-chilled unit compared to after operation. The drop in the high-pressure side pressure can be attributed to the fact that the refrigerating effect per unit flow rate (between d and a) is improved by supercooling the Eva-chilled unit, and the heat load can be processed even at a low flow rate. Note that the pressure on the low-pressure side was almost the same during and after the operation, considering the showcase internal temperature was 2 °C and the compressor unit evaporation temperature was -10 °C, which enabled constant control over the low-pressure side of the cycle.

4.3 Energy saving effect by the Eva-chilled unit

Table 4 shows the effect of energy saving when the Eva-chilled unit operates and stops at almost the same outside air temperature and thermal load rate. All results showed that both the cycle COP and system COP were higher during the operation of the Eva-chilled unit than after operation. Furthermore, it can be seen that the energy-saving effect of some data at intermediate temperatures is lower than that of the other data, considering the energy-saving effect is low in the intermediate temperature range when comparing the performance curves of cycle COP and outside temperature of the Eva-chilled unit when it operates and stops. In the high-temperature range, the energy saving effect of the data increased as the outside air temperature increased. In this experiment, the cycle COP and system COP rates improved by 25% and 21%, respectively, when the Eva-chilled unit operated at an outside air temperature of 34 °C and a load rate of 89%. Generally, in a refrigeration cycle, as the thermal load rate and outside air temperature increase, the refrigerant flow rate is increased to increase the difference between the refrigerant temperature and outside air temperature to increase the amount of heat radiation in the outdoor unit. As a result, the pressure on the high-pressure side increases, thereby increasing the power consumption. In this experiment, the refrigeration effect was improved owing to the operation of the Eva-chilled unit and the equivalent load could be processed even at reduced refrigerant flow rates. Therefore, it is considered that the COP can be improved by reducing the power consumption owing to the decrease in the compressor frequency.

Table 4 Energy saving effect by the Eva-chilled unit.



Outside air temp.	Thermal heat rate	Operating state	COP_{cycle}	COP_{system}	Effect of enegry saving of COP_{cycle}	Effect of enegry saving of COP_{system}
°C	%	—	—	—	%	%
4.8	63	Stopped	3.86	3.69	11	2
		Operating	4.27	3.75		
15	61	Stopped	3.04	2.93	16	6
		Operating	3.54	3.11		
25	54	Stopped	2.45	2.32	14	6
		Operating	2.8	2.47		
34	46	Stopped	2.08	1.95	23	14
		Operating	2.56	2.22		
5.1	77	Stopped	3.73	3.59	18	9
		Operating	4.42	3.9		
15	93	Stopped	2.99	2.88	16	10
		Operating	3.48	3.16		
24	86	Stopped	2.62	2.43	11	8
		Operating	2.9	2.62		
34	89	Stopped	1.74	1.66	25	21
		Operating	2.18	2.01		

4. CONCLUSIONS

In this study, we connected an Eva-chilled unit to a refrigerated showcase and conducted a performance verification experiment from May 2019 to February 2020 (outside air temperature 4.8–34 °C). The following results were obtained:

(1) Based on the cycle diagrams at outside air temperatures of 9.5, 23.5, and 33.5 °C during and after the operation of the Eva-chilled unit, the pressure on the high-pressure side was found to be lower during the operation of the Eva-chilled unit, which was attributed to the supercooling of the Eva-chilled unit.

(2) We confirmed that the energy-saving effect was higher when at high outside air temperature values . At an outside air temperature of 34 °C and thermal load rate of 89%, we observed 25% and 21% improvement in cycle COP and system COP. Furthermore, the energy-saving effect of some data at intermediate temperatures was lower than the other data, considering the energy-saving effect was found to be low in the intermediate temperature range on comparing the performance curves of cycle COP and the outside temperatures during and after the Eva-chilled operation.

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要約

地球温暖化の観点から、冷凍空調システムの省エネ化はますます重要になってきている。当社は2009年に、ビル用マルチエアコンやモジュールチラーの省エネ技術としてエバチルドシステムと呼ばれる過冷却装置を開発した。本機は小型冷却塔なようなものであり、主に散水による蒸発潜熱を利用して、冷媒配管内の液体冷媒を冷却することで、ピーク時の消費電力やシステム全体のエネルギー消費量の削減に貢献できる。そこで本研究では、食料品スーパー業の冷凍冷蔵ショーケースに着目し、開発したユニットをそのシステムに付加することで、サイクル性能が向上することを実験的に検証した。本実験は、冷媒R410Aを使用し、外気温度4.8～34°C、熱負荷率25～100%、エバチルドユニット運転時と停止時の条件で実施した。その結果、エバチルドユニットを運転した時のシステムCOPは、外気温度34℃、負荷率89%時に21%向上することを確認した。また、エバチルドユニットの運転時の高圧側の圧力は、エバチルドユニットの停止時のときよりも低いことがわかった。