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Experimental Study for Investigating the Optimum Operating Conditions of a Seawater Ice Machine
해수제빙장치의 최적 운전 조건 탐색을 위한 실험적 연구

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Key Words : Seawater Ice Machine(해수제빙장치), Coefficient of Performance(성적계수), Superheat(과열도), Seawater Ice(해수얼음)

Abstract : This paper investigates the optimum operating conditions to construct total automatic control system with high energy efficiency of a newly developed seawater ice machine. The machine has an electronic expansion valve(EEV) and a variable speed rotating drum with an evaporator installed inside. The coefficient of performance(COP) was used as an index to evaluate energy efficiency of the machine. At first, the opening angle of EEV was adjusted to obtain COP of the machine at a constant speed of the drum. Then, we checked seawater ice product versus opening angles of the EEV. Finally, effect of drum's rotating speed in response to product of seawater ice and seawater ice temperature were considered.

1. Introduction

Recently, the demand of fresh fishes is increasing due to change of the paradigm which emphasizes the quality over the quantity in dietary life. Freshwater ice, in spite of many defects, has mainly served a role to keep the fishes fresh.

The seawater ice can maintain the freshness of fishes longer than freshwater ice because of its low freezing point. Moreover, it can reduce some damages to the surface of the fishes by means of the osmotic pressure. Energy saving is also possible with the seawater ice in a ship by saving on transportation of freshwater ice from the land.

Hence the seawater ice machine with high energy efficiency was newly developed to produce the seawater ice. It was designed as rotating drum type which has an evaporator inside of drum to minimize installation space. In addition, it was made as automated device which has an electronic expansion valve(EEV) to obtain the maximum coefficient of performance(COP) and an inverter to gain the maximum production of seawater ice.

In this paper, we investigate the optimum operating conditions to make total automatic control system with high energy efficiency of the seawater ice machine.

As the seawater ice machine is based on a basic refrigeration cycle, it consists of 4 major components: a compressor, an evaporator, a condenser, and an expansion device. In the basic refrigeration cycle, controllable variables are speed of the compressor, speed of heat exchangers' cooling fan motor and opening angle of the EEV. Many previous studies about the refrigeration system have focused on analysis of dynamic performances and characteristics on the evaporator and expansion valve by using

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numerical and experimental method[1~7]. The cooling target of the system has been mainly air or pure water. However, seawater is rarely dealt with the cooling target. In addition, the evaporator is installed inside of a rotating drum in this seawater ice machine.

Therefore, we deal with COP and the production of the seawater ice as index of evaluation of the system performance in the seawater ice machine. The opening angle of EEV and the rotating speed of drum are set as control parameters of the system to consider availability and serviceability of end user. The opening angel of EEV and the rotating speed of drum are controlled by a step motor driver and an inverter respectively.

The COP and production of seawater ice in response to the change of opening angle of EEV and the drum's rotating speed were analyzed throughout some experiments.

2. Performance of the machine

Fig. 1 shows a configuration of the seawater ice machine(SIM) based on the basic refrigeration cycle.

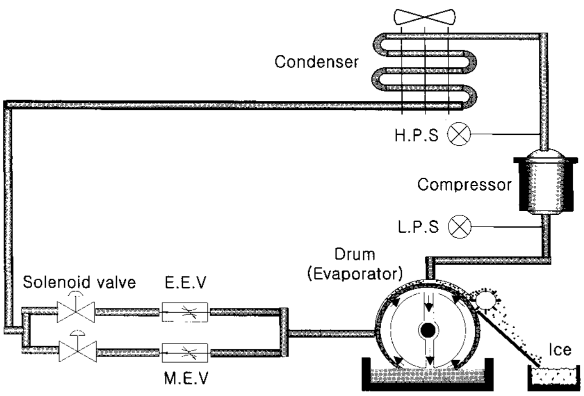


Fig. 1 Schematic diagram of the SIM

It is noted here that the evaporator is positioned inside of rotating drum. To rotate the drum, an induction motor installed on the rotating shaft of the drum should be driven by a V/f constant type inverter. Refrigerant is sprayed toward inner surface of the drum and then the surface of the drum is cooled by the refrigerant.

The seawater ice is made of natural seawater in a tank and it sticks to the surface of the drum while the drum is rotating. The seawater is supplied indirectly from its storage tank or directly from the sea. A cutter is needed to separate the ice from the surface of the drum. Also, the thickness of the seawater ice can be controlled by adjusting the rotating speed of the drum or the sinking time of the drum in seawater.

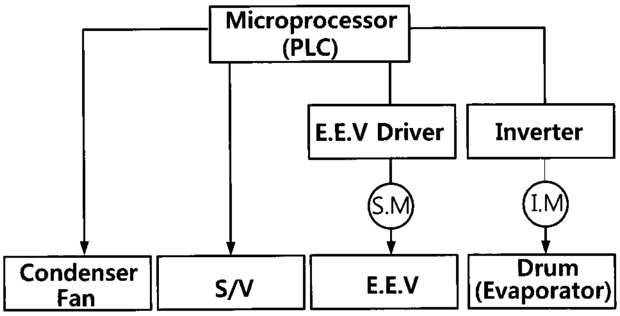


Fig. 2 Control system of a SIM

The EEV driven by the step motor driver is set on basic cycle to control the mass flow rate of the refrigerant.

Fig. 2 represents the control system of the seawater ice machine. A programmable logic controller(PLC) is used as main sequential controller. The PLC controls the EEV driver, the inverter to change the opening angle of EEV and the rotating speed of drum. On/off control of an electronic solenoid valve and a condenser fan are conducted by the PLC.

This study is aimed at construction of automatic control system to progress energy efficiency and to maximize seawater ice product of the seawater ice machine described previously. The COP is used as an index to evaluate the energy efficiency and it is calculated in two different methods. One is conducted by P-h diagram based on temperature information. The other depends on the production of the seawater ice and the power consumption of the compressor.

In general, the COP of the basic refrigeration cycle is defined as equation (1).

$$COP = \frac{q}{A_w \times 860} \qquad (1)$$

Here, q[kcal/h] means cooling capacity, A_w[kW] indicates work input of compressor.

When we use the P-h diagram as Fig. 3, equation (2) is available.

$$COP = \frac{h_1 - h_4}{h_2 - h_1} \qquad (2)$$

Here, $h_i(i=1\sim4)$[kcal/kg] means each enthalpy at the P-h diagram calculated from temperature information.

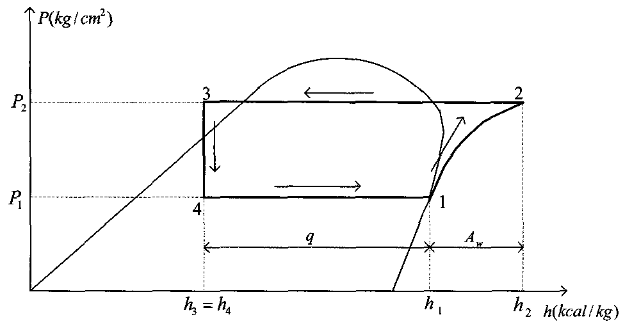


Fig. 3 P-h diagram

The COP also can be calculated by using Eq. (3).

$$COP = \frac{Q \cdot M}{W \times 860} \qquad (3)$$

Here, Q[kcal/kg] is the sum of latent heat and the sensible heat of the seawater, M[kg/h] is the production of the seawater ice, W[kW] is the power consumption of the compressor respectively.

3. Experiments and Results

3.1 Experimental equipment

Photo. 1 shows a configuration of the prototype of seawater ice machine. It consists of a reciprocating compressor, an air-cooled condenser with two cooling fans, an EEV driven by the step motor driver, and a rotating drum with an evaporator driven by the inverter.

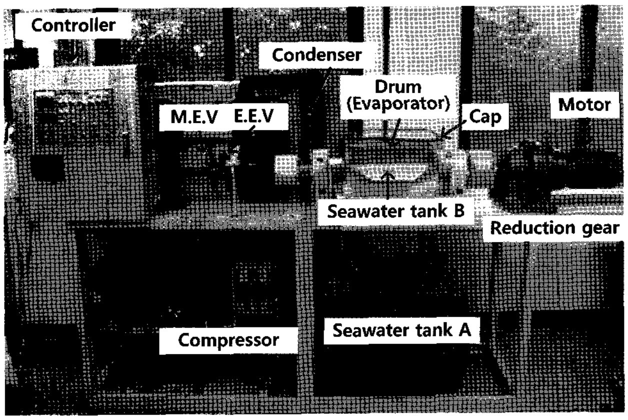


Photo. 1 Configuration of experimental system

Table 1 Specification of the test unit

Unit	Specification
Compressor	Danfoss, Φ3, 380V, 60Hz, 5.5kW
Condenser	Air-cooled fin and tube type
Evaporator	Rotating drum type
EEV	JHEV 14A, DC 12V
Refrigerant	R-22
Inverter	Φ3, 380~480V, 60Hz, 2.2kW
Motor	Φ3, 220/380V, 60Hz, 1.5kW

Table 1 shows the specification of the test unit of the seawater ice machine system.

To calculate the COP, the temperature of each part of the components is measured by the thermocouples and saved in data acquisition system in real time. The input power of the compressor is measured by the power meter. The temperature of seawater is 14℃ and the temperature of producted seawater ice is -15~-5℃.

The rotating speed of drum is adjusted in the range over 2~10rpm with step size 2rpm by the inverter. The opening angle of EEV is also adjusted in the range over 50~100% with step size 10% by the driver.

3.2 Experimental method

There are two different methods to determine the COP. In first method(case 1), it is expressed as the ratio of the cooling capacity of the evaporator and the work input of the compressor.

Therefore, it can be calculated by using P-h diagram which is plotted according to the temperatures and pressures of the system. In second method(case 2), the COP is defined as the ratio of the removed energy from seawater and the power input to the compressor. The removed energy from seawater is estimated according to the laten heat and the sensible heat of the seawater and the production of the seawater ice.

At first, experiments are focused on the calculation of the COP according to the change of the opening angle of EEV by using Eq. (2) and (3). The superheat, the temperature differences between outlet and inlet of the evaporator, is also considered to prevent refrigerant liquid back phenomenon and to obtain the maximum COP. The optimum opening angle of EEV satisfying the maximum COP can be decided by considering superheat without liquid back phenomenon simultaneously. Also, the COP from Eq. (2) and the one from Eq. (3) are compared. Through a preliminary experiment, superheat was proven very high at the opening angle less than 50%. On the other hand, the COP was very low at the same angle area. Therefore, in this experiment, the opening angle of EEV was adjusted in the range over 50~100%.

Next, both the COP and the production of seawater ice are analyzed simultaneously in response to change in the speed of rotating drum. The superheat and the temperature of the seawater ice are considered to find the optimum operating conditions. The rotating speed of drum is adjusted in the range over 2~10rpm under fixed opening angle of EEV at 90%. The optimum speed of rotating drum can be decided on the basis of some data such as the COP, the product of seawater ice, the temperature of seawater ice, and the superheat. The sampling period of data acquisition is set at 2sec. The production of seawater ice is measured by an electronic scale during 5 minutes.

The speed of the rotating drum was calculated by equation (4) considering gear ratio.

$$N = \frac{120 \times f}{P}(1-s) \tag{4}$$

Here, N[rpm] means rotating speed, f[Hz] is the frequency, P is the number of motor's pole and s is the slip respectively.

3.3 Experimental results and discussions

Fig. 4 shows the P-h diagrams when the opening angle of EEV are 50%, 60%, 70%, 80%, 90%, 100% respectively, and the speed of drum is 4rpm. The COP of case 1 is calculated by the P-h diagram, and the COP of case 2 is obtained from the production of the seawater ice.

Fig. 5 indicates the COP and the superheat(SH) versus the opening angle of EEV when the drum

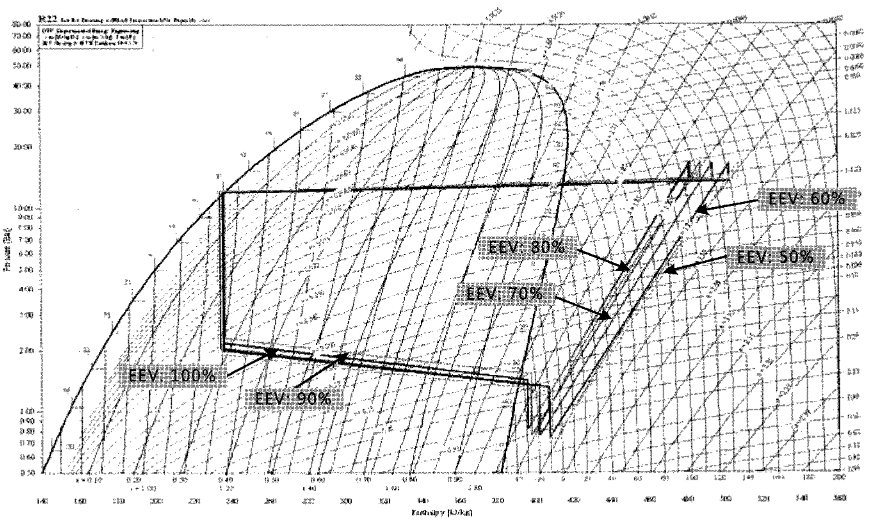


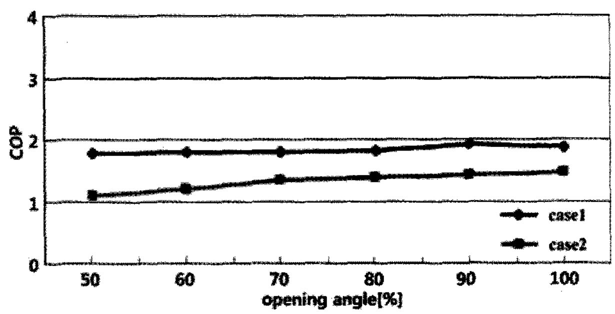
Fig. 4 P-h diagram for obtaining COP

speed is 4rpm.

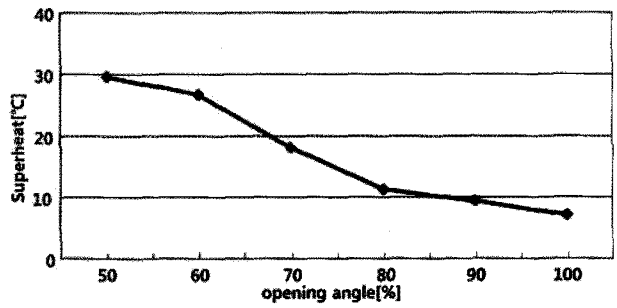
The COP is the highest at 90~100% of EEV. However, liquid back might happen at this angle because of low superheat. Therefore, it is not adopted as optimum operating conditions. Since the COP is high within 7~10℃ range of superheat, optimum angle of EEV is decided as 85~90% of the seawater ice machine. The maximum COP in the case 1 is 1.92 approximately.

The heat transfer rate supplied to the refrigerant is equal to the removed energy from seawater in ideal system, but the real experimental system has heat loss when the heat exchange takes place between the evaporator and seawater. Therefore, the experimental results show that the COP of case 2 is smaller than the one of case 1.

Fig. 6 shows electrical power as input of the compressor and the production of seawater ice as output of the evaporator when the drum speed is 4rpm. From Fig. 6, it can be seen that the production of the seawater ice is increased when the opening angle of EEV becomes bigger. The electrical power is varied in the range of 4.48~4.96㎾ with the variation of the opening angle of EEV.

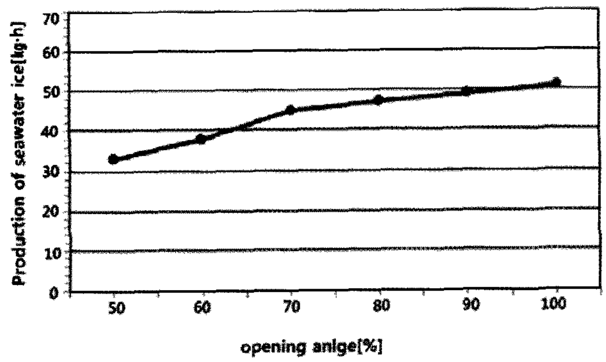


(a)

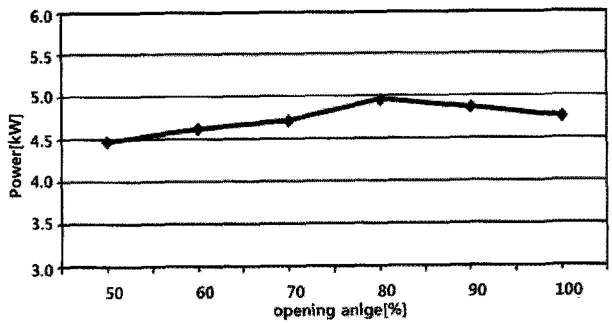


(b)

Fig. 5 COP and SH versus opening angle of EEV(case 1 and case 2)



(a)



(b)

Fig. 6 Electrical power and production of ice versus opening angle of EEV(case 2)

Fig. 7 represents the production and temperature of ice and the superheat versus the rotating speed of drum. From Fig. 7, it can be seen that the production of the seawater ice is improved with increasing rotating speed of drum, and the temperature of seawater ice was raised with the rotating speed of drum. On the other hand, the COP and the superheat are almost the same in spite of the variation of the drum speed. This means that the system has trade-off relation between product of ice and temperature of ice to guarantee long freezing state.

4. Conclusion

This paper investigates the optimum operating conditions to develop the automatic system with highly energy efficient seawater ice machine.

The opening angle of EEV and the speed of rotating drum which had an evaporator inside of

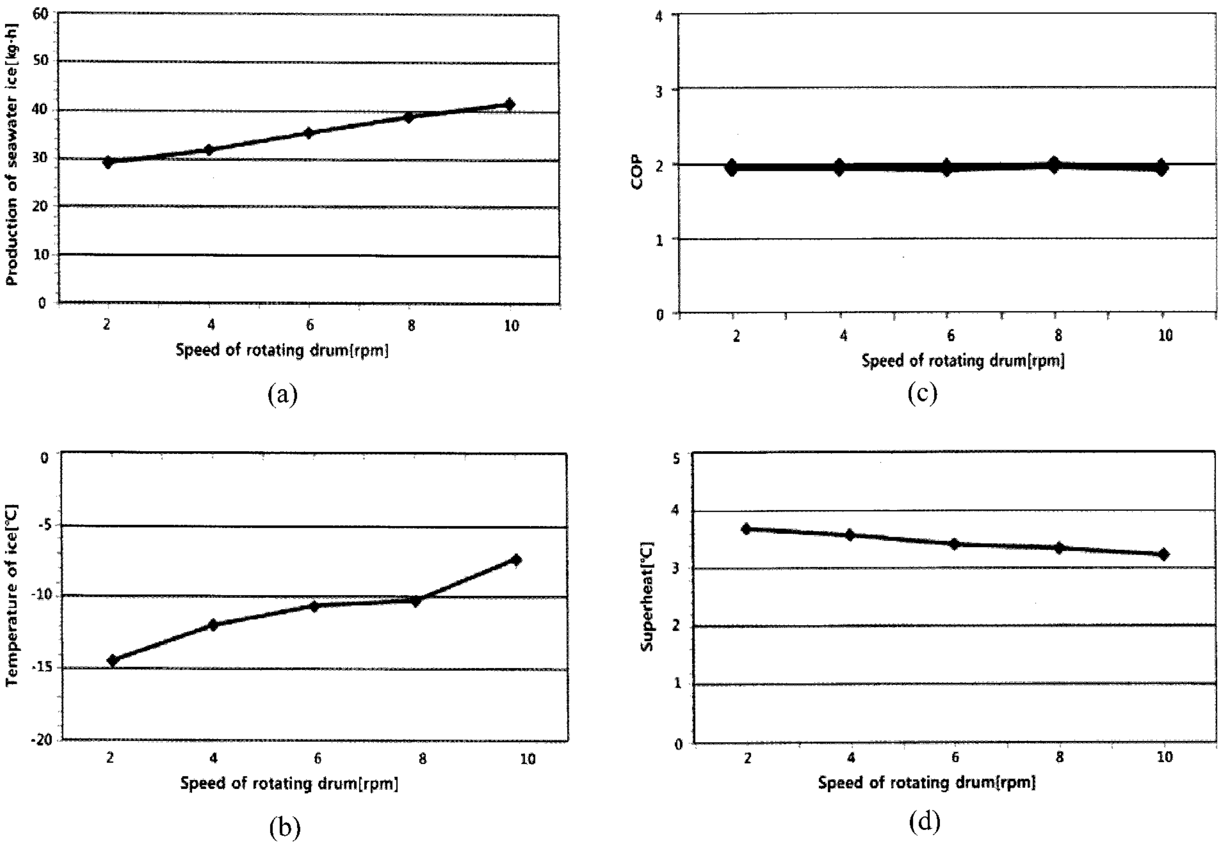


Fig. 7 Production and temperature of seawater ice, and SH versus the speed of rotating drum

it were selected as main control variables. The COP and production of the seawater ice were used as evaluating index of optimum operating conditions.

The main results of this paper were as follows:

(1) The optimum angle of EEV was confirmed as 85~90% considering COP and the liquid back phenomenon.

(2) The production of the seawater ice depends on both rotating speed of drum and opening angle of EEV.

(3) The optimum speed of rotating drum will be determined considering the trade-off relation between the production and temperature of seawater ice.

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