Effects of seawater flow rate and evaporation temperature on performance of Sherbet type ice making machine

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Abstract. This study analyzes performance of the sherbet type ice making machine using seawater with respect to seawater volumetric flow rate, evaporation temperature, cooling water inlet and seawater inlet temperature as variables. Cooling water inlet and seawater inlet temperature are set considering average temperature of South Korea and the equator regions. Volumetric flow rate of seawater range is 0.75-1.75 LPM in this experiment. The results obtained from the experiment are as follows. As the seawater volumetric flow rate increases, or seawater inlet temperature increases, evaporation capacity tends to increase. At the point of seawater inlet temperature of 27°C and volumetric flow rate of 1.0LPM, evaporation capacity is over 2kW. On the other hand, results of COP change tendency are different from that of evaporation capacity. It appears to increase until volumetric flow rate of 1.0LPM, and decrease gradually from volumetric flow rate of 1.5LPM. This is due to the increase of compressor work to keep the evaporation pressure in accordance with the temperature of heat source. As the evaporation temperature decreases from -8 to -15°C, the evaporation capacity increases, but the COP decreases.

1. Introduction
Recently as well-being food is getting attention through the world, high quality fish as well as meat and fowl are in high demand. For fish, high quality is related to freshness. So, low temperature storage of fish as soon as they are caught is necessary in order to keep the freshness. Normally, fishery boats need ice to maintain freshness of fish, but littoral fishery boats in South Korea are small crafts less than 30-100 tons. It is difficult for them to be equipped with ice making machine, individually. These small sized fishery boats without ice making machines load ice at port before departure, and should return to port before exhausting the ice. For this reason, duration of voyage for littoral fishery boats in South Korea is usually within 7 days, and even shorter when a lot of fish are caught. To extend the duration and increase the number of catches, researches on developing compact ice making machines small enough for being installed on small vessels have been conducted actively. Ice made from the ground is usually angled cube in its shape and made of freshwater. Using freshwater to make ice gives merits of getting water easily and being produced on ground anytime. On the other hand, its demerits are insufficient cooling capacity and slow cooling speed when it is used for maintaining freshness of catches. Large and angled shape of the ice has the less surface to exchange heat between the ice and fish, so fish take longer time to cool. Also, the ice should be poured into fish storages with salt to prevent from osmotic pressure.
resulting from salinity difference between the ice and fish. Aside from this, using freshwater ice might cause the following problems: difficulty of adjusting salinity, damages on fish due to its crystalline shape. Damaged fish can rot quickly and are hard to be commercialized. Therefore, researches on developing machines making solid-liquid two-phase sherbet type ice have been being conducted throughout the world. The related researches are as follows.

Stamatiou et al. [1] examined basic crystallization mechanism of a fluidized bed ice slurry generator and a scraped surface ice slurry generator, which are commonly used.

Mounier et al. [2] showed experimental comparison between super-cooled water jet type and scraped surface type ice making machines. The super-cooled water jet type machine has the lower initial cost and energy consumption than those of the scraped surface type. Additionally, the study showed results about enhanced heat transfer characteristics.

Lakhdar et al. [3] studied heat transfer resistances in scraped surface heat exchanger. Variables in the study were blades rotating speed and solute concentration.

Li et al. [4] investigated optimal operating conditions of seawater ice making machines. The study proposed effects of rotating speed of drum type ice making machines on temperature of produced seawater ice, amount of ice and refrigeration performance.

Yoon et al. [5] analyzed performance of seawater ice making machines that consist of two stages vapor-compression cycles. The study presented that R22, R600a and R717 have higher COP in the system. Besides, some variables such as condensing temperature, compression efficiency, super-heating degree and sub-cooling degree were considered important for enhancing COP.

Sherbet or slurry type ice, usually produced by double-pipe heat exchanger, has fine particles, resulting in less damage to the fish. Also, this kind of system is easy to adjust salinity in fish storage since it freezes seawater directly. That is why it has been already commercialized abroad. In spite of these advantages, studies related to ice making machines for small sized vessels are still desired in South Korea. Thus, this research conducts study on developing compact ice making machine using double-pipe heat exchanger and analyzes its performance characteristics.

2. Sherbet type ice making machine using seawater

Figure 1 shows schematic diagram of a sherbet type ice making machine using double-pipe heat exchanger. The sizes of machine are 1,400 mm wide, 650 mm long and 1,500 mm high. The machine weighs approximately 400 kg. These sizes are only for experimental equipment, and the machine which will be installed on boats might be different for different boat sizes. The machine consists of a compressor, an evaporator, a condenser, a receiver, an expansion valve, an oil separator and filter dryer. The evaporator is a double-pipe type with screw shaped scrapers. The scrapers are rotated by a motor installed on upper side of the evaporator. Its working principle is as following.

Vapor state working fluid with high pressure and temperature from the compressor outlet flows into the double-pipe type condenser after passing the oil separator. The working fluid is liquefied in the condenser by exchanging heat with cooling water, and flows to the expansion valve after passing the receiver, the filter dryer and a solenoid valve sequentially. In the expansion valve, the liquid state working fluid is expanded by wire drawing effect to the evaporation pressure. Expanded working fluid evaporates in the evaporator by exchanging heat with seawater thereby the seawater will be frozen. Then, the working fluid after getting heat from seawater flows to the compressor, completing the cycle. The compressor in this experiment is an inverter-type compressor, and the expansion valve is an electronic expansion valve. The expansion valve regulates evaporation pressure by loading super-heating degree from evaporator outlet. The evaporator in the experiment is semi-flooded type having superiority of cooling efficiency. But it has demerit of difficulty in recovering oil perfectly. In order to make oil circulation well, oil separator is installed between the compressor and the condenser. The condenser used in the experiment is a double-pipe heat exchanger made of titanium. Temperature of cooling water used to condensate the vapor state working fluid is maintained by a constant temperature bath. Likewise, another constant temperature bath controls temperature of seawater at the evaporator inlet.
3. Experimental conditions and methods

3.1 Experimental conditions
Table 1 shows operating conditions of the experiment. Initial seawater salinity was determined by common coastal salinity of 32% in South Korea. Based on related researches regarding slurry ice, freezing occurs too fast if evaporation temperature is too low, which may stop the scraper rotating. In this experiment, not only energy aspects such as COP but also finding sustainable operating conditions were considered important. That was why evaporation temperature condition of -10°C was set as standard condition. Standard inlet temperature of cooling water was 27°C based on general regulation of refrigeration equipment for the ocean industries. Working fluid was R22, considered high performance and having general use. Scraper rotation speed was 350 rpm.

| Parameter                                      | Value                  | Unit |
|------------------------------------------------|------------------------|------|
| Initial salinity                               | 32.0*                  | ‰    |
| Flow rate of seawater                          | 0.75*, 1.0, 1.25, 1.50, 1.75 | LPM  |
| Inlet temperature of seawater                  | 10*, 15, 20, 27        | °C   |
| Evaporation temperature                        | -8, -10*, -15          | °C   |
| Inlet temperature of cooling water             | 27.0*, 32.0            | °C   |
| Refrigerant                                    | R22                    |      |
| Scraper rotation speed                         | 350                    | rpm  |
| Super-heating degree                           | 8                      | °C   |

*Standard condition
3.2 Experiment methods

Experiment was conducted as follows. The constant temperature bath maintained the temperature of seawater as both cooling water and heat source. The temperature was measured precisely by T-type thermocouple. In order to measure condensation pressure and evaporation pressure, pressure measurement devices were attached on inlet and outlet of both condenser and evaporator. Flow meters were installed at outlet of receiver and seawater tanks, so that it measured flow rate of refrigerant and seawater. Once the compressor started operating, super-heating degree was controlled by the expansion valve, and evaporation pressure was adjusted in accordance with compressor rotating speed. A pump to supply seawater into evaporator is micro motion gear pump, which could adjust flow rate of seawater close to 0.1LPM. Another pump to supply cooling water into condenser could control condensation pressure and sub-cooling degree by adjusting flow rate of cooling water. When the system was in a stable state, measurement devices measured pressure, temperature and flow rate. Those were recorded on a computer by a data logger. The stable state was defined as when temperature, pressure and flow rate were within the error range of 0.5°C, 5 kPa and 0.05 kg/min for 15 minutes, respectively.

3.3 Data analysis

Evaporation capacity can be calculated by equation (1) as following.

\[ Q_{eva} = m_{ref} \times \Delta h \]  

(1)

The \( m_{ref} \) means mass flow rate of working fluid measured by a flow meter, and \( \Delta h \) means difference of enthalpy at inlet and outlet of the evaporator. System COP can be calculated by equation (2) below. In equation (2), \( Q_{eva} \) means the evaporation capacity, and \( W \) is compressor consumption power from a power meter.

\[ \text{COP} = \frac{Q_{eva}}{W} \]  

(2)

Table 2 shows uncertainty analysis of experiment data. The uncertainty is obtained by using Moffat’s method [6]. The \( P_H \) and \( P_L \) denote condensation and evaporation pressures, respectively. Also, \( T_C \) and \( T_E \) represent condensation and evaporation temperatures, respectively.

| Parameter | Systematic error | Random error | Total error |
|-----------|------------------|--------------|-------------|
| \( P_H \) | 1.825083 kPa     | 0.948 kPa    | 0.185 %     |
| \( P_L \) | 0.334425 kPa     | 0.768 kPa    | 0.60 %      |
| \( T_C \) | 0.47775 °C       | 0.054 °C     | 1.377 %     |
| \( T_E \) | 0.26175 °C       | 0.037 °C     | 3.552 %     |
| \( m_{ref} \) | 0.07787 kg/min   | 0.001 kg/min | 10.004 %    |

4. Results and discussions

4.1 Effect of seawater flow rate and inlet temperature

Figures 2 and 3 present evaporation capacity and COP with respect to seawater flow rate and seawater temperature to evaporator, respectively. The evaporation capacity \( (Q_{eva}) \) grew when volumetric flow rate of seawater increased. Also, the higher temperature of seawater resulted in the higher evaporation capacity. This is caused by two factors. The first factor is the increase of temperature difference between seawater and refrigerant, and the second factor is the rise of flow rate. Those factors affect heat exchange duty, so increase of those two factors contributes to rise of evaporation capacity. While evaporation capacity presented direct proportion value with changing volumetric flow rate of seawater, the tendency of COP was inversely proportional. That is, it reached peak value and then decreased gradually. In case
that the inlet temperature of seawater was 10°C and 15°C, COP showed peak value at volumetric flow rate of seawater of 1.0LPM. Evaporation capacity had maximum value of 2.1kW when seawater inlet temperature and volumetric flow rate of seawater were 27°C and 1.0LPM. On the other hand, COP had minimum value of 2.78 at same working condition. If inlet temperature or volumetric flow rate of seawater increases, the evaporation temperature and pressure rise. Then, rotating speed of the compressor increases so that evaporation pressure is maintained constantly, and it leads to increased compressor consumption power.

Since COP is a function of both evaporation capacity and compressor consumption power, each parameter regarding the working conditions should be considered simultaneously to analyze tendency of COP. When COP tends to decrease, it means increment of compressor consumption power has more effect on COP than that of evaporation capacity at the same working condition.

On the other hand, if increment of evaporation capacity takes the larger portion than that of compressor consumption power, COP tends to increase. For these reasons, COP shows inconstant tendency according to changing volumetric flow rate and inlet temperature of seawater, as shown in figure 3.
4.2. Effect of evaporation temperature and heat sink temperature

Figures 4-6 show effects of evaporation temperature and heat sink temperature on evaporation capacity, COP and mass flow rate of refrigerant.

Evaporation capacity increased as evaporation temperature decreased due to the enlarged temperature difference between refrigerant and seawater. Additionally, it can be found that mass flow rate of refrigerant increased as the evaporation temperature decreased based on figure 6. The reason why the mass flow rate increased could be explained with analysis of COP.

COP had a different tendency from evaporation capacity. At the lower evaporation temperature, the lower COP was obtained. Increase of compressor consumption power was analyzed to be the main reason for this, and the followings are supporting reasons for increasing compressor consumption power. Firstly, decrease of evaporation temperature enlarged pressure difference between inlet and outlet of the compressor. Secondly, the larger pressure difference resulted in lower compressor efficiency. Lastly, the compressor should rotate with faster speed to get the lower evaporation, and simultaneously the expansion valve should reduce its opening. Here, the faster compressor rotating increases the mass flow rate of refrigerant, while reduced opening of the expansion valve decreases it. Considering both figure 4 and figure 5, increment of refrigerant flow rate by compressor is bigger than decrement by expansion valve, and the increase of the mass flow rate of refrigerant with the decrease of evaporation temperature was shown in figure 6 [7, 8].

Therefore, evaporation capacity in figure 4 increased as evaporation temperature decreases not only for the reason regarding enlarged temperature difference mentioned above, but also increased mass flow rate of working fluid.

Moreover, when heat sink temperature increased which refers to increase of condensation pressure, COP presented the same tendency with respect to changing evaporation temperature. The higher heat sink temperature also caused the larger pressure difference between compressor inlet and outlet. So, when seawater temperature flowing into the condenser was at 32°C, the COP revealed the lower value than that of the case with the seawater temperature of 27°C. Also, COP of ordinary compressor is shown in figure 5, which can get from BITZER software [9], and COP from the experiment is approximately 17% higher.

![Figure 4](image)

**Figure 4.** Evaporation capacities with regard to evaporation temperature
Figure 5. System COP with regard to evaporation temperature.

Figure 6. Refrigerant mass flow rate with respect to evaporation temperature

5. Conclusion
This study evaluated the performance of the compact seawater slurry ice making machine applying double-pipe heat exchanger for small vessels. The parameters used for experimental analysis were the volumetric flow rate and inlet temperature of seawater, the evaporation temperature and heat sink temperature. The summary of the experimental results is as follows.

(1) As the volumetric flow rate of seawater increased, the evaporation capacity also increased. This result was caused by two reasons as follows. The first reason is increase of the temperature difference between seawater and refrigerant. The second one is that the mass flow rate of refrigerant was increased by the increase of compressor rotating speed to maintain the evaporator pressure constantly.
(2) When the volumetric flow rate and the inlet temperature of seawater increased, COP presented inconstant tendency. The inconstant tendency of the COP was influenced by correlation of the changes between compressor consumption power and evaporation capacity.

(3) The evaporation capacity was affected by either the evaporation temperature or the condensation temperature. The enlarged temperature difference between them and the increased mass flow rate of working fluid increased the evaporation capacity.

(4) The COP decreased when the evaporation temperature decreased. The compressor rotated fast to keep the evaporator pressure from decreasing, and it resulted in increase of mass flow rate of refrigerant. While, the reduced opening of the expansion valve decreased the mass flow rate of refrigerant. Increment of the mass flow rate of refrigerant by compressor and decrement by expansion valve influenced on not only the compression consumption power but also the COP.

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