Development of a High Efficient Heat Pump System using Seawater Heat Source and Exhaust Energy with the Automatic Decontamination Device

Oh, Jong-Taek, Professor, Department of Refrigeration and Air Conditioning Engineering, Chonnam National University, 50 Daehak-ro,Yeosu, Chonnam 550-749, Republic of Korea. (ohjt@chonnam.ac.kr)
Choi, Kwang-Il, Department of Refrigeration and Air Conditioning Engineering, Chonnam National University, 50 Daehak-ro,Yeosu, Chonnam 550-749, Republic of Korea.
Pham, Quang-Khai, Graduate School, Chonnam National University,50 Daehak-ro,Yeosu, Chonnam 550-749, Republic of Korea.
Seol, Won-Shil, EME Ltd. Co.,33 Airport-ro, Gangseo-Ku, Pusan 618-142, Republic of Korea.
Kwon, O-Kyung, KITECH, KITECH Cheonan Headquarters 35-3, Cheonan-si, Chungcheongnam-do, 330-825 Republic of Korea.

Abstract: The heat pump system using seawater heat source and exhaust energy without fouling of heat exchangers is developed and its performance characteristics of heating and cooling operation are presented. The heat pump system is made of a waste heat recovery system and a vapour compression refrigeration system and the automatic decontamination device. The working fluid is R-22. The heat pump system COPs are measured during heating and cooling operation modes for an indoor culture system, and the resultant COPs are 12.5 and 11, respectively, which are higher than those of the heat pump itself. Therefore, the performance of the heat pump system using exhaust energy and seawater heat source with a decontamination device is excellent compared with that of a general heat pump. The experimental data can be effectively used for the design of the high efficient heat pump using seawater heat source and exhaust energy.

Key Words: Waste heat recovery, Seawater heat source, automatic decontamination device, Vapor compression cycle, COP

1 INTRODUCTION

The heat pump is an energy-efficient and environment-friendly apparatus for heating and cooling of built environment. Since the 1950s, researches have been developed heat pump system structure, thermodynamics, working fluids, operation controlling, numerical simulation and economical analysis (Arif et al. 2009).

From 1985 (January) to 1986 (February), The Fisheries Research Center of the Japan Kinki University used heat pump system to breed fish (sea breams) fry in land based aquaculture system, and COP of system was about 2.8 (Michiyasu and Tadao Tsuji 1992). This study showed heat pump system can be used economically, energy saving in breeding fish in land based aquaculture system (Kim IB 1993). Recently, Oh et al. have been developed a high efficient heat pump system using exhaust water heat source that can be used to breed flatfishes in land based aquaculture system. This study showed that the COP is about 6, respectively, and energy saving is eleven times of the maximums and five times of the average than an oil boiler system (Oh et al. 2000).

In this study, for the purpose of fouling seawater treatment in plate heat exchangers, the ceramic ball are installed to ball collector and ball separator as the automatic decontamination device, here it is refined the fouling seawater. The seawater is compressed and boosted by water pump and ejector to clean when the heat exchanger plates is fouled. Fouling seawater is separated by the cyclone. Where the ball ceramic is dropped into a collector and separator and a pure seawater is delivered to breed fish in the farm.

The automatic decontamination device (ADD) is developed in effort to refined fouling seawater, the ADD is retrofitted for heat pump system, and specially it is designed to enable a quick cleaning of the fouling on the plate's surface. A comparison of the COP between the heat pump system with ADD and itself was also presented.

2 EXPERIMENTAL APPARATUS AND METHOD

2.1 General remarks

In this study the experimental facility shown in Figure 1, is specially constructed for the purpose. The major components of the experimental apparatus are; heat recovery, compressor, condenser and evaporator. The heat pump is one-stage refrigeration cycle, and was typically classification as a water-to-water heat pump. Two PHEs that made from copper were used for condensing and evaporating. The heat recovery system is used to heat exchange of exhaust water and new seawater that is made of stainless steel.

The temperature of coastal seawater and fresh water in Korea vary from 4^0C to 30^0C every year. The seawater from sediment cistern at first was pumped to the first PHE where it was preheated (in winter) or precooled (in summer) by water of indoor culture system. The sediment water at the outlet then delivered to condenser to increase the temperature and flow into the indoor culture system.

The fouling water from the other outlet of the first PHE was continue pumped to the second PHE. After exchanging heat, fouling water was delivered to the cyclone where it is separated to ball and pure water. The balls then were accumulated in ball collector while the pure water go back to the sediment cistern. When the ejector was used, the ball from collector will be mixed with the water from indoor culture system and go to the first PHE for the new cycle.

The automatic decontamination device includes ball separator and ball collector. The ejector and water pumps are installed in heat pump system for the purpose of fouling treatment in plate heat exchanger surfaces.

2.2 Working refrigerant loop

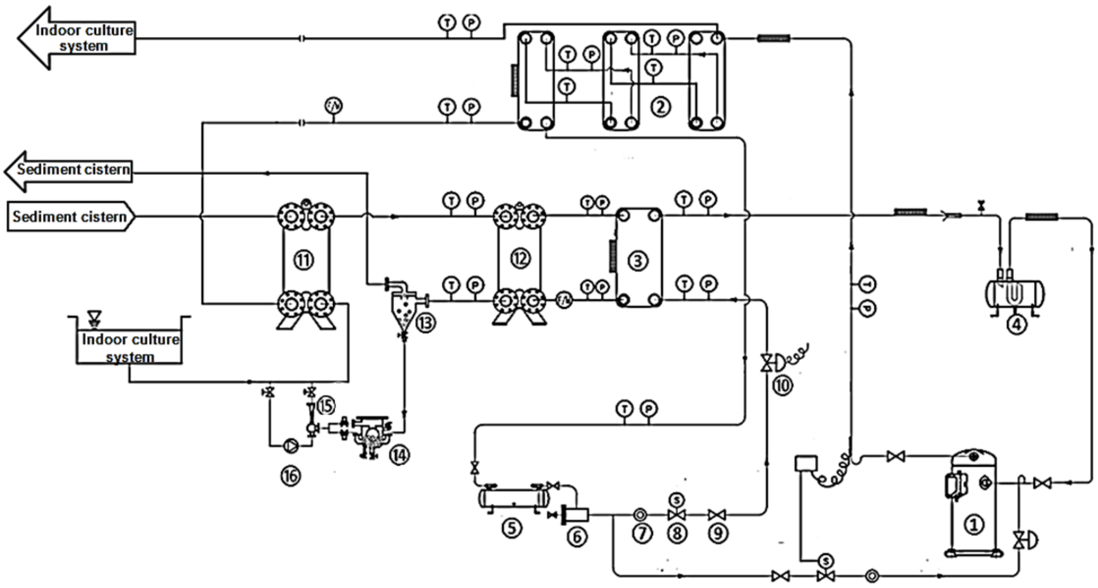
The schematic of the working refrigerant loop is also illustrated in Figure 1. A high temperature and pressure gas of □compressor enter in the □condenser. The water is heated by heat exchange in the condenser. After condensing in the condenser the refrigerant liquid enter a □receiver. The refrigerant liquid of receiver is passed through the □core - dryer, □sight glass, □solenoid valve, □shutdown valve and □expansion valve. From there the refrigerant liquid is changed by the low temperature and pressure refrigerant. This vapour-liquid refrigerant flow into □evaporator. The water is cooled by heat exchange in the evaporator, and the refrigerant is evaporated. After evaporating in the evaporator, the refrigerant vapour and any unevaporated liquid are separated in the □accumulator. The refrigerant vapour is compressed in the compressor.

2.3 Cleaning plate heat exchangers loop

Fouling occurs when impurities cling on the heat exchanger surfaces, and it can decrease heat transfer effectiveness significantly. For the fouling treatment in heat recovery systems, as show in Figure 1, the waste water is compressed and boosted by □water pump and ejector, and it is passed to the first and the second heat recovery. It is mixed with impurities cling to clean on the plate heat exchanger surfaces. The waste water is passed through ball separator, here, the ceramic ball is separated it by the cyclone. The new water from ball separator is passed to ball collector for refining and mixed waste water circulation for cleaning plate heat exchanger surfaces.

2.4 Test procedure

The heat pump is installed the automatic decontamination device, and is operated to determine COP. The refrigerant flow rate in heat pump was controlled by electric expansion valve. All data were taken after the operating conditions reached a steady state that all temperature and refrigerant flow rate has not changed.



 Compressor Receiver Shutdown valve Ball separator
 Condenser Core - dryer Expansion valve Ball collector
 Evaporator Sight glass 1st heat recovery Ejector
 Accumulator Solenoid valve 2nd heat recovery Pump

Figure 1: Schematic diagram of heat pump system

Table 1: Experimental conditions

Parameter		**Dimension**
Ceramic ball	$m^2.h.^0C/kcal$	0 – 0.000496
Compressor	Type	Copeland - ZR380KC
Condenser (KAORI)	Temperature (^0C)	13 ~ 28
	Heat transfer area (m^2)	7.176
	Number of plates	40
Evaporator (KAORI)	Temperature (^0C)	-10 ~ 7
	Heat transfer area (m^2)	10.77
	Number of plates	100
Heat recovery (Model DX-17DLH-1p-95)	Number of plates	95
	Heat transfer area (m^2)	15.81
Refrigerant	R22	

2.5 Plate heat exchanger area of heat recovery system

This heat pump system used the PHE (plate heat exchanger) for the heat recovery system, condenser and evaporator. Fundamental performance model is to be simplified for the calculation of heat transfer and PHE area. For analysis of heat transfer characteristic of PHE, Cooper A. and Usher J.D's correlation is used to measure turbulent flow in PHE chevron angle (β) 120°.

$$\mathrm{Nu} = 0.2\,\mathrm{Re}^{0.67}\,\mathrm{Pr}^{0.4}(\eta / \eta_W)^{0.1} \tag{1}$$

In the equation (1), the overall heat transfer coefficient with a calculated heat transfer coefficient can be calculated as follows.

$$1/U = 1/h_\mathrm{h} + 1/\lambda_\mathrm{p} + 1/h_\mathrm{c} + \mathrm{R_f} \tag{2}$$

where λ_p and R_f are thermal conductivity and fouling factor of the PHE, respectively.

The characteristic analysis of the heat exchanger can be carried out using ε-NTU method (Lee et al. 2000). The NTU method has gained greatest acceptance in connection with design of compact heat exchangers where a large surface area per unit volume exists.
Heat exchanger efficiency was mentioned in the previous section as

$$\varepsilon = \text{Actual heat transfer rate} / \text{Maximum possible heat transfer rate} \tag{3}$$

The actual heat transfer rate is given by

$$\dot{q} = C_h(t_{hi} - t_{ho}) = C_c(t_{co} - t_{ci}) \tag{4}$$

The maximum possible heat transfer rate is expressed by

$$\dot{q}_{\max} = C_{\min}(t_{hi} - t_{ci}) \tag{5}$$

This is true because the maximum heat transfer would occur if one of the fluids were to undergo a temperature change equal to the maximum in the heat exchanger, (t_{hi}-t_{ci}). The fluid experiencing the maximum temperature change must be the one with the minimum value of *C* to satisfy the energy balance.

The fluid with the minimum value of C may be the hot or the cold fluid. For $C_h = C_{min}$, using Eqs. (4) and (5)

$$\varepsilon = \dot{q} / \dot{q}_{\max} = C_h(t_{hi} - t_{ho}) / C_{\min}(t_{hi} - t_{ci}) = (t_{hi} - t_{ho}) / (t_{hi} - t_{ci}) \tag{6}$$

For $C_c = C_{min}$

$$\varepsilon = \dot{q} / \dot{q}_{\max} = C_c(t_{co} - t_{ci}) / C_{\min}(t_{hi} - t_{ci}) = (t_{co} - t_{ci}) / (t_{hi} - t_{ci}) \tag{7}$$

It is, therefore, necessary to have two expressions for the efficiency (Eq. (6) and (7)). When efficiency is known, the outlet temperature may be easily computed.
For example, when $C_h < C_c$

$$t_{co} = \varepsilon(t_{ci} - t_{hi}) + t_{hi} \tag{8}$$

Also

$$t_{co} = \left(\dot{q} / C_c\right) + t_{ci} = \left[C_h / C_c(t_{hi} - t_{ho})\right] + t_{ci} \tag{9}$$

$$t_{co} = \left[\left(C_h / C_c \right) . \varepsilon . (t_{hi} - t_{ci}) \right] + t_{ci} \tag{10}$$

The NTU parameter is defined as UA/C_{min} and may be thought of as a heat transfer size factor. That may also be observed that flow configuration is unimportant when C_{min}/C_{max} = 0. This corresponds to the situation of one fluid undergoing a phase change where c_p may be thought of as being infinite. Evaporating or condensing refrigerant as well as condensing water vapor are examples where C_{min}/C_{max} = 0. The NTU method has gained greatest acceptance in connection with design of compact heat exchangers where a larges surface area per unit volume exists.

2.6 COP of Heat Pump System

The COP_{HP} of heat pump is then equal to the heat output divided by the work input:

$$COP_{HP} = Q_c / AW_{comp} = (Q_e + AW_{comp}) / AW_{comp} = 1 + Q_e / AW_{comp} \tag{11}$$

The heating COP_{hs} of heat pump system are different with the COP_{HP} of heat pump because the total input energy is more than the compressor power. The heating COP_{hs} of heat pump system is defined as

$$COP_{hs} = Q_{tc} / AW_e \tag{12}$$

Where, the Q_{tc} is the sum of the condensation heat energy and the rejected heat energy from a motor, the AW_e is the sum of the compressor work (AW_{comp}) and the electricity energy of a condensation fan, etc.

And the COP_{cs} calculation of cooling is the same as the heating calculation method in heat pump system. The cooling COP_{cs} of heat pump is defined as

$$COP_{cs} = Q_{te} / AW_e \tag{13}$$

Where, the Q_{te} is the sum of the evaporation heat energy and the heat flow energy of the surrounding.

The compressor and expansion valve are as follows: Assumption for the characteristic analysis of heat pump system.
(1) The compressor is a company manufacture.
(2) The pressure variation in heat exchanger has nil.
(3) The expansion valve has a constant enthalpy expansion.

3 RESULT AND DISSCUSION

3.1 Simulation in Heat Pump System

3.1.1 Heating Operation

Figure 2 shows the heating capacity of a heat pump system along with various refrigerant evaporation temperatures. As shown in Figure 2, the heating capacity increased with an increase of evaporation temperature, and decrease of condensation temperature. Figure 3 shows the COP_{hs}(heating) of heat pump system along with various refrigerant evaporation temperatures. The COP_{hs} increased with an increase of evaporation temperature, and decrease of condensation temperature. It is similar to the trends as heating capacity.

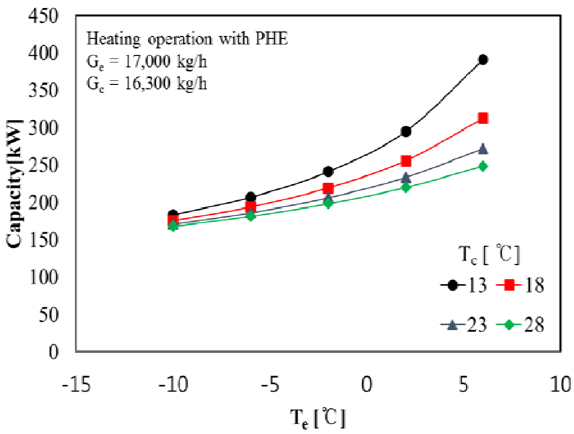


Figure 2: Heating capacity of heat pump system, G_e= 17,000 kg/h; G_c = 16,300 kg/h

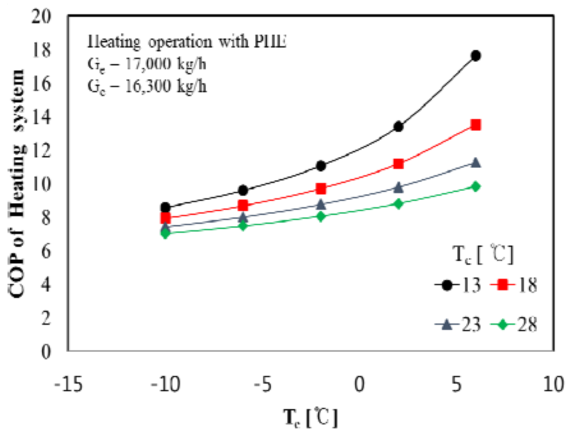


Figure 3: COP_{hs} (heating) of heat pump system, G_e= 17,000 kg/h; G_c = 16,300 kg/h

3.1.2 Cooling Operation

Figure 4 shows the cooling capacity of a heat pump system along with various refrigerant evaporation temperatures. As shown in Figure 4, the cooling capacity increased with increase of evaporation temperature. Figure 5 shows the COP_{cs} (cooling) of heat pump system along with various refrigerant evaporation temperatures. This is similar to the trends as shown in Figure 3. That is, the COP_{cs} increase with a decrease of condensation temperature when the evaporation temperature is constant.

3.2 Comparison of simulation and experimental data in Heat Pump

The COP of simulation result and experimental data is compared with changing evaporation and condensation temperatures simultaneously.

3.2.1 Heat pump COP with new heat exchangers

Figure 6 and Figure 7 show the COP_{hs} (heating) and COP_{cs} (cooling) of heat pump with using new heat exchangers, respectively. As shown in figures, The COP of simulation is higher about 20% than that of experimental data. And Figure 6 and Figure 7 has a bigger error with increasing evaporation and condensation temperature when compare simulation value with experimental data.

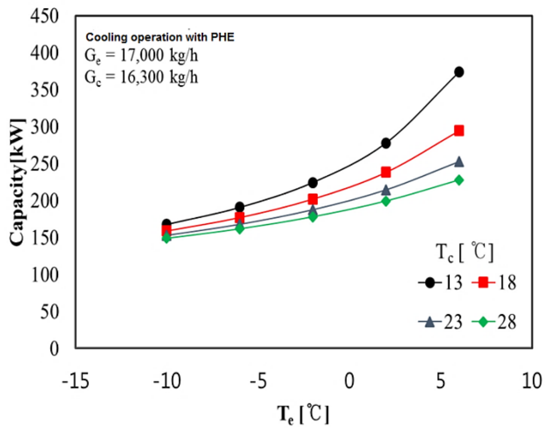


Figure 4: Cooling capacity of heat pump system, G_e= 17,000 kg/h; G_c = 16,300 kg/h

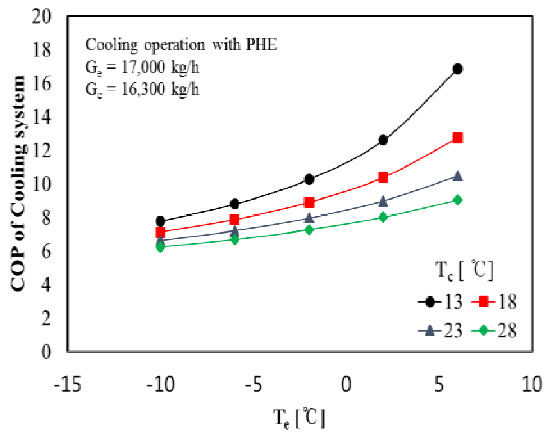


Figure 5: COP_{cs} (cooling) of heat pump system, G_e= 17,000 kg/h; G_c = 16,300 kg/h

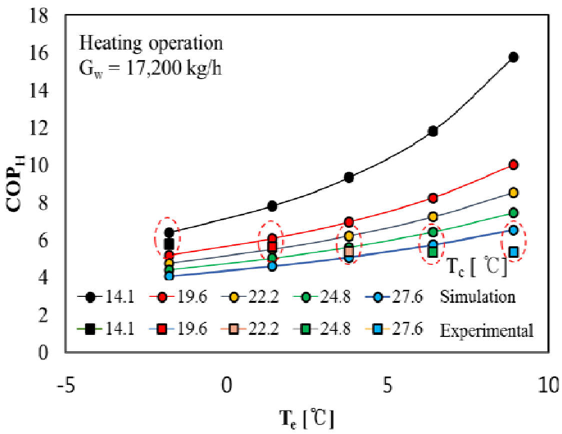


Figure 6: Comparison of COP of experimental data and simulation result in heating operation with new heat exchangers

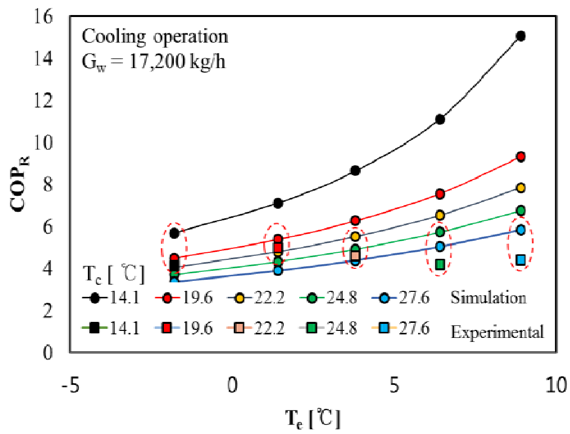


Figure 7: Comparison of COP of experimental data and simulation result in cooling operation with new heat exchangers

3.2.2 Heat pump COP with fouling heat exchangers

Figure 8 and Figure 9 show the COP_{hs} (heating) and COP_{cs} (cooling) of heat pump with using fouling heat exchangers. As shown in figures, The COP of simulation is higher about 20% than that of experimental data. Namely, it is similar to the trends as Figure 6 and Figure 7, respectively.

3.2.3 Heat pump COP with cleaning heat exchangers

Figure 10 and Figure 11 show the COP_{hs} and COP_{cs} of heat pump with using cleaning heat exchangers. As shown in figures, The COP of simulation is higher about 13% than that of experimental data.

Therefore, The COP of heat pump with using new heat exchangers is highest of heat pump with using cleaning and fouling.

3.3 COP of heat pump system in indoor culture system

3.3.1 Heating Operation

Figure 12 shows the COP along water temperature of sediment cistern when the heat pump

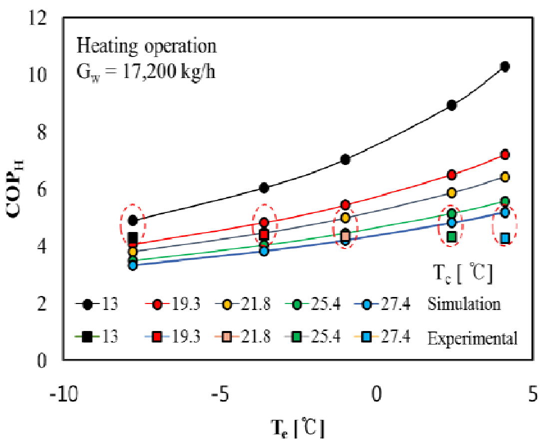


Figure 8: Comparison of COP of experimental data and simulation result in heating operation with fouling heat exchangers

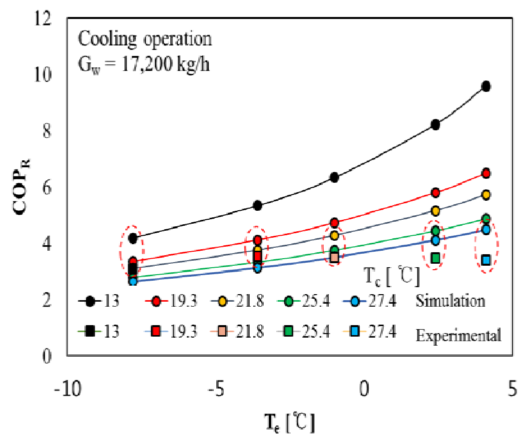


Figure 9: Comparison of COP of experimental data and simulation result in cooling operation with fouling heat exchangers

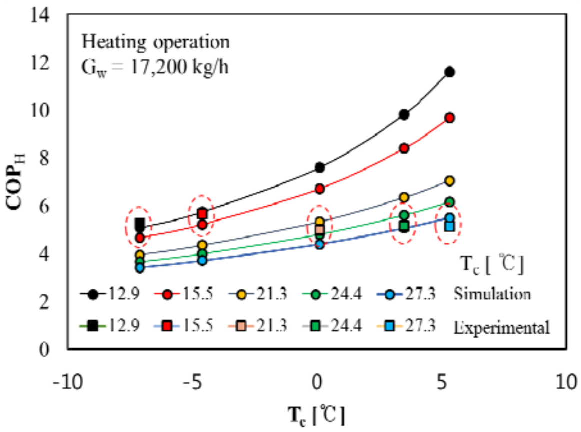


Figure 10: Comparison of COP of experimental data and simulation result in heating operation with cleaning heat exchangers

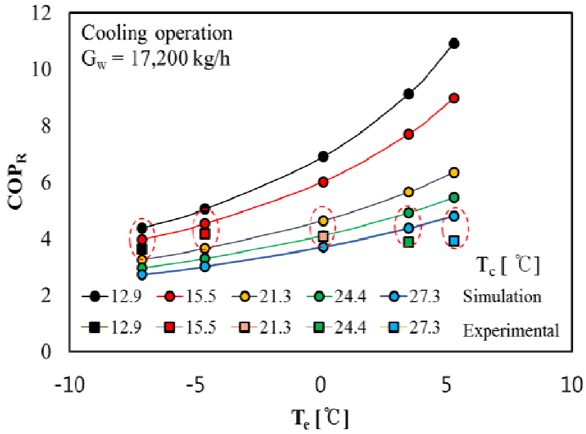


Figure 11: Comparison of COP of experimental data and simulation results in cooling operation with cleaning heat exchangers

system did operate heating. As can be seen in the figure, at a constant sediment cistern water temperature, 4^{0}C, the supply water temperature is heated to 18.7^{0}C. And the COP of heat pump system is about 18.

The region A in Figure 12 represents a ON/OFF operation of a compressor for a supply water temperature control. The region B shows a heating operation for a supply water temperature variation at a constant sediment cistern temperature. As shown in the figure, the supply water temperature in the indoor culture system remained constant of 18.7^{0}C under a constant sediment cistern water temperature, 5^{0}C. In the tests of experimental apparatus, the supply water temperature is 18.7^{0}C because a heat loss is caused by the surroundings of indoor culture system. The COP of heat pump system is 18 when a run was conducted as indicated region B of Figure 12. These results suggest that the heat pump system has operated at a steady state.

3.3.2 Cooling Operation

Figure 13 shows the COP along with water temperature of sediment cistern when the heat pump system operated under the cooling condition. This is similar to the trends as shown in Figure 12. The supplied water temperature entered into indoor culture system is controlled at a constant, 20.1^{0}C. In Figure 13, the region A is the beginning of a cooling operation, the region B is a cooling operation process for a supply water temperature variation at a constant

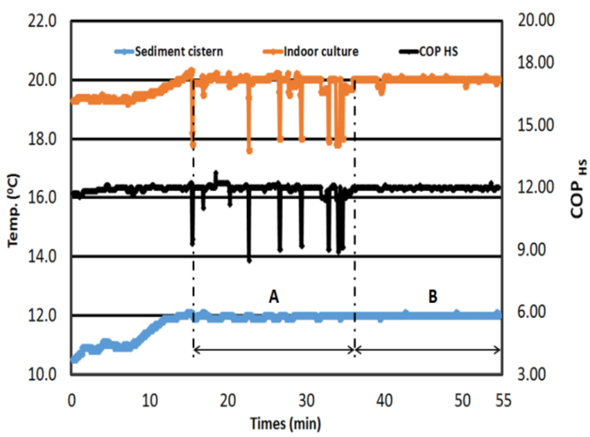


Figure 12: COP_{HS} of heating operation of heat pump system, T_{tank}=20.1^{0}C, G_w=6000kg/h

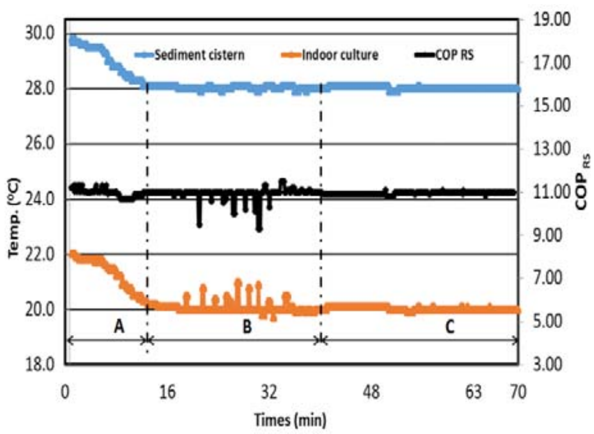


Figure 13: COP_{RS} of cooling operation of heat pump system, T_{tank}=20^{0}C, G_w=6000kg/h.

sediment cistern water temperature, 28^{0}C. The COP of heat pump system is from 10.8 to 11 when it was operated in region B and C. These results proved consistent in several tests.

4 CONCLUSIONS

The result of experimental involving a high efficient heat pump system using seawater heat source and exhaust energy with the automatic decontamination device may be summarized as follows:

1. The COP of simulation is higher about 20% than that of experimental data in heat pump with using plate type heat exchanger.
2. The fouling factor is effect on performance of this system. The COP decrease with its increase.
3. The COP of heat pump with automatic decontamination device is higher than a heat pump itself on a heating and cooling operations.
4. The heating and cooling COP of heat pump system is 18 and 12.5 when the heat pump system has operated with a steady state in indoor culture system, respectively.

5 ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) Grant no. (2011T100100464) of the Energy Technology Development.

6 REFERENCES

Kim IB (1993). “Growth direction of fishes culture, Korean Aquaculture”, p 21-54.

Michiyasu K (1992). “Development of the high efficiency production system for a flatfish aquaculture”, Refrigeration, pp 1187-1192.

Tadao Tsuji (1992). “Heat pump application for fish spawning and breeding”, Refrigeration, pp 8-15.

Takashi, U (1994). “Development of a heat pump system using low seawater temperature as the heat source”, The Resarch Report of Hokkaido Electric Power Company; pp 458.

Oh JT, et al (2000). “Development of high efficient heat pump using seawater heat source for indoor culture system”. Proceedings of the SAREK 2000 Summer Annual Conference, pp. 526-531.

Lee TH, et al (2000). “Measurement of air side heat transfer coefficient of wire-on-tube type heat exchanger”, Korean Journal of Air-Conditioning and Refrigeration Engineering 2000, pp 161-169.

Arif Hepbasli, Yildiz Kalinci (2009). “A review of heat pump water heating systems”. Renewable and Sustainable Energy Reviews, pp.1211–1229.