DEVELOPMENT OF HIGH EFFICIENT HEAT PUMP SYSTEM USING THE HEAT SOURCE OF EXHAUST WATER

Jong-Taek Oh, Professor, Department of Refrigeration Engineering, Yosu National University, Yosu, Chonnam 550-749, Korea
Kwang-Il Choi, Graduate School, Yosu National University, Yosu, chonnam 550-749, Korea
Hoo-Kyu Oh, Professor, Department of Refrigeration and A/C Engineering, Pukyong National University, Pusan, 608-737, Korea

ABSTRACT

A high efficient heat pump system using exhaust water heat source is developed. It enables us to control a supply water temperature of land based aquaculture system automatically. First, a computer simulation and an experiment for an increase in COP of heat pump system were conducted. The predicted COP are compared with experimental data, which are obtained for refrigeration capacities 5 RT and water supply volume 6 m^3/h, and a controllable temperature 18℃ inside indoor culture system in the range of natural water temperature 4℃-30℃. The data show a good agreement, and maximum COP is 18. Second, the heat pump system with supply seawater volume 40 m^3/h is operated in land based aquaculture system. The total energy cost of heat pump system is compared with that of boiler system during 400,000 fish seedling production of spotted sea bass. The saving energy of the heat pump system is eleven times of the maximums and five times of the average than an oil boiler system.

1. INTRODUCTION

A computer simulation and an experiment of high efficient heat pump system using unused energy were conducted. The study was primarily focused on the development of heat pump system using exhaust water heat source in land based aquaculture system. The improvement of energy efficiency by using unused energy in heat pump system has not been fully studied. These studies for energy saving and conservation of global environment are needed. For the improvement of energy efficiency in heat source machine increasing emphasis is being placed on the optimization design of heat pump system.

The object of developing a high efficient heat pump system is to increase income from aquaculture by output increment with energy saving and optimum water temperature control of land based aquaculture system.

Till now, for the purpose of controlling the water temperature of land based aquaculture system, boiler or ice has been in practice according to the season (winter/summer). Moreover, there has not been an alternative system for this. Therefore, the cultured fish often died by shock of low temperature in winter season and propagation of germs in summer season.(Kim 1993, Michiyasu 1992) It is essential to develop a heat pump system to solve these problems.

From 1985 (January) to 1986 (February), The Fisheries Research Center of the Japan Kinki University did use heat pump system to breed fish(sea breams) fry in land based aquaculture system, and the operating COP was found to be about 2.8. This study reported that heat pump system can be used economically and to save energy in breeding fish in land based aquaculture system.(Tadao 1989) Recently, The Hokkaido and Mitsubishi Electric power company did develop heat pump system that can be used to breed flatfishes in land based aquaculture system. The development study reports that the COP of heat pump system is about 7 and energy saving is considerately higher than that of oil boiler system.(CADDET, 1996) However, this method cannot be used for cooling seawater. Also it is not compact and has an indirect cooling mode using brine.

The temperature variation of coastal seawater and fresh water in Korea is from 4℃ to 30℃ every year.(Homepage, 2001) And the water temperature needed for breeding becomes varied depending on the kind of fish. Furthermore, the south east coast of the Korean Peninsula has cold-seawater band because a warm current and a cold current cross in the summer.

Development study of high efficient heat pump system, which is able to use exhaust water heat source and unused energy is limited. Besides, a method for optimum water temperature control in land based aquaculture system, which could protect this fish from temperature extremes, is lacking. In this background, the present computer simulation and experimental investigation have been carried out with an objective of reducing the use of oil, saving energy and to increase farming output. For the purpose of fully development and operation of heat pump system, two type heat pump systems were made. The one is a supply water volume 6 m^3/h, the other is a supply water volume 40m^3/h and operated to fry culture production of spotted sea bass in land based aquaculture system. The study also attempts to establish the design as well as manufacture know-how of heat pump system that is able to use exhaust water heat source and unused energy.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1 General Remarks

The experimental facility shown in Figure 1 was specially constructed for the purpose. The major components of the experimental apparatus were; a heat recovery system, compressor, condenser and evaporator, electric expansion valve, high receiver, in door culture system and sediment cistern.

Basically, heat pump is one-stage compression refrigeration cycle, and a typical classification for water (space) heating and cooling is a water-to-water heat pump.(Oh et al. 2000) Heating-cooling changeover was accomplished in the refrigerant or water circuit. A full

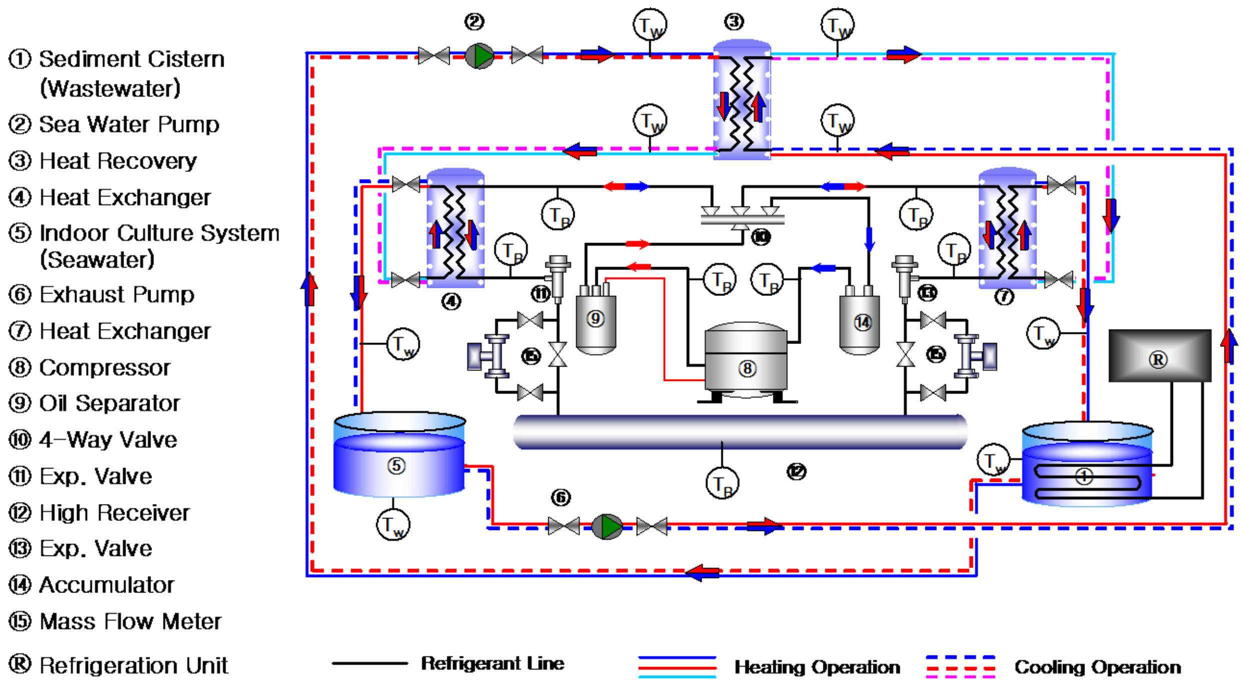

Figure 1. Schematic diagram of heat pump system.

heat pump system is given in Photo 1.

For the purpose of water circulation, two pumps were installed in heat pump system. The one is a supply water pump, the other is a exhaust water pump. As shown in Figure 1, the water of sediment cistern was thrown away into sea or river from land based aquaculture system. But it was reused to condense (or evaporate) after heat exchange at Figure 1.

The refrigeration unit was installed so as to control experimental condition of exhaust water inside sediment cistern (see Photo 1). The volumetric of compressor is 107.71㎤/rev, and a evaporator capacity is 5RT. The evaporator and condenser are plate heat exchanger, these are made of copper. The heat recovery system is made of stainless steel (SUS304)(Alfa Laval, 1994),

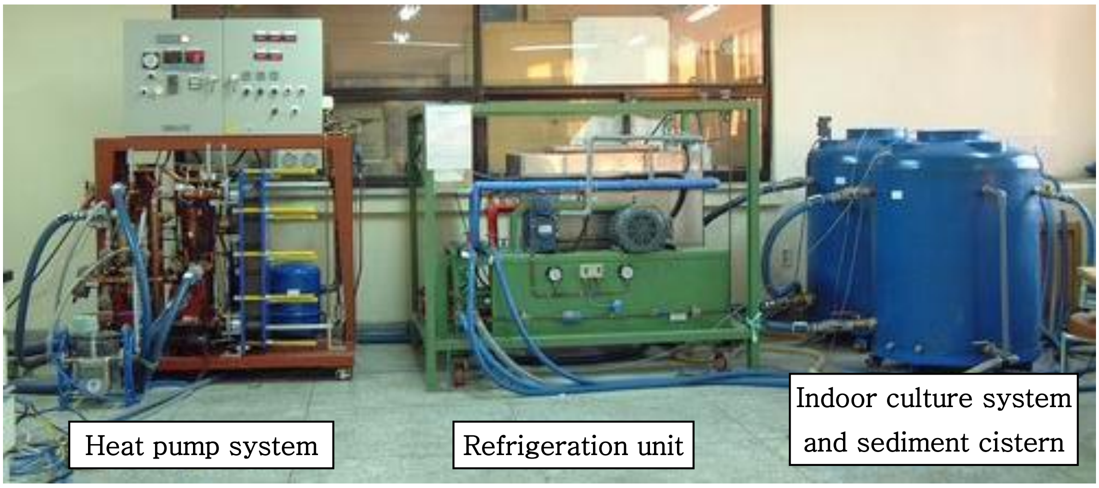

Photo 1. High efficient heat pump system with supply water volume 6 m^3/h.

Photo 2. High efficient heat pump system of supply seawater volume 40 m^3/h using seawater and exhaust water heat source in land based aquaculture system.

and used to recover exhaust heat.

But the material of a plate heat exchanger of supply water volume 40 m^3/h for land based aquaculture system is titanium (see Photo 2). It's used to heat exchange of refrigerant and sea water. Because the heat sink and source is used to seawater, it has to consider corrosion.

2.2 Working Refrigerant Loop

The schematic of the working refrigerant loop is also illustrated in Figure 1. First of all, a high temperature and pressure gas of compressor enter in the oil separator. The refrigerant is separated from oil in it. The refrigerant coming from oil separator was passed through the condenser (if it is heating, number is ④, and if it is cooling, number is ⑦). The water is heated by heat exchange in the condenser. After condensing in the condenser the refrigerant liquid enter a ⑫high receiver. The refrigerant liquid of high receiver is passed through the electric expansion valve (⑬heating or ⑪cooling). From there the refrigerant liquid is changed by the low temperature and pressure refrigerant. This vapor-liquid refrigerant flow into evaporator (⑦ heating or ④cooling). The water is cooled by heat exchange in the evaporator, and the refrigerant is evaporated. After evaporating in the evaporator, the refrigerant vapor and any unevaporated liquid are separated in the ⑭accumulator. The refrigerant vapor is compressed in the ⑧compressor. The ⑩four-way valve is turnover heating or cooling cycle that compares a water temperature of ①sediment cistern with water of ⑤indoor culture system automatically.

2.3 Water Loop

The water loop is constructed by two pumps for water circulation of indoor culture system and sediment cistern. As show in Figure 1, the water of ①a sediment cistern is passed to ③heat recovery system by water pump. Here, it is exchanged with the water of indoor culture system, and the exhaust heat is recovered, and it becomes preheating (winter season) or precooling(summer season). The water after heating or cooling is passed through heat exchanger (condenser or evaporator), where it is controlled to a specific temperature, and the water is supplied to ⑤indoor culture system. The water of indoor culture system is used to breed fish in the farm, and then the water is exhausted to the sea. But the exhausted water is reused to recover the exhaust heat and heat source in the experimental system. Therefore, the water of ⑤indoor culture system is passed to ⑦heat exchanger via ③heat recovery system by ⑥water pump. The water heat source of ①sediment cistern and ⑤indoor culture system is exchanged in the ③heat recovery system, and then the water of indoor culture system runs passed through ⑦heat exchanger, where the water is supplied to the sediment cistern after it is used to heat source. At the same time, the water of a sediment cistern is passed through the ④heat exchanger (condenser or evaporator), and then the water is supplied to indoor culture system after the sediment cistern water temperature is controlled by heat transfer of refrigerant.

2.4 Test Procedure

The heat pump system was operated by indoor culture system temperature of 18.7℃, water supply volume 6 m^3/h, and the auxiliary refrigeration unit.

First, for the cooling operation of the heat pump system, the water temperature of indoor culture system increased to 30℃ by heater. Second, the auxiliary refrigeration unit is operated, and the heat pump system controls a water temperature (18.7℃) in indoor culture system. After cooling experiment is finished, the heating operation is changed in heat pump system. The refrigerant flow rate in heat pump was controlled by electric expansion valve. All data were taken after the experimental conditions reached a steady state where all temperature and refrigerant flow rate has not changed during two hours at least.

3. SIMULATION FOR DEVELOPMENT OF HIGH EFFICIENT HEAT PUMP SYSTEM

3.1 PHE 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.

In the single phase (water/water) flow, 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°.

$$Nu = 0.2\,Re^{0.67}\,Pr^{0.4}\left(\frac{\eta}{\eta w}\right)^{0.1} \tag{1}$$

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

$$\frac{1}{U} = \frac{1}{h_h} + \frac{t}{\lambda_p} + \frac{1}{h_c} + R_f \qquad (2)$$

t and λp is thickness and thermal conductivity of the PHE, R_f is fouling factor.

The characteristic analysis of the heat exchanger can be carried out using ε-NTU method.(Mc Quiston et al. 1994, Lee 1982) The NTU method has gained greatest acceptance in connection with design of compact heat exchangers where a large surface area per unit volume exists.

The use of heat recovery system can recover exhaust heat in heat pump system and can be seen in Figure 1. The purpose of simulation is to find a moderate PHE area of heat recovery system in heat pump system. Figure 2 and 3 shown simulation results. In Figure 2 and 3, A and G_w are the PHE area of the heat recovery system and the water flow rate, and ΔT is the difference between high inlet temperature and low outlet temperature of a waste heat recovery system(see Figure 1, ○,3). Figure 2 shows the PHE area variation along with different temperature ΔT as a function of the sediment cistern temperature. As can be seen in the figure, the PHE area of a heat recovery system a considerably decreased against the increase of different temperature ΔT. This is because NTU(Number of Transfer Units) decreased against a different temperature increase. Figure 3 is a graph of the PHE area variation along a different temperature ΔT as a function of the water flow rate. These are similar to the trends as shown in Figure 2, but the PHE area increased with a water flow rate increase less variation the sediment cistern temperature of Figure 2.

3.2 COP of Heat Pump System

The *COP* of heat pump is then equal to the heat output divided by the work input:

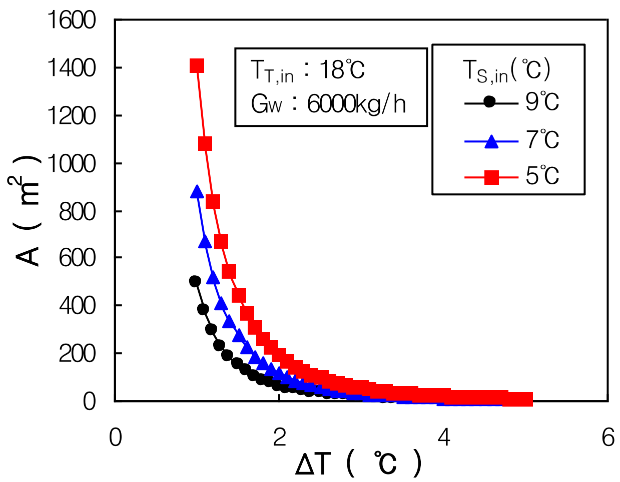

Figure 2. Simulation Results of PHE area at different sediment cistern temperatures, $T_{H,in}$ = 18°C, G_W = 6000 kg/h.

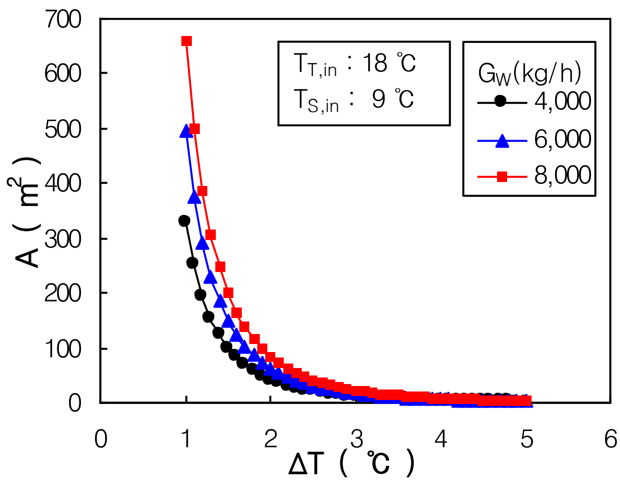

Figure 3. Simulation Results of PHE area at different sediment cistern temperatures, $T_{H,in}$ = 18°C, $T_{L,in}$ = 9°C.

$$COP_{HP} = \frac{Q_c}{AW_{comp}} \frac{Q_e + AW_{comp}}{AW_{comp}} = 1 + \frac{Q_e}{AW_{comp}} \tag{3}$$

It is thus seen that the COP_{HP} of a heat pump is always greater than 1. That is, a heat pump always produces more heat energy than work energy consumed.

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

$$COP_{HS} = \frac{Q_{tc}}{AW_e} \tag{4}$$

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.

The cooling COP_R of heat pump is defined as

$$COP_R = \frac{Q_e}{AW_{comp}} \tag{5}$$

And the COP_{RS} calculation of a cooling is the same as the heating calculation method in heat pump system

$$COP_{RS} = \frac{Q_{tc}}{AW_e} \tag{6}$$

Where, the Q_{te} is the sum of the evaporation heat energy and the heat low 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 model (MT64HM3C).
(2) The pressure variation in heat exchanger has nil.
(3) The superheat and subcooling is 5℃ in the condenser and evaporator.
(4) The expansion valve has a constant enthalpy expansion.
(5) The power of water (seawater) pump is not considered because it is used in the existing facilities of indoor culture system.

Figure 4 shows the flow chart of the COP simulation program along with different temperature of heat recovery system in heat pump system. Figure 5 and 6 are graphs of a simulation result. Figure 5 shows the heating COP of a heat pump system along with different temperature ΔT for various refrigerant evaporation temperatures. As shown in figure, the heating COP increased with a high evaporating temperature and a low ΔT. But, as shown in the Figure 2 and Figure 3, the PHE area increased against the decrease ΔT, also it is causes the heat pump system to be large and needs a higher manufacture cost, and the increases pressure drop.

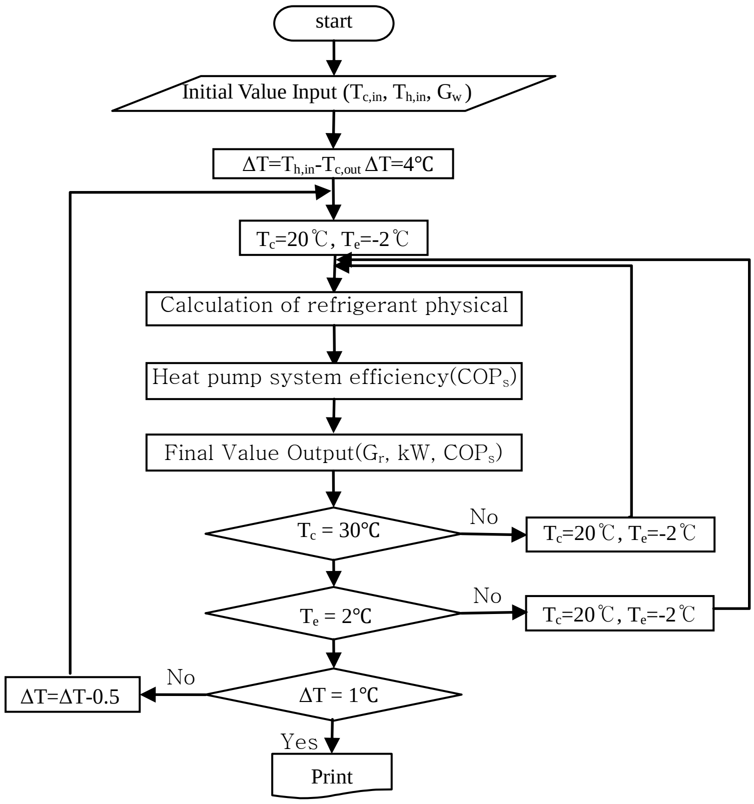

Figure 4. Flow chart of COP simulation in heat pump system.

If the evaporating temperatures increase, the PHE area should be increased because refrigerant temperature and LMTD (Limited Mean Temperature Difference) decrease. Computer simulation for the various condensing temperature tests are presented in Figure 7~8. In Figure 7, for a constant ΔT, evaporating temperature, T_e, the water flow rate, G_w, the heating COP, increased against

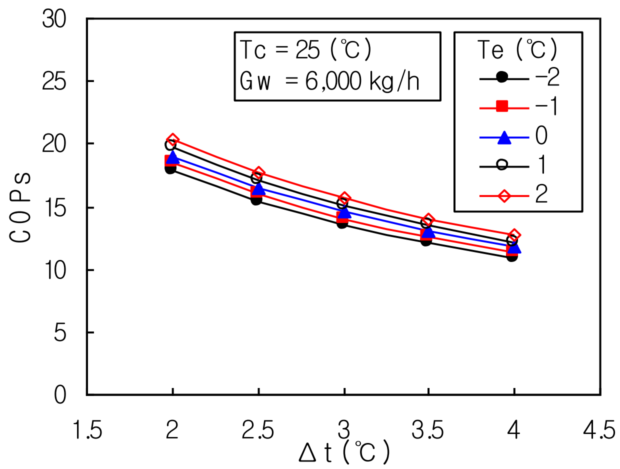

Figure 5. Results of the heating COP simulation at different evaporation temperatures in heat pump system, Tc = 25℃

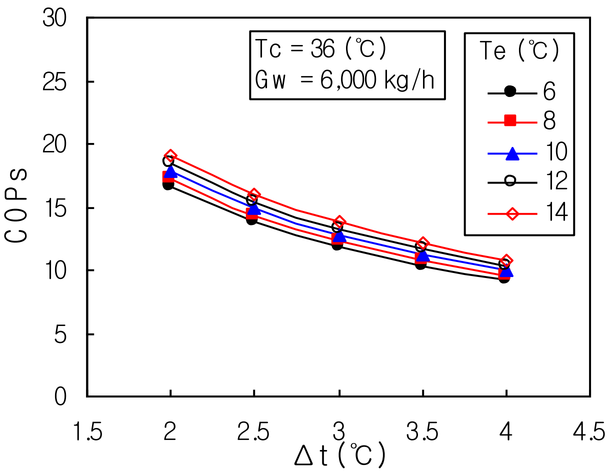

Figure 6. Results of the cooling COP simulation at different evaporation temperatures in heat pump system, Tc = 36℃

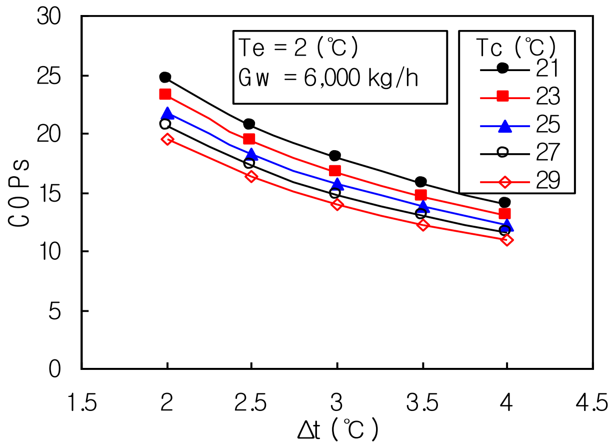

Figure 7. Results of the heating COP simulation at different condensation temperatures in heat pump system, Te = 2℃

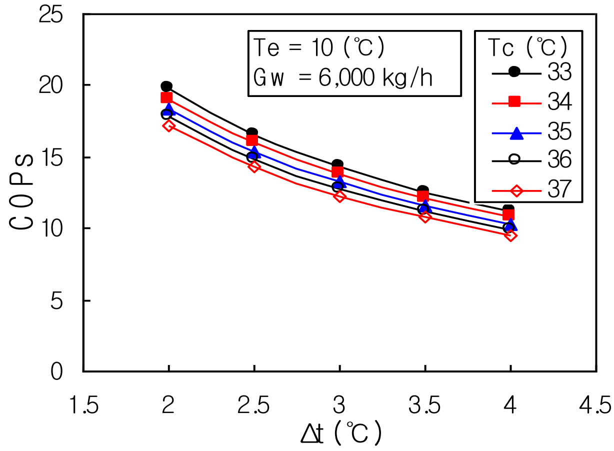

Figure 8. Results of the cooling COP simulation at different condensation temperatures in heat pump system, Te = 10℃

decrease in condensing temperature, T_c. For a constant T_c, the heating COP increased against decrease in ΔT. The same trend can also be seen in Figure 5. As seen in figure, for a condensing temperature, 25℃, and ΔT, 2.4, the COP is 18. From these results, for the purpose of the COP increase and an economical heat pump system manufacture, we can decide a evaporating temperature, 2℃, and a condensing temperature, 25℃.

Figure 8 shows the cooling COP variation as the parameter of condensing temperature under a constant evaporating temperature and water flow rate. These are similar to the trends as shown in Figure 7. But because evaporating and condensing temperatures increased more than those given in Figure 7, the cooling COP is found to decrease than that given in Figure 7.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Heating Operation

Figure 9 shows the COP along water temperature of sediment cistern when the heat pump system did operate heating. As can be seen in the figure, at a constant sediment cistern water temperature, 4℃, the supply water temperature is heated to 18.7℃. And the COP of heat pump system is about 18.

The region A in Figure 9 represents a ON/OFF operation of a compressor for a supply water temperature control. The region B shows a heating operation for a

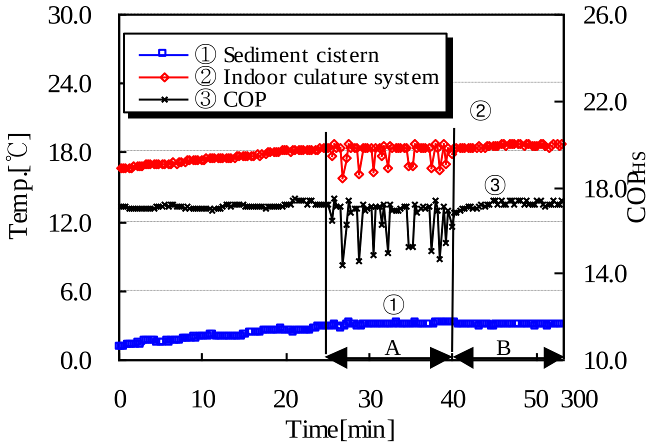

Figure 9 COP_{HS} of heating operation of heat pump system, T_{tank}=18.7℃, G_w=6000kg/h supply water temperature variation at a constant sediment cistern temperature. As shown in the figure, the supply water temperature in the indoor culture system remained constant of 18.7℃ under a constant sediment cistern water temperature, 4℃. In the tests of experimental apparatus, the supply water temperature is 18.7℃ 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 9. These results suggest that the heat pump system has operated at a steady state.

4.2 Cooling Operation

Figure 10 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 9. The supplied water temperature entered into indoor culture system is controlled at a constant, 18℃. In Figure 10, 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 sediment cistern water temperature, 30℃. The COP of heat pump system is from 12.5 to 13 when it was operated in region B and C. These results proved consistent in several tests.

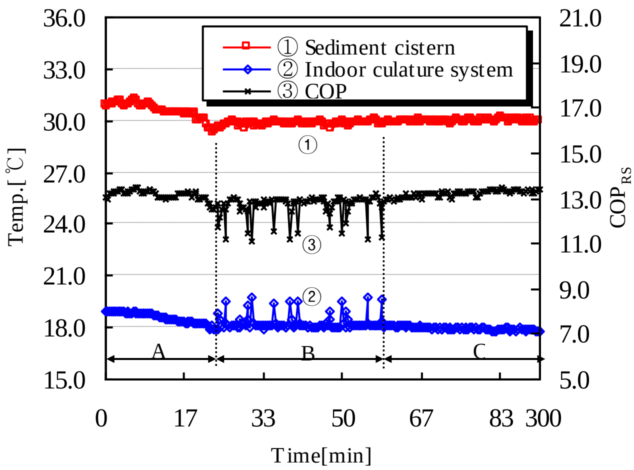

Figure 10. COP_{RS} of cooling operation of heat pump system, T_{tank}=18℃, G_w=6000kg/h.

5. OPERATION OF HEAT PUMP SYSTEM IN LAND BASED AQUACULTURE SYSTEM

5.1 The COP comparison of heat pump and heat pump system

The heat pump system is operated seedling production of spotted sea bass, Lateolabrax maculates of in land based aquaculture system belonging to Hae Woen Fishery Company(in Yosu , Korea). It can always control feed temperature 18 ℃~19℃ and feed volume 40m^3/h (see Photo 2). Figure 11 shows the comparison heat pump COP (see Equation 3) and heat pump system COP (see Equation 4) along with the time when the heat pump system did operate heating. As can be shown in figure, at a natural seawater temperature, 10℃, the supply water temperature is heated to 19℃, and the COP of heat pump and heat pump system is about 6 and 12 respectively. Therefore, the COP of heat pump system is two times higher than that of heat pump.

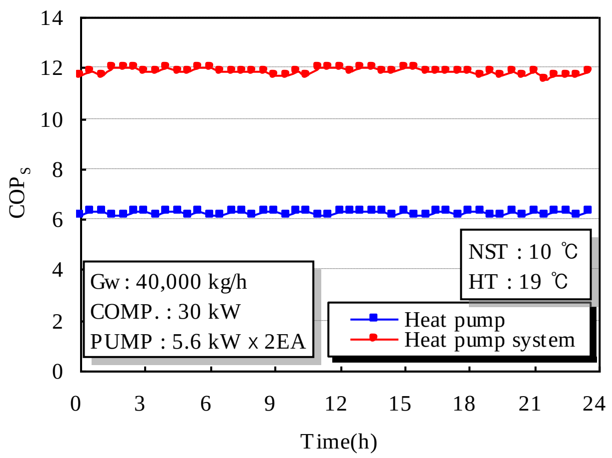

Figure 11. Comparison of heat pump COP and heat pump system COP with operation

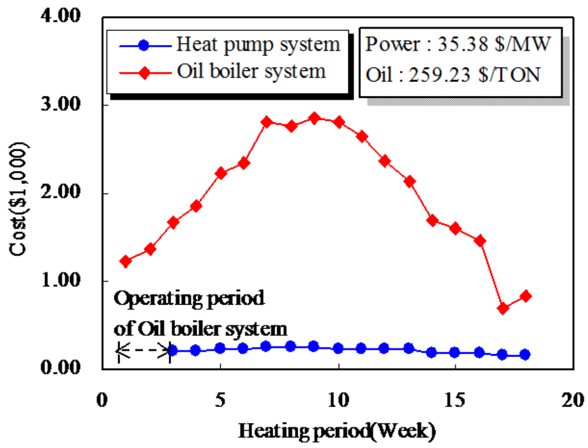

Figure 12. Comparison of production cost with heating period in heat pump system and oil boiler system.

5.2 Comparison of total energy cost

Figure 12 is a graph of making comparison of total energy cost with heating period in a heat pump system and an oil boiler system during 400,000 fish seedling production of spotted sea bass. The part shown in dotted line in Figure 12 did operate an oil boiler system during the fertilization, that is, the heating period does not supply seawater in land based aquaculture system. As show in the figure, the saving energy of the heat pump system is eleven times of the maximums and five times of the average than an oil boiler system.

6. CONCLUSIONS

The results obtained from this study, by the computer simulation and the experiment involving a heat pump system using unused energy and using exhaust seawater heat source in land based aquaculture system, may be summarized as follows.

1. The computer simulation data show a good agreement with the experiment data.
2. The PHE area of a heat recovery system a considerably decreases against the increase in different temperature, ΔT.
3. On the basis of the computer simulation data, the COP, to make a economical heat pump system that can be used in land based aquaculture system is 18, when the difference in temperature of inlet-outlet, ΔT is 2.4℃, and evaporating temperature, 2℃ and condensing temperature, 25℃.
4. The saving energy of the heat pump system is eleven times of the maximums and five times of the average than an oil boiler system, during 400,000 fish seedling production of spotted sea bass.
5. The PHE is used to heat recovery system, evaporator and condenser. And, heat sink and heat source are water, specially, the heat source is used to exhaust water(unused energy).

Therefore, it reveals that the energy efficiency is very higher than a general heat pump in a heating and cooling operation.

ACKNOWLEDGMENTS

The authors wish to acknowledge that this work was supported by the Ministry of Maritime Affairs & Fisheries(KMI Grant No. 1907030-2) and the Ministry of Commerce, Industry and Energy(KEMCO Grant No. 1999-E-TD01-P-08), and Reitechnology Co.

NOMENCLATURE

$T_{H,in}$ Inlet temperature of high heat source
$T_{L,in}$ Inlet temperature of low heat source
$T_{S,in}$ Natural seawater temperature
$T_{T,in}$ Water tank temperature
η Viscosity

REFERENCES

Alfa Laval, 1994, A Technical Reference Manual, Artec.
CADDET, 1996, CADDET Demo. 389 JP93. 512/IX. H03.
Oh J. T., Cho, K. I., Yoon K. Y., Park K. W., Oh H. K., 2000, Development of high efficient heat pump using seawater heat source for indoor culture system, Proceedings of the SAREK 2000 Summer Annual Conference(Ⅰ), pp. 526-531.
Homepage of National Fisheries Research and Development Institute, 2001, http://www.nfrda.re.kr/news/news_main.htm.
Kim I. B., 1993, Growth direction of fishes culture, Korean Aquaculture, Vol. 6, No. 1, pp. 21-54.
Lee T. H., Lee J. S., Park J. J. and Yun J. Y., 2000, Measurement of air side heat transfer coefficient of wire-on-tube type heat exchanger, Korean Journal of Air-Conditioning and Refrigeration Engineering, Vol. 12, No. 2, pp. 161～169.
Mc Quiston F. C. and Parker J. D., 1994, Heating, Ventilating, and Air Conditioning, John Willey & Sons, pp. 570～584.
Michiyasu K., 1992, Development of the high efficiency production system for a flatfish aquaculture, Refrigeration, Vol. 67, No. 780, pp. 1187～1192.
Tadao Tsuji, 1989, Heat pump application for fish spawning and breeding, Refrigeration, Vol. 64, No. 735, pp. 8-15.