13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

An air-water dual-source heat pump system for shrimp ponds

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Abstract

Ponds in farmland have been widely used for shrimp culture in eastern coastal regions of China. To maintain the pond water temperature in winter, an environment-friendly, energy-saving and low-cost heating system is urgently needed. This paper proposed a new air-water dual-source heat pump system (AWDSHPS), which is equipped with two parallel evaporators, one taking heat from air and the other from water in idle ponds. The two heat sources can be used separately or simultaneously, based on ambient conditions and heating demand. A validated load model is built to calculate heating demand accurately. Another simulation model is applied to fulfill system design and performance prediction. Furthermore, operational strategy of full growing season is optimized. The results showed that, compared with the same system in which only air source is used, the AWDSHPS has higher evaporating temperature. That increases from -7.7°C to -3.2°C at ambient temperature of 0°C, resulting in 7% increase in energy efficiency and 27% increase in heating capacity. Therefore, system energy performance becomes more stable, reducing the heat pump size to lower both initial investment and operating costs.

Keywords: heat pump; shrimp pond; dual heat sources; energy saving

1. Introduction

To meet the growing market demand, a vast quantity of whiteleg shrimp, *Litopenaeus vannamei*, is farmed in humid and cold eastern coastal regions of China. In there, thousands of farming ponds have been excavated in farmland. There are three growing seasons every year. Two are in winter, one from November to January and the other from February to April. To maintain the normal growth of shrimp, an acceptable pond water temperature range is 20°C~32°C [1]. This range is much higher than local average ambient temperature of 5° C in winter. Thus, additional heat input is urgently needed.

Thanks to inexpensive investment and low operating costs, the coil-fired boilers were popular among local farmers in the past few years. However, given the serious pollution to the environment, regional authorities banned coil-fired boilers for shrimp culture. Therefore, an alternative heating system is urgent to be designed. It should be environment-friendly, energy-saving and low-cost.

Among the existing heating technologies, heat pump is the first choice. Depending on the heat source, traditional heat pump technologies are divided into various types, among which ground source heat pump (GSHP) and air source heat pump (ASHP) is most popular. The former takes ground, groundwater, or surface water as heat source and sink. It is widely used owing to high thermal-efficiency and relatively low operating costs [2, 3]. However, inappropriate application of GSHP may cause environment risks, including thermal pollution and groundwater contaminations [4]. Other potential risks also have been pointed out by many researchers [5-7]. As for ASHP, which takes air as heat source, is also favorable for its simple structure, low initial cost and high energy efficiency [8]. But in practical applications, energy performance of ASHP is often unsatisfactory [9]. The sensitivity to environmental temperature and heating capacity attenuation caused by frosting are two main problems [10, 11]. Besides, some dual-source heat pump (DSHP) systems have been proposed, mainly for producing domestic hot water, space heating and cooling for buildings [12-14].

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However, the various traditional heat pump system mentioned above is not suitable for local shrimp culture. If GSHP is used, thermal imbalance will be a problem because there is no heat injected back to ground in summer. The shrimp pond needn't be cooled at that time. Groundwater contamination is another concern. Regional authorities have banned groundwater heat pumps. As for ASHP, oversize scale is needed as a result of its unstable poor performance under low temperature conditions, which brings about a higher initial investment.

To solve the above problems, in this paper, we proposed a new air-water dual-source heat pump system (AWDSHPS) according to local practices. It can absorb heat from air and water in idle ponds separately or simultaneously, based on weather condition and heating demand. With water as additional heat source, the system benefits from more stable energy performance, lower investment and operating costs. In order to achieve these, a load model of shrimp pond was built and validated first, as shown in section 2. In section 3, with the help of load model, heating demand was calculated accurately. Then the new AWDSHP system was designed and optimized using GREATLAB. In section 4, the system energy performance was analyzed in different modes under various working conditions. Based on that, in section 5, the operational strategy of full growing season in winter was optimized to minimize power consumption. Lastly, the conclusions were provided in section 6.

2. Load model

In this section, based on the principles of thermodynamics and heat transfer, load model of shrimp pond was built first, and then validated with experimental data. This model will be used to calculate heating demand for system design, as shown in section 3.2. Moreover, in section 5, it will be used to simulate pond water temperature of full growing season.

2.1. Modeling

The typical ponds we studied here are of uniform size, about 40m long, 9m wide and 1m deep. At the top, the pond is covered with one or two layers of transparent plastic film for insulation. The bottom is directly the soil. The real picture is shown in Fig. 1.

Fig. 1. Picture of shrimp pond in farmland

The energy balance of the shrimp pond is made up of multiple heat transfer processes. Heat input is mainly from solar radiation and external equipment, while heat loss from conduction through soil, heat transfer between water and inner cover (convection, radiation, evaporation and condensation), convection with air outside, and sky radiation.

Fig. 2 demonstrates the energy fluxes in the water volume and at the covering surface. Note that the heat capacity of plastic surface is ignored because of its small thickness (about 1×10^{-4}m) and negligible heat mass. Considering the energy balance, we have,

$$Q_{\mathrm{r,w,f}} + Q_{\mathrm{a,w,i}} + Q_{\mathrm{c,w,g}} + Q_{\mathrm{l,w}} - Q_{\mathrm{sr,w}} - H = c_{\mathrm{w}} m_{\mathrm{w}} \frac{dT_{\mathrm{w}}}{d\tau} \tag{1}$$

$$Q_{\mathrm{r,w,f}} + Q_{\mathrm{a,i,f}} + Q_{\mathrm{l,f}} + Q_{\mathrm{sr,f}} - Q_{\mathrm{r,f,o}} - Q_{\mathrm{a,f,o}} = 0 \tag{2}$$

where every term of equation represents a kind of heat transfer. $Q_{\mathrm{r,w,f}}$, for example, is the radiation between water and film. All symbols can be found in Nomenclature.

Each of heat transfer processes, listed in Eq.1. and Eq.2. above, can be defined by a mathematical expression. Since this paper mainly focuses on the performance of the new proposed system, specific methods are not introduced here. Relative information can be easily found in professional books and papers [15, 16].

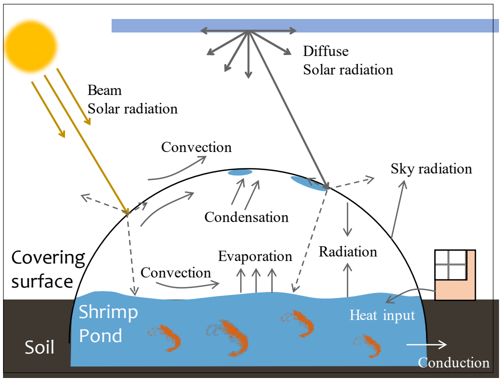


Fig. 2. Energy fluxes in the water volume and at the covering surface

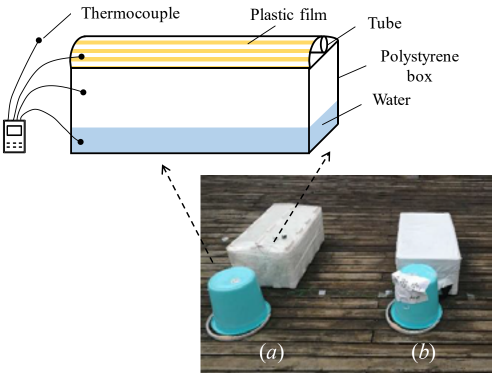


Fig. 3. Shrimp pond model (a-covered with 2 layers transparent PE film, b-covered with 1 layer)

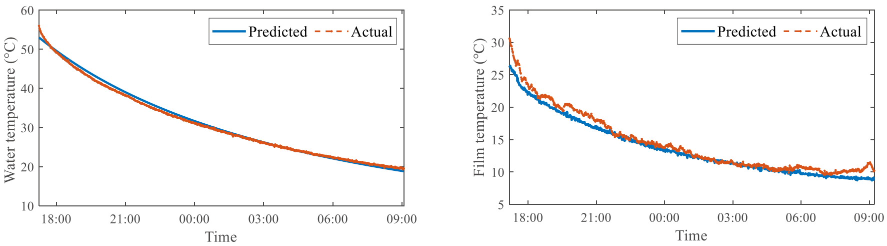


Fig. 4. Comparison of simulation and test data

2.2. Model validation

In order to validate the accuracy and reliability of load model, an experiment was conducted. We first made a simple shrimp pond model, as shown in Fig. 3. The open polystyrene box is used to simulate the pond. Some water is stored inside. Plastic film covers it on top, supported by a horizontal tube. The film material is the same as the actual use. To acquire data for further validation, temperatures of stored water, covering film, internal and external air were measured once a minute. A simple digital thermometer, coupled with K-type thermocouples, was used. Measurement uncertainty of ±1°C is acceptable here. Besides, this experimental model can be employed to compare effect of various insulation schemes, such as covering different layers of film.

By modifying relative geometric parameters and boundary conditions of the original load model, we achieved a suitable model for the polystyrene box. Then above experimental data were used to calibrate the property parameters of film, including thermal conductivity, radiation transmittance and so on. The model after calibration can well predict the water and film temperature, as shown in Fig. 4. Later, these calibrated parameters will be substituted into the original load model.

3. System design

In this section, the working principle for the new AWDSHPS is first introduced, and its simulation model is developed later using GREATLAB [17]. This simulation model can predict system performance, as shown in later sections 4 and 5.

3.1. System description

Fig. 5 is the schematic diagram of the new AWDSHPS. The heat pump unit is composed of two parallel evaporators (fin-tube type for air-cooled one and brazed plate type for water-cooled one), a rotary compressor, a brazed plate condenser, two expansion valves, a reserving valve, etc. Unlike the traditional system, another evaporator is adopted to absorb heat from water in heat storage ponds. These ponds are idle in winter because less shrimp are farmed to reduce risk and achieve higher market price. Having heat taken from the heat storage ponds, the water temperature should not be below 0°C. They keep energy balance by absorbing solar energy at daytime. Heat absorbed, together with the power input, is then transferred to the secondary refrigerant (25% ethylene glycol solution with a freezing point of -10°C) in the condenser. The heated secondary refrigerant flows through the bottom pipes to provide heat, keeping shrimp pond water temperature above 20°C. In addition, the shrimp pond is covered with one film more than the heat storage pond to achieve a balance between energy-saving and investment.

By closing and opening the expansion valves, the unit can take heat from air and water separately or simultaneously. Thus, three heating modes can be fulfilled: (a) air source heating mode, ASHM; (b) water source heating mode, WSHM; (c) air-water source heating mode, AWSHM. With water as additional heat source, the heating system benefits from higher surrounding temperature, therefore, better system performance would be obtained from higher evaporating temperature. Moreover, the heating capacity attenuation caused by defrosting, which is common in air source heat pump system, can be mitigated.

3.2. System modeling

Based on the validated load model in section 2 and meteorological data from the past 5 years, we accurately calculate heating demand of shrimp pond. The result shows, with heat input at a constant level of 16kW, the water temperature of shrimp pond can be maintained in the range of 20°C~31°C during full growing season. Fig. 6 is the simulation result of the typical growing season in 2017. Consequently, the heating capacity of heat pump is designed at 16kW.

As to design conditions, extremely serious ones that possibly encountered in future operation, are usually adopted. Design conditions in this case are listed in Table 1. For heat sink, the water temperature of shrimp pond is set to 20°C. For heat source, both air and water of heat storage pond should be considered. For one thing, in the worst case, water temperature of heat storage pond is the freezing point, 0°C. For another, although the lowest ambient temperature is roughly -10°C in farming region, the water in heat storage pond can be alternative heat source in the cold winter. Given the days of ambient temperature below 0°C is no more than 7% in recent five years, ambient temperature is set to dry bulb temperature of 0°C and web bulb temperature of -1°C.

Table 1. Design conditions of the AWDSHPS

Water temperature of shrimp pond	Ambient temperature (DB/WB)	Water temperature of heat storage pond
20°C	0/-1°C	0°C

According to design requirements mentioned above and engineering practice, we developed the system simulation model in GREATLAB, which is a well-validated vapor-compression system modeling and analysis tool. Since this paper focused on the proposed AWDSHPS and its operating performance during full growing season, modeling methods are not described here. Detailed information can be found in the references [17, 18]. Fig. 7 is the system model of the novel AWDSHPS using GREATLAB, of which the operating principle is in accordance with that shown in Fig. 5.

Based on the design conditions (Table 1), component performance got from manufacturers and size limitations, we carried out the system optimum design with simulations. Specifications are listed in Table 2. On this basis, we can analyze system performance at design and off-design conditions in later section.

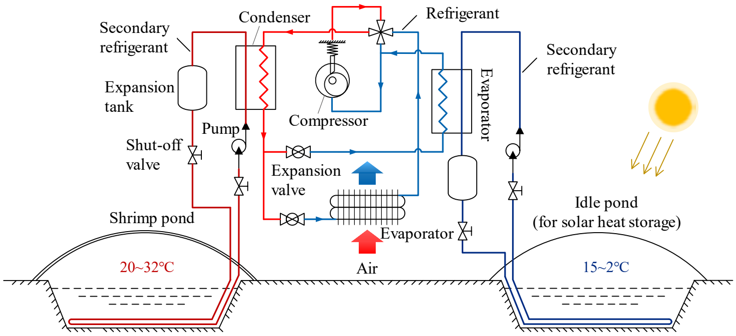


Fig. 5. Schematic diagram of the AWDSHPS

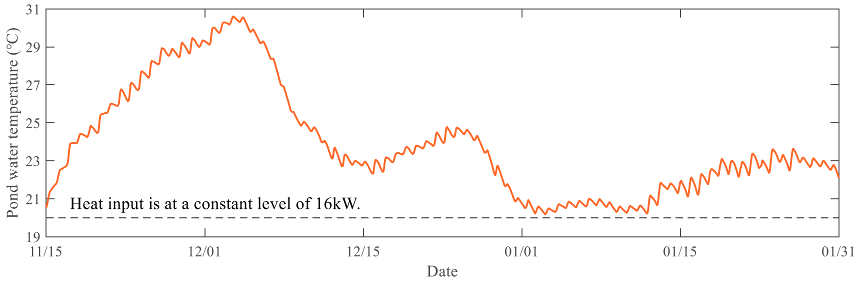


Fig. 6. Pond water temperature of full growing season (2017/11~2018/1)

Table 2. Specifications of the optimum system design

Name	Specification	Simulation model type
Refrigerant	R410A	REFPROP 9.0
Compressor	Rotary	Curve-fitting model
Condenser	Brazed plate	1D incremental model
Air-cooled evaporator	Finned-tube, three rows, 1300mm×914.4mm×50mm	Incremental tube-by-tube model
Water-cooled evaporator	Brazed plate	1D incremental model
Expansion device	EXV	Curve-fitting model
Fan	Axial Fan, variable speed	Curve-fitting model
Pump	Centrifugal pump, variable speed	Curve-fitting model

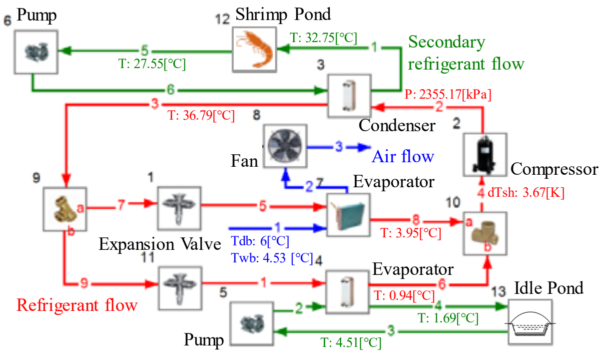


Fig. 7. Screenshot of system model in GREATLAB

4. System performance analysis

In this section, system performance at design and off-design conditions were numerically analyzed. Ambient temperature varies in the range of -5°C to 15°C. For simplicity, water temperature of heat storage pond is always 5°C higher than the ambient. As shown in Fig. 8, with the increment of ambient temperature, system COP and heating capacity increase almost linearly as well. For the three heating modes, system in WSHM has the highest COP with an average of 3.7, followed by 5% decrease in AWSHM and 10% in ASHM. As to the heating capacity, system in all three modes can meet the desired value of 16kW when ambient temperature is above 2°C. Even at serious conditions that ambient temperature drops to -5°C, the WSHM and AWSHM can still satisfy this requirement.

Above comparison of COP and heating capacity in three modes partly demonstrates the advantages of additional heat source of water. That of evaporating temperature in Fig. 9 further reveals this. In comparison to very low ambient temperature at night or cold winter, water temperature of heat storage pond is about 5°C higher owing to its huge heat capacity. Therefore, taking heat from water or air and water together will lead to an increase in evaporating temperature. The system performance benefits from it. For example, the evaporating temperature increases from -7.7°C in ASHM to -3.2°C in AWSHM at ambient temperature of 0°C, resulting in 7% increase in energy efficiency and 27% increase in heating capacity. Furthermore, higher evaporating temperature mitigates the influence of frosting. The air-cooled fin-tube evaporator is easy to frost in winter due to relatively lower evaporating temperature and higher humidity ratio. For conventional air source heat pump system, frosting often occurs at the working condition that ambient temperature is below 7/6°C according to Chinese standard [19]. Under that working condition, the relative evaporating temperature in ASHM of this system is about -3°C. By comparison, the same evaporating temperature (-3°C) in AWSHM of this system appears at ambient temperature of 0°C. That means frosting can only happen on the most severe days with proper heating mode switch, thus the heating capacity attenuation is much smaller than that of air source heat pump system. That's why the new system can be downsized, which lower both initial investment and operating costs.

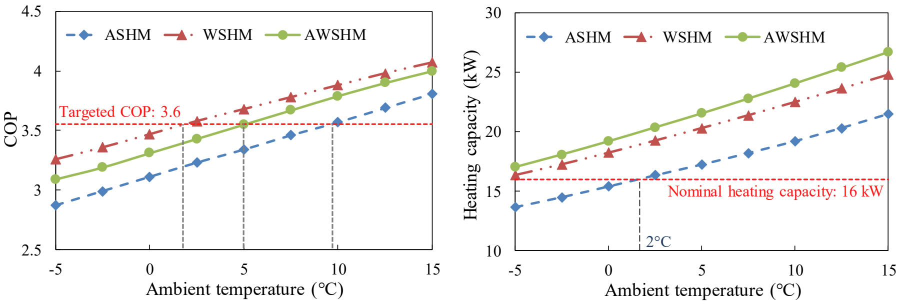


Fig. 8. System performance versus ambient temperature

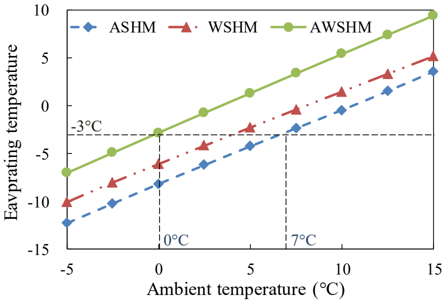


Fig. 9. Evaporating temperature versus ambient temperature

5. Operational strategy of full growing season in winter

The proposed AWDSHPS will be applied to heat shrimp pond for the whole growing season, nearly 3 months. To generate better operational strategy, two aspects should be considered. Firstly, timely heating mode switch. According to comparison and analysis in section 4, at severe conditions, system performance in ASHM is very poor. Although the other two modes perform better, they cannot always enable because the heat absorbed from heat storage pond is limited. Otherwise, excessive heat loss will lead to icing. Thus, WSHM or AWSHM should be adopted at severe conditions while ASHM at better ones. Secondly, proper on-off operation. In the early days when ambient temperature is above 15°C, system efficiency is high but additional heat input is unnecessary. With time going on, the ambient temperature gradually decreases, resulting in growing heating demand. Meanwhile, the energy performance gets worse and worse. However, shrimp pond water temperature can fluctuate in a large range of 20°C~32°C. Thus, a certain amount of heat can be stored. At the beginning of growing season, we can turn on heat pump unit to store oversupply of heat, keeping pond water temperature at a high level. So, shrimp pond requires less heat in cold winter when system is underperforming. More power is saved to compensate for early input.

Based on load model and system model, we optimized the operational strategy. Fig. 10 is the overall logic diagram. With historical meteorological data and strategy mode as input, AWDSHPS model calculates heat input to shrimp pond and heat absorbed from heat storage pond. The two outputs are then given to subsequent load models, from which water temperature of full growing season is finally obtained. According to this procedure, operational strategy is optimized with minimum power consumption as objective and water temperature as constraints.

For ease of application, we introduce a simple optimized operational strategy here. The principles are,

- If water temperature of shrimp pond is below 23°C, turn on machine. Select ASHM, WSHM or AWSHM at ambient temperature of greater than 10°C, 5~10°C, or less than 5°C, respectively.
- If water temperature of shrimp pond exceeds 23°C, turn off machine.

The following command of mode switch is shown in Fig. 11.

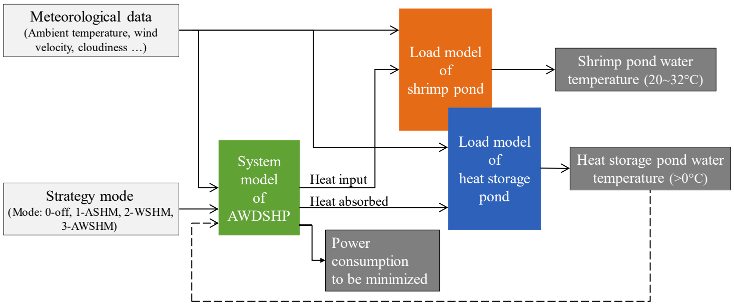


Fig. 10. Block diagram showing the optimization logic

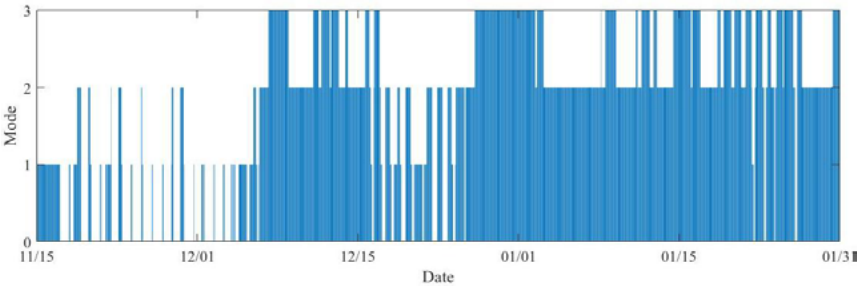
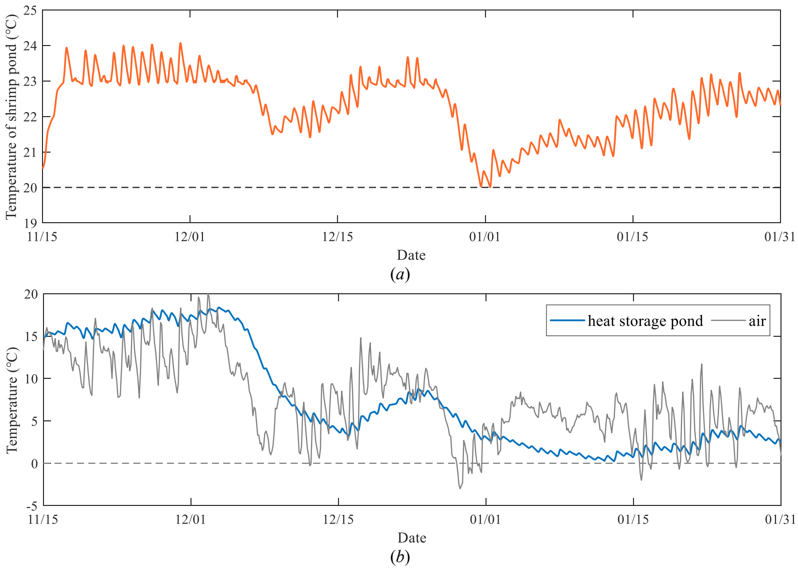


Fig. 11. Mode switch during full growing season (0-off, 1-ASHM, 2-WSHM, 3-AWSHM)



By substituting above strategy into the model, the results obtained are shown in Fig. 12. Water temperature of shrimp pond fluctuated from 20°C to 24°C, which is suitable for shrimp culture. That of heat storage pond always keeps above 0°C, which ensures the heat absorption in WSHM and AWSHM. Besides, the fluctuation of shrimp pond water temperature is less than that in Fig. 6, resulting in lower power consumption.

Consequently, we reduced the total power consumption to 8372kWh. Multiplied by local average electricity price of 0.55CNY per kWh, total operating costs were 4600CNY. The initial investment of our new AWDSHPS is approximately 16000CNY, of which heat storage pond is not included. Since all heat storage ponds have been excavated before. They are used for shrimp farming in summer but idle in winter. By comparison, coil-fired boiler with shrimp pond covered 1-layer film was common in the past. According to calculation by load model and on-site investigation, total coal consumption was about 11360kg and corresponding costs were 10220CNY. As a result, approximately 55% of energy costs can be saved with our new AWDSHPS.

6. Conclusions

In this study, a new AWDSHPS was proposed for shrimp culture. The load model of shrimp pond was built, experimentally validated, and then used for heating demand calculation. Furthermore, system design and modelling were fulfilled using GREATLAB and system energy performance was analyzed. At last, operational strategy of full growing season was optimized and a simple but effective one was adopted for practical use. All in all, main conclusions can be drawn as follows.

The proposed AWDSHPS is proven to have more stable energy performance, lower investment and operating costs than traditional heat pump systems. It is more suitable to replace original coil-fired boilers. This type of system can also be considered for other aquaculture applications, especially where two suitable heat sources are available.

With water in idle pond as additional heat source, the AWDSHPS has shorter defrost cycle and better energy performance. At ambient temperature of 0°C, for example, the evaporating temperature increases from -7.7°C to -3.2°C, resulting in 7% increase in energy efficiency and 27% increase in heating capacity.

For multiple heat source systems, the characteristics of different heat sources should be deeply understood. In this case, heat storage capacity of water source and performance attenuation of air source are comprehensively considered. With optimized operational strategy in full growing season, the total costs reduced by 55% relative to that of boiler heating. This value could be bigger by adopting better strategy, which is expected to be further discovered.

Nomenclature

AWDSHPS	air-water dual-source heat pump system
ASHM	air source heating mode
ASHP	air source heat pump
AWSHM	air water source heating mode
c	specific heat (kJ kg-1 K-1)
COP	coefficient of performance
GSHP	ground source heat pump
H	heat input (kW)
m	mass (kg)
Q	heat transfer (kW)
T	temperature (°C)
WSHM	water source heating mode

Greeks	
τ	time (s)
Subscripts	
a	convection
c	conduction
f	film
g	ground
i	inner
l	latent
o	outside
r	radiation
sr	solar radiation
w	water

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