Performance evaluation of a ground source heat pump system based on ANN and ANFIS models

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Abstract: The aim of this work is to calculate the heat pump coefficient of performance (COP) and the system COP of a ground source heat pump (GSHP) system based on an artificial neural network (ANN) model and (adaptive neuro-fuzzy inference system (ANFIS) model. In order to get the training and test data, a GSHP system of an office building in China was monitored in the summer of 2013, and the system uses a GSHP unit and a water chiller unit as the cooling source. To calculate the heat pump COP, the water temperature entering/exiting the condenser and the water temperature entering/exiting the evaporator of the GSHP unit were used as input layer of ANN and ANFIS models. While six parameters including the water temperature entering/exiting the condensers of two units and the water temperature entering/exiting the user side were used as the input layer. Some statistical methods were adopted to evaluate the accuracy of the calculation models. The results show that the models provide high accuracy and reliability for calculating performance indexes of GSHP system with fewer parameters.

Keywords: Artificial neural network   ANFIS   Ground source heat pump   COP

1. Introduction

GSHP uses the low grade energy stored in the shallow level of the earth to heat or cool the building. It has been applied to real projects widely these years thanks to its high energy efficiency, energy-saving, environment-friendly and the ability to use the low level energy [1]. Calculation of the real-time evaluation indexes is important for system evaluation, system optimization and fault diagnosis of the GSHP system. But for most of the GSHP projects which have been put in operation, the monitoring system has't been installed. It is hard to get all the parameters needed when we calculate the evaluate indexes such as coefficient of performance（COP） because of the lack of the measuring device in the system or the diagnosis of the sensors or other reasons.

Some authors have tried calculating the evaluation indexes of some system or equipment with low cost parameters while ANN and ANFIS are used frequently in the researches. Artificial neural network is an information processing idea that is inspired by the way of biological nervous systems, such as the brain, processing information[2]. It can tackle complex problems in actual situations with the advantages of of learning ability, memory simulating and nonlinear approximation. ANFIS is created combining neural networks and fuzzy models, it has the advantages of the fuzzy processing, self learning and the nonlinear approximation.

H.M. Ertunc calculated the winter COP of a horizontal GSHP based on ANN model using the

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air temperature leaving/entering the condenser, the water temperature leaving/entering the evaporator and the ground temperature as the input layer parameters[3]. Haslinda [4] built an ANN model for a standard air-conditioning system of a passenger car to calculate the cooling

Nomenclature

ρ	water density (kg/m^3)
c	specific heat capacity of water ($kJ/(kg \cdot K)$)
m_g	water mass flow on the evaporator side of the GSHP unit (m^3/h)
m_{ls}	water mass flow on the load side of air conditioning system (m^3/h)
$T_{gevap,i}$	evaporator inlet water temperature of the GSHP unit (^oC)
$T_{gevap,o}$	evaporator out water temperature of the GSHP unit (^oC)
$T_{gcond,i}$	condenser inlet water temperature of the GSHP unit (^oC)
$T_{gcond,o}$	condenser outlet water temperature of the GSHP unit (^oC)
$T_{cevap,i}$	evaporator inlet water temperature of the chilled water unit (^oC)
$T_{cevap,o}$	evaporator out water temperature of the chilled water unit (^oC)
$T_{ccond,i}$	condenser inlet water temperature of the chilled water unit (^oC)
$T_{ccond,o}$	condenser outlet water temperature of the chilled water unit (^oC)
W_g	power consumed by the GSHP unit (W)
W_c	power consumed by the chilled water unit (W)
$W_{l,p}$	power consumed by the water pump on load side (W)
$W_{gss,p}$	power consumed by the water pump on ground source side (W)

$W_{cts,p}$ power consumed by the water pump on cooling tower side (W)

$T_{l,i}$ inlet water temperature on the load side (W)

$T_{l,o}$ outlet water temperature on the load side (W)

capacity, compressor power input and the coefficient of performance (COP) of the automotive air-conditioning (AAC) system. The input layer parameters of ANN model are the compressor speed, air temperature at evaporator inlet, air temperature at condenser inletand air velocity at evaporator inlet. Arzu S [5] calculated the COP of a single stage vapor compression refrigeration system with inner heat exchanger based on ANN model and ANFIS model using the evaporator temperature, condenser temperature, sub cooling temperature, superheating temperature and cooling capacity. ZHAO Jing [6,7] made a post evaluation before the renovation of a central air-conditioning system of a large-scale public building and a prediction evaluation after the retrofit scheme is determined. The prediction evaluation model was built based on Back-Propagation Artificial Neural Network by the use of MATLAB Neural Network Toolbox.

ANN and ANFIS are applied in many fields. In the HVAC area, they have been used in load prediction, energy management and controlling system, fault diagnosis, system identification and other aspects [8].The aim of this thesis is to calculate the heat pump COP and the system COP of the GSHP based on ANN and ANFIS model through a low number set of data. For getting the training and test data, a GSHP system of an office building in China was tested in the summer of 2013.

2. System description and monitoring data analysis

2.1 System description

In this study, a GSHP system of an office building was monitored for a cooling season in summer of 2013. The office building was located in Shaoxing China. The cooling load and heating load of the office building (air conditioning area: 7320 m^2) were 618 kW and 403kW at design conditions, respectively. The schematic diagram of the air conditioning system for cooling mode is illustrated in Fig1. Two heat pumps were were selected as the cooling source according to the heating and cooling load, one is a total heat recovery GSHP unit (cooling capacity: 315kW; heating capacity: 343.7kW; COP: 5.78 and 4.48 in cooling season and heating season respectively) and the other on is a water chiller unit (cooling capacity: 307kW; heating capacity: 326kW; COP: 5.45 and 4.32 in cooling season and heating season respectively). Two units can run simultaneously or run by itself depending on the requirement. The total recovery GCHP unit supplies domestic hot water. The total heat recovery GSHP unit rejected heat to the ground by means of buried pipes while the water chiller unit dissipate heat through cooling tower.

Moreover, the air conditioning system includes three water pumps on source side, a water pump on cooling tower side, three water pimps on user side, two hot water pumps and a heat insulating water tank. 140 boreholes were designed. The drilling diameter, borehole spacing and the borehole depth were 150mm, 4m and 50m respectively. Single-U, double-U and three-U heat exchangers were selected and the outer diameter of pipe is 32mm.

The water return from air conditioning terminal releases heat to the refrigerating fluid in the evaporator of the GSHP unit or the water chiller unit and then goes back to the air conditioning terminal to cooling the house. The circulating water from the buried pipes extract the heat from the refrigerating fluid in the condenser of the GSHP unit and reject the heat to ground. The cooling water from the cooling tower absorb heat from the refrigerating fluid in the condenser of the water chilled unit and is cooled by cooling tower.

Some measuring devices were installed in the system to get running data. The water temperatures entering and existing condenser , evaporator and the air conditioning terminal were measured by temperature sensors. The flow rate of water entering and existing condenser , evaporator and the air conditioning terminal were measured by flow sensors. Both the temperature sensors and flow sensors were installed with wireless transmitting module which can transmit the data collected. Wireless smart electric meters were used to measure the power consumed by cooling tower, GSHP unit, water chilled unit and water pumps, the data also transmitted by wareless transmitting module. The wireless signal acquisition module collect data from wireless transmitting module and supply them to the local sever through internet or local area network. Then we can get the data from the monitoring platform of local sever.

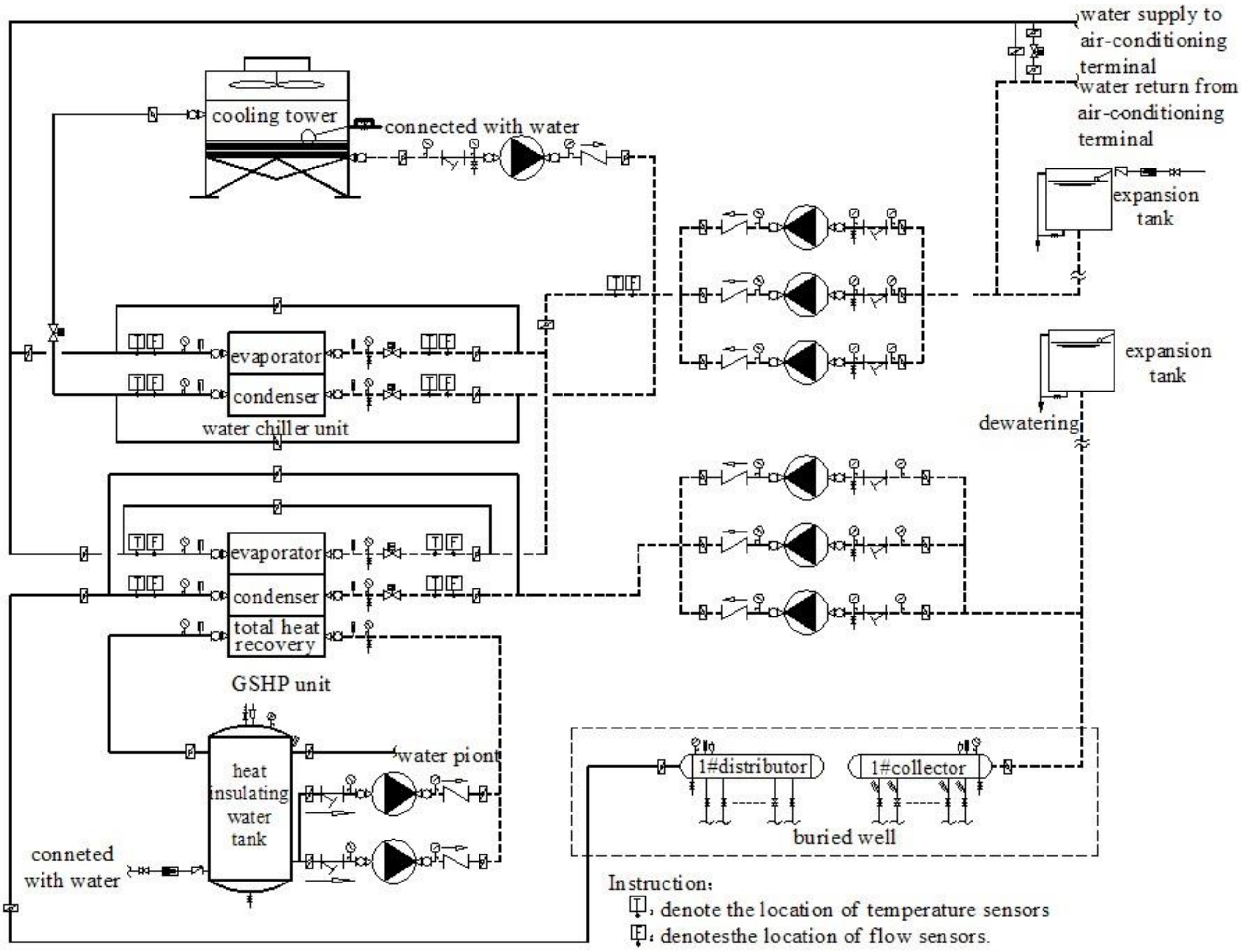

Fig.1. Schematic diagram of the air conditioning system for cooling mode

2.2 Monitoring data analysis

The GSHP in Shaoxing was monitored every 15 minutes during normal office hours from June 1st to June 27st, 2013. We had obtained 729 data patterns total in these 27 days. The COP of GSHP unit was obtained by Eq.(1) and the COP_s of the GSHP air conditioning system was calculated by Eq.(2) to verify the results from ANN and ANFIS approach.

$$COP = \frac{Q_{g,\ cl}}{W_g} \tag{1}$$

Where the cooling capacity of the GSHP unit $Q_{g,cl}$ is defined as Eq.(2)

$$Q_{g,\ cl} = \rho c m_g (T_{gevap,i} - T_{gevap,o}) \tag{2}$$

$$COP_s = \frac{Q_s}{W_g + W_c + \sum W_{i,p}} \tag{3}$$

Where Q_s is the cooling capacity of the airconditioning system defined as Eq.(4) and $\sum W_{i,p}$ is the total power consumed by all the water pump defined as Eq.(5)

$$Q_s = \rho c m_{ls} (T_{ls,o} - T_{ls,i}) \tag{4}$$

$$\sum W_{i,p} = W_{ls,p} + W_{gss,p} + W_{cts,p} \tag{5}$$

During the monitoring period, the GSHP unit was running all the time but the chilled water unit was intermittent running. The measured running data values of the GSHP air conditioning system are given in Figs. 2-4. Fig.2 shows the variation of $T_{gevap,i}$, $T_{gevap,o}$, $T_{gcond,i}$ and $T_{gcond,o}$ of the GSHP unit with its COP. We can see that $T_{gevap,i}$, $T_{gevap,o}$, $T_{gcond,i}$ and $T_{gcond,o}$ variate in 9.6~17.1^{o}C, 8.0~14.3^{o}C, 28.9~40.7^{o}C and 25.7~37.2^{o}C. COP of the GSHP unit is between 2.5~5.4. The mean difference of $T_{gevap,i}$ and $T_{gevap,o}$ is 2.33^{o}C , for $T_{gcond,i}$ and $T_{gcond,o}$, it is 2.72^{o}C. COP of the GSHP unit shows an opposite direction of changing trend approximately with the changing trend of $T_{gcond,i}$ and $T_{gcond,o}$. It indicates that in a certain range, the lower of the output water temperature of ground source well, the higher of GSHP unit COP which means the better operation performance of the GSHP unit. Fig. 3 hows the variation of $T_{cevap,i}$, $T_{cevap,o}$, $T_{ccond,i}$, $T_{ccond,o}$ and W_c of the chilled water unit. The power consumed by the chilled water unit means that the running state of this unit is off. Fig.4 shows the variation of $T_{l,i}$, $T_{l,o}$ and the system COP_s. We can see that $T_{l,i}$ and $T_{l,o}$ variate in 8.2~14.3°C, 9.5~17.0°C. The system COP_s is between 1.3~4.0. The mean difference of $T_{l,i}$ and $T_{l,o}$ is 2.1°C.

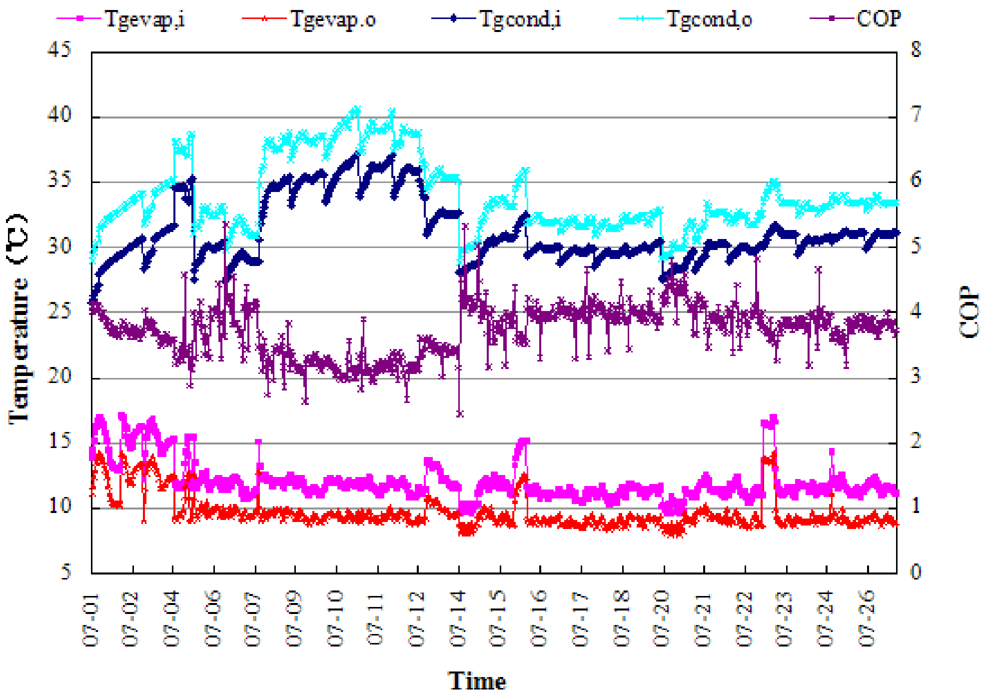

Fig.2. The variation of water temperature, COP of GSHP unit

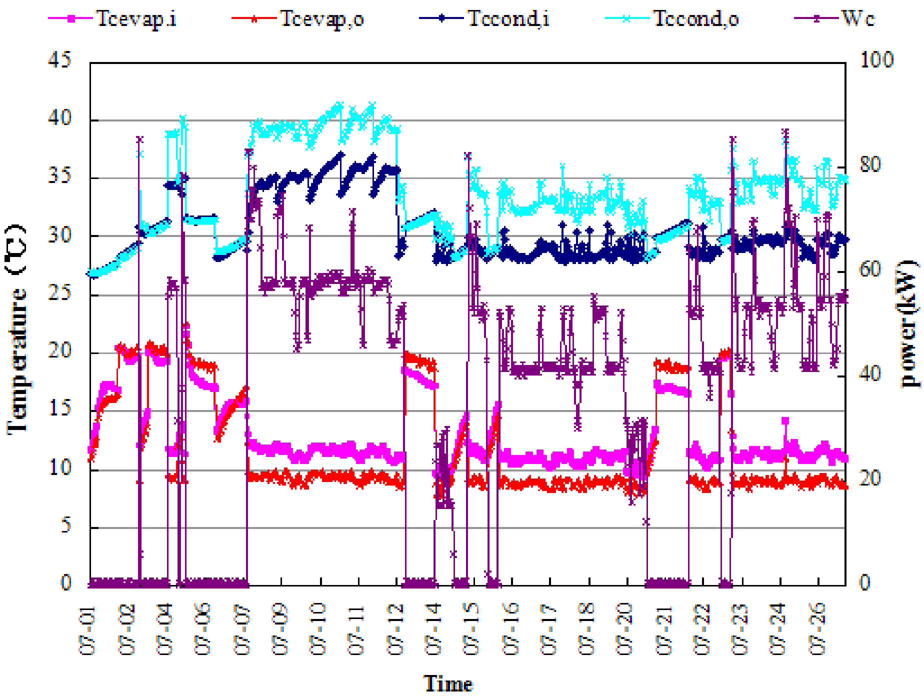

Fig.3. The variation of water temperature, power consumption of chilled water unit

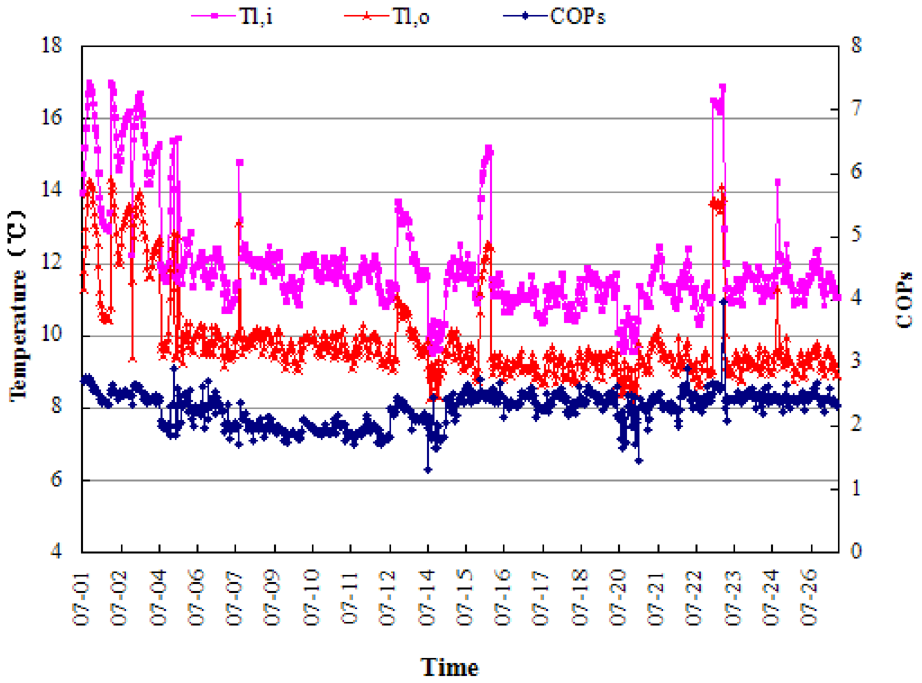

Fig.4. The variation of water temperature on the load side and the system COP_s

3. Artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS)

3.1 Artificial neural network (ANN)

ANN is interconnected by lots of joins (or named as neurons) which are nonlinear information processing units with multiple inputs and single output. Every point stands for an activation function which can be defined in many ways such as threshold function, sigmoid function and hyperbolic tangent function [9].

ANN operates much as a “black box” model, requiring no detailed information about the system. On the other hand, they learn the relationship between the input and the output based on the training data [10]. There are numerous algorithms available for training neural network models. The most popular one is the back propagation algorithm, which has different variants. Standard back propagation is a gradient descent algorithm.

A typical BP artificial neural network structure is illustrated by Fig.4. It includes three layers: input layer, hidden layer and the output layer. The input layer receives the input signals by weights, and transfers the processed signal to the hidden layer; the hidden layer is inner processing layer which converses the information, it can be classified as single hidden layer and multiple hidden layer, the last hidden layer exports information to the output layer. After a further processing, a forward propagation learning process is completed. The output layer exports the information processing results, but if the actual output is not agree with the expected result, ANN will steps into the mean square error (MSE) back propagation stage. The cycle of information forward propagation and error back propagation is a adjustment process of each layer’ weights, it is also the learning process of ANN. The process won’t stop until the MSE decreases to an acceptable level or the training epochs are reached.

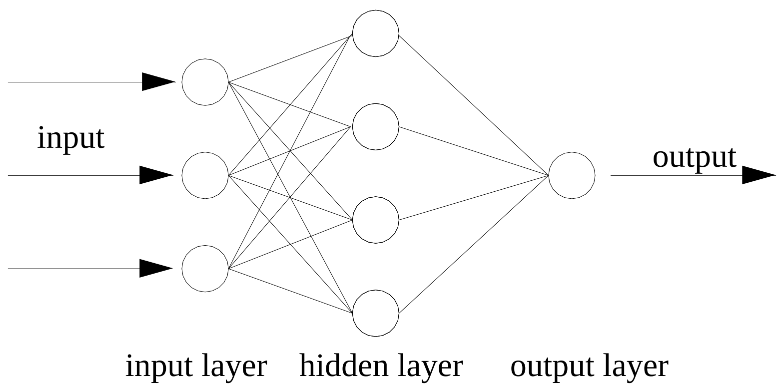

Fig.5. A typical BP artificial neural network structure

3.2 Adaptive neuro-fuzzy inference system (ANFIS)

The Adaptive neuro-fuzzy inference system (ANFIS) was came up with by Jang Roger, its function is similar with the first order Sugeno fuzzy inference system. ANFIS combined the self-learning ability of neural network and the advantage of fuzzy inference together, being able to approximating any linear or nonlinear system [33]. ANFIS is based on data sets rather than experience or intuitions, the membership function and the fuzzy rule are obtained by learning with the data sets. This is important for the complex system or the system whose properties are not realized fully by people [34].

The typical structure of ANFIS is illustrated by Fig.5 [35], the membership functions of one layer are same (set the output of the layer of i as $O_{l,i}$), x, y is the input of the system and f is the output.

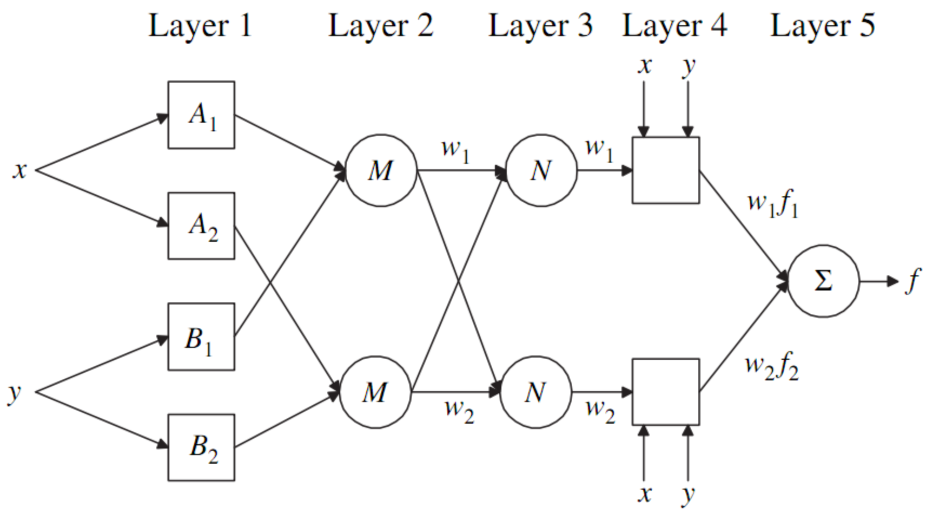

Fig.6. The structure of a typical ANFIS model

The first layer: the input signals are fuzzified by the nodes in this layer.

$$O_{1,i} = \mu_{Ai}(x), i = 1,2 \; O_{1,i} = \mu_{Bj-2}(y), i = 3,4 \quad (5)$$

Where A/B are fuzzy sets, $O_{l,i}$ is the membership function of the fuzzy sets, the default is bell-shape.

The second layer: the nodes in this layer is to calculate the fitness of each rules,

$$O_{2,i} = \omega = \mu_{Ai}(x)\mu_{Bi}(y), i = 1,2 \quad (6)$$

The third layer: normalize the fitness of each rules.

$$O_{3,i} = \overline{\omega} = \omega/(\omega_1 + \omega_2), i = 1,2 \quad (7)$$

The fourth layer: calculate the output of each rules

$$O_{4,i} = \overline{\omega} f_i = \overline{\omega}(p_i x + q_i y + r_i), i = 1,2 \quad (8)$$

The fifth layer: there is only one node in this layer which can calculate the final output of the system.

$$O_{5,i} = y = \sum_i \overline{\omega} f_i = \frac{\sum_i \overline{\omega} f_i}{\sum_i \omega}, i = 1,2 \quad (9)$$

A hybrid algorithm which combined the black propagation and the test squares method together is adopted to train ANFIS, it can help the system to model the data sets.

4. ANN and ANFIS models for case study

The ANN and ANFIS models for calculating the GSHP unit COP is illustrated in Fig.6. The ANN and ANFIS have the same parameters $T_{gevap,i}$, $T_{gevap,o}$, $T_{gcond,i}$ and $T_{gcond,o}$ in the put layer and the same parameters COP in the output layer. The ANN and ANFIS models for calculating the system COP_s is illustrated in Fig.7. The ANN and ANFIS have the same parameters $T_{gcond,i}$, $T_{gcond,o}$, $T_{ccond,i}$ and $T_{ccond,o}$ in the put layer and the same parameters COP_s in the output layer. $T_{ccond,i}$ and $T_{ccond,o}$ values are set as 0 when the running state of the chilled water unit is off which means these values make no difference to COP_s.

Both for the models for calculating the GSHP unit COP and the system COP, 424 data patterns from July 1st to July 16st selected from the total 729 data patterns were used for training the ANN model, the total data patterns included 1030 patterns from July 1st to July 28st were used for testing the trained ANN model.

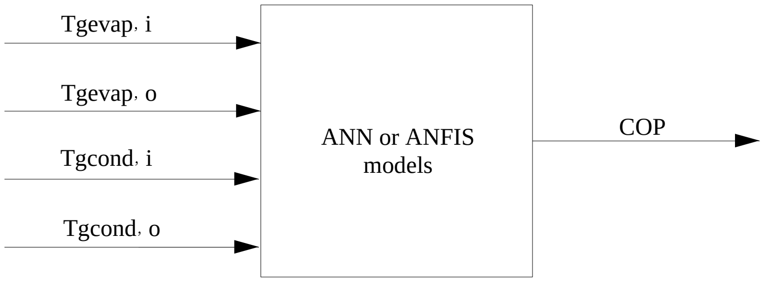

Fig.7. ANN and ANFIS models for calculating GSHP unit COP

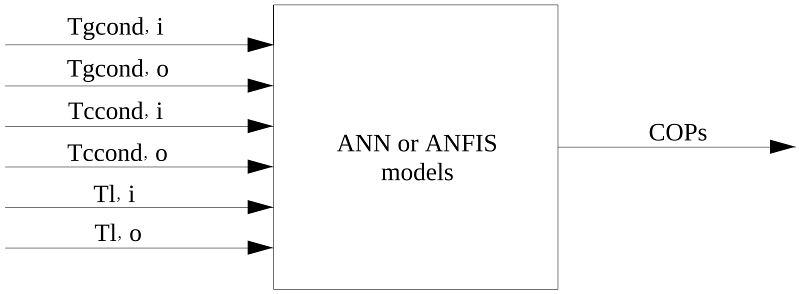

Fig.8. ANN and ANFIS models for calculating system COP_s

$$m = \sqrt{n+l} + \alpha \tag{9}$$

$$m = \sqrt{nl} \tag{10}$$

$$m = \frac{1}{2}(n+l) + \sqrt{t} \tag{11}$$

Where m is the number of neurons on hidden layer; n is the number of neurons on input layer; l is the number of neurons on output layer; α is a constant value between 0~10 and t is the number of training data patterns. For ANFIS model, three membership functions named Gaussmf are chosen, the training epochs is 600, and the MSE is 0, other parameters are default value. ANN and ANFIS models were programmed in the MATLAB 7.0 environment.

The main training program of ANN model is as following:

```
[Input,mintraininput,maxtraininput] = premnmx(traininput);    % Normalize the input data
net=newff(minmax(Input),[14,1],{'tansig','purelin'},'trainlm');    % Build an ANN
net.trainParam.epochs=5000;    % Set the training epochs as 5000
```

net.trainParam.goal=1E-06;   % The training goal is 1E-07

[net,tr]=train(net,Input,t);   % Train the net

save net   % Save the net

The main testing program of ANN model is as following:

[Testinput] = tramnmx(testinput,mintraininput,maxtraininput);   % Normalize the input data

load net   % Load the trained net

output=sim(net,Testinput);   % Get the output by the net

The main program of ANFIS model is as following:

fismat=genfis1(trndata,[numMFS1numMFS2numMFS3],char(mfType1,mfType2,mfType3),'constant'); % generate the initial ANFIS using mesh cutting method

[Fis, error, stepsize, chkFis, chkEr]=anfis(trnData,fisMat,trnOpt,disOpt,chkData);   % train the model based on training data

anfis_cop=evalfis(chkdata1,chkFis);   % input the testing data to the trained ANFIS and get the output we need

Some statistical methods, absolute error ε, relative error δ, root-mean squared (RMS), absolute fraction of variance (R^2) were adopted to validate the model, they were obtained by Eqs(12)-(15) respectively. The smaller of absolute error ε,root-mean squared (RMS)and relative error δ, the more accurate of the ANN model. Absolute fraction of variance (R^2) was in the range of (0~1), value of 1 denotes perfect model.

$$\varepsilon = x_{calculate,m} - x_{actual,m} \tag{12}$$

$$\delta = \frac{x_{calculate,m} - x_{actual,m}}{x_{actual,m}} \tag{13}$$

$$RMS = \sqrt{\frac{\sum_{m=1}^{n}(x_{calculate,m} - x_{actual,m})^2}{n}} \tag{14}$$

$$R^2 = 1 - \frac{\sum_{m=1}^{n}(x_{calculate,m} - x_{actual,m})^2}{\sum_{m=1}^{n}(x_{actual,m})^2} \tag{15}$$

Where $x_{calculate,m}$ is the value calculated byANN models; $x_{actual,m}$ is the actual value; n is the number of data patterns.

5. **Results and discussions**

Suitable ANN and ANFIS models were developed by trail and error. Figs. 8-9 are the plots of GSHP COP calculated by the ANN and ANFIS model vs. the corresponding values obtained from experiments respectively. Figs. 10-11 are the plots of system COP_s calculated by the ANN and ANFIS model vs. the corresponding values obtained from experiments respectively. And for the system COP_s the statistical values are showed in Table 2.

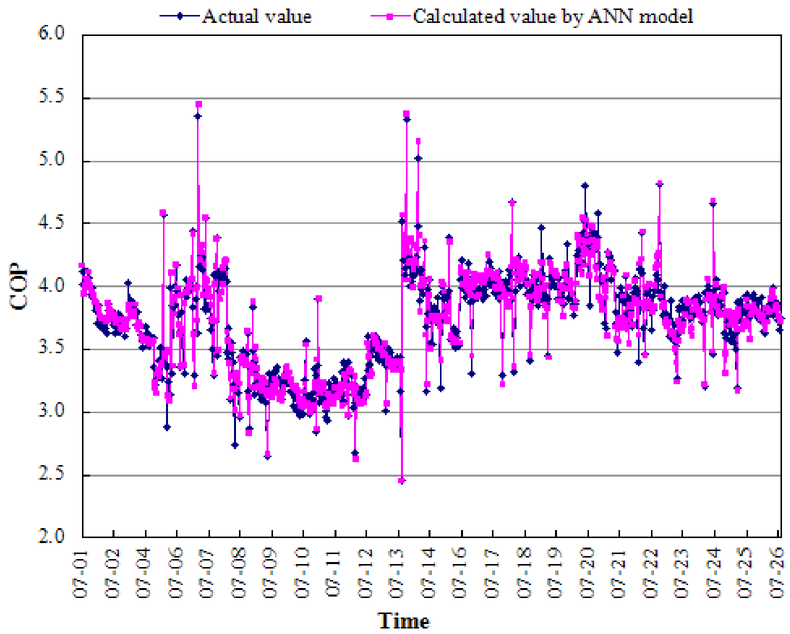

Fig.9. Comparison of actual and ANN calculated values of the GSHP COP

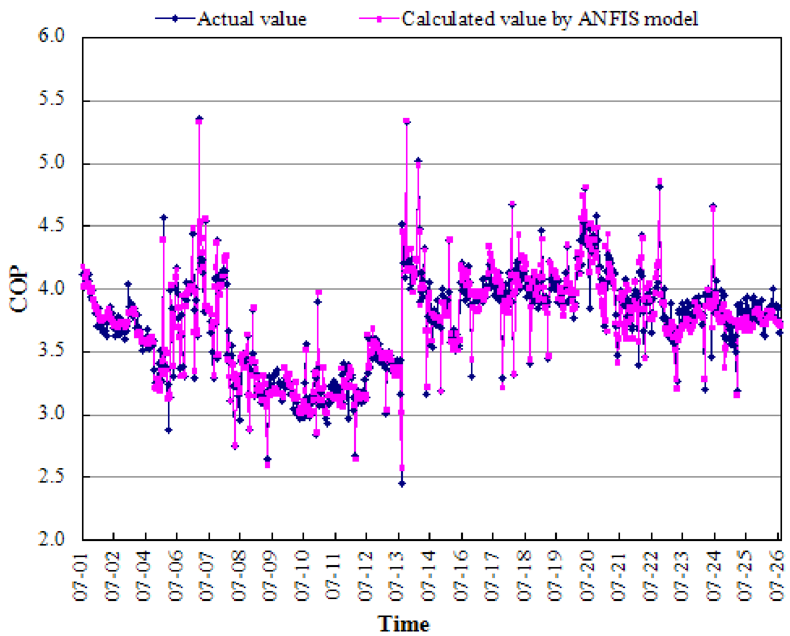

Fig.10. Comparison of actual and ANFIS calculated values of the GSHP COP

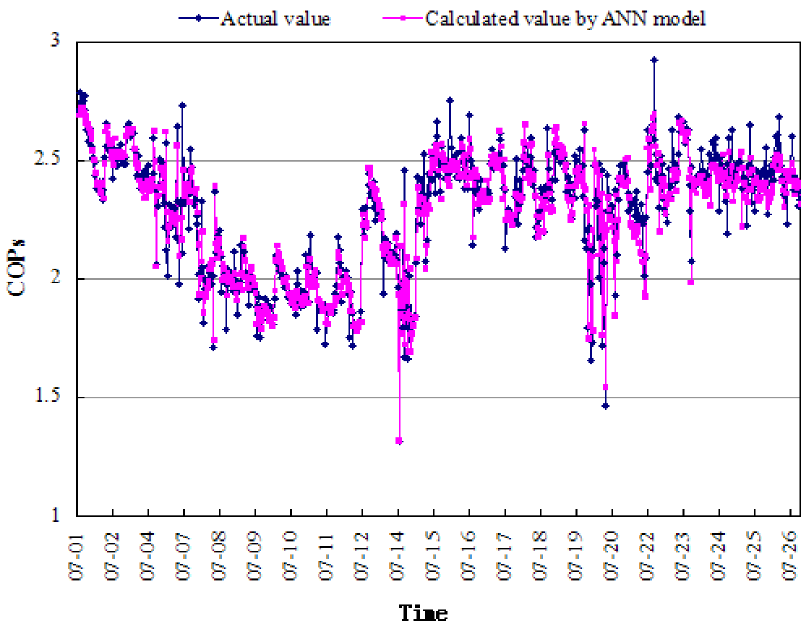

Fig.11. Comparison of actual and ANN calculated values of the system COP_s

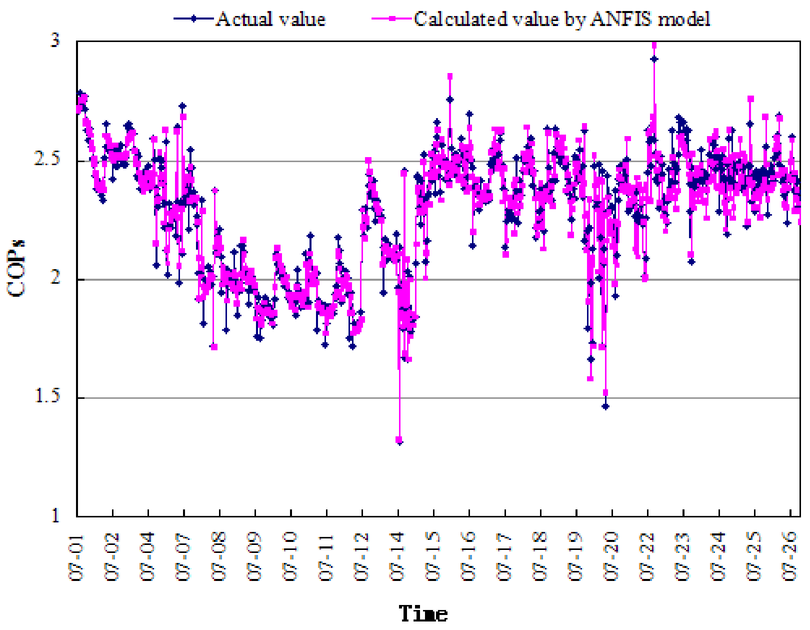

Fig.11. Comparison of actual and ANFIS calculated values of the system COP_s

Table 1

Comparison of ANN and ANFIS statistical values for calculated GSHP COP

	RMS	R^2	ε	δ
ANN	0.09943	0.99929	-0.29~0.26	-9%~7%
ANFIS	0.09601	0.99934	-0.28~0.32	-10%~9%

Table 1

Comparison of ANN and ANFIS statistical values for calculated system COP_s

	RMS	R2	ε	δ
ANN	0.06475	0.99920	-0.21~0.27	-9.8%~10%
ANFIS	0.05524	0.99942	-0.20~0.18	-9%~7.8%

Figs. 8-11 show that calculated values by ANN and ANFIS models agree well with the actual values. Once been trained, the models can calculate the GSHP COP and the system COP_s in high precision just based on fewer parameters. What's more, the models have high calculation accuracy not only for the trained data patterns but also for the untrained data patterns which shows they have an excellent capability of generalization.

For calculating the GSHP unit COP, the properties of the ANN and ANFIS models which are evaluated by statistical values are tabulated in Table 1. The relative error δ of ANN models are all within 10% and the relative error δ of 94.2% data patterns are within 5%. And for ANFIS models, the relative error δ of all the data patterns are within 10% too and of 92.% data patterns are within 5%. For calculating the system COP_s, the properties of the ANN and ANFIS models which are evaluated by statistical values are tabulated in Table 2. The relative error δ of all the data patterns are within 10% for both ANN model and ANFIS model. The relative error δ of 89.6% data patterns are within 5% for both ANN model and it is 94.9% for ANFIS model. The relative errors are all within the acceptable limits.

From Table 1 and 2 we can see that ANN and ANFIS models both have a good calculation accuracy. the relative error δ and absolute error ε of them are all very low. Whether for the heat pump COP or for the system COP_s, ANFIS model always have a higher accuracy than ANN models, the absolute error, the relative error and RMS are smaller, R^2 is closer to1, it proves that the ANFIS models is more appropriate to calculate the GSHP COP and the system COP_s based on fewer parameters.

6. Conclusion

In this thesis an ANN and an ANFIS models were built based on fewer parameters to calculate the important performance evaluation indexes: the GSHP COP and system COP of the GSHP system. To obtain the training and test data for the calculation model, a GSHP air conditioning system were monitored in a cooling season. One GSHP unit and a chilled water unit connect in parallel in the system. For the ANN and ANFIS models for calculating the GSHP COP, the parameters in the input layer are: the evaporator inlet and outlet water temperature of the GSHP unit and the condenser inlet and outlet water temperature of the GSHP unit. For the ANN and ANFIS models calculating the system COP_s, six parameters are in the input layer: the condenser inlet and outlet water temperature of the GSHP unit, the the condenser inlet and outlet water temperature of the chilled water unit and the inlet and outlet water temperature on the load side of the system.

424 data patterns are used as training data and all the data patterns (729 data patterns) are used as test data. The trained models can calculate the performance indexes of the GSHP system. Some statistical methods, absolute error ε , relative error δ , root-mean squared (RMS), absolute fraction of variance (R^2) were adopted to validate the model. The results show that the ANN and ANFIS models are capable to calculate the GSHP unit COP and the system COP_s with a good accuracy based on fewer parameters and ANFIS model shows better performance.

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