ANNUAL ENERGY-USING SIMULATION OF SEPARATE HEAT-PIPE HEAT EXCHANGER

Dan-dan Zhu[1], Da Yan[1], and Zhen Li[2]
[1]Department of building science, Tsinghua University, Beijing, China
[2]School of Aerospace, Tsinghua University, Beijing, China

ABSTRACT

A kind of separate heat-pipe heat exchanger (SHP exchanger), which can move heat from indoor air to outdoor air by making use of their temperature difference, uses much less energy consumption than air-conditioning system in base station due to none of compressor. This study built up an annual energy-using simulation module of SHP exchanger in DeST by building the model of SHP exchanger and accomplishing the coupling calculation of it and the model of dynamic thermal process in building. Besides, the verification and application of this simulation work shows that it can assist the design of air-conditioning system in base station.

INTRODUCTION

Millions of base stations have been built for data processing and transmission in mobile communication system in China in recent years. Statistics showed that the power consumption of base stations accounted for more than 90% the total power consumption of telecoms companies, in which air-conditioning system uses more than 40% power in base stations (Hu Wei et al., 2008). Therefore, it is how to reduce the power consumption for air-conditioning system that is the key to achieve base stations' energy-saving.

The size of base station is generally small, about 20～30 square meters and electrical equipment mainly includes communication equipment and air-conditioning system. As communication equipment operates continuously releasing high heat of 100～400W/m^2, cooling is required even in winter. Besides, as there is little ventilation to insure air cleanliness and indoor moisture source, moisture load is so little that dehumidification is not required in air-conditioning.

Now split-unit or precision air-conditioner is used in most base station in China, resulting in long-time operation and high power consumption. There are some methods to solve this problem in study and application, for instance, compressor frequency control, adaptive control of air-conditioner, new refrigerant and using natural cooling resource (Hou Fu-ping, 2006). For using natural cooling resource, there are plate-type heat exchanger or heat pipe exchanger and supplying outdoor air directly (Liu Jie et al., 2008). And of them Separate Heat Pipe exchanger (SHP exchanger), moving heat from indoor air to outdoor air by working fluid flowing in pipe when outdoor air temperature is below indoor one, is a very energy-saving way because of none compressor.

As the heat transfer performance of SHP exchanger working in base station is related with many factors such as outdoor meteorological parameter, indoor casual gain, building parameter etc., its performance in all condition is required to calculate by simulation. However, the simulation study of heat pipe has mainly focused on heat pipe components so far, instance for, computational fluid dynamics (CFD) simulation of flowing fluid, heat transfer simulation of heat pipe unit (Wang Yue et al., 2000), and lacks simulation combining heat-pipe equipment and dynamic thermal process in building. So this study aims at building up a simulation module of SHP exchanger in the building energy simulation software —— DeST for the simulation of room temperature and energy consumption in all condition to help designing air-conditioning system in base station.

OPERATING PRINCIPLE

Heat-pipe is a high-efficient component of heat transfer by the flow and phase change of its working fluid with the advantage of large density of heat discharge, good isothermality and simple structure. The structure of SHP exchanger is as Figure 1 shown. The evaporator (the indoor unit) is located in the bottom of room with a fan and the condenser (the outdoor unit) is upper outdoor with another fan, which are connected by a gas pipe and a liquid pipe. When heat-pipe working, indoor air heats the evaporator to vaporize its working fluid resulting in the pressure rise in the evaporator that makes the vapor flow to the condenser through the gas pipe, where the vapor condenses into liquid with heat release, and then the liquid goes back to the evaporator because of its gravity and capillary force. In this way, the heat of indoor air is moved to the outdoor air.

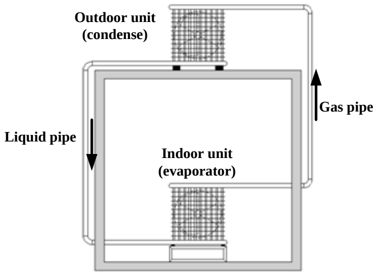

Figure 1 The structure of SHP exchanger

As thermal resistance of heat exchanger and limited airflow volume of fan, it is when outdoor air temperature is blow than indoor air temperature a certain threshold that SHP exchanger can work, and the threshold is defined as the operating temperature difference. When SHP exchanger cannot work regularly or keep the room temperature under the setting one, a split-unit air conditioner is required to cool the indoor air. So SHP exchanger and split-unit air conditioner is needed at the same time in base station.

MODELING

The annual energy-using simulation module of SHP exchanger includes the model of dynamic thermal process in building and SHP exchanger.

MODEL OF DYNAMIC THERMAL PROCESS IN BUILDING

The simulation of dynamic thermal process in building is to calculate room temperature in a given building under different meteorological parameters, operating status and cooling or heating sent by the environment control system, which is the basis of all thermal process analysis in building. Now this process can be accomplished by lots of building simulation software, such as DOE-2, Energy plus, DeST etc. and in this study the software DeST is chosen, the simulation result of which has been verified by many methods (DeST team of Tsinghua University, 2006).

MODEL OF SHP EXCHANGER

In this part, the gray-box model of SHP exchanger is built up by analysing its heat transfer performance and experimental results.

Firstly, SHP exchanger's heat transfer performance is analysed by the method $\varepsilon - NTU$ theoretically. When the filling rate of heat pipe is constant, the pressure drop of the vapour from the evaporator to the condenser is so little that the evaporating and condensing temperature are nearly the same. Some assumptions about both the evaporator and condenser are set as follows: countercurrent flow between air and fluid in heat pipe, the face velocity constant, the thermal capacity of air constant, heat transfer coefficient of the entire heat transfer surface nearly the same, and the connected pipes between the evaporator and condenser are adiabatic.

Firstly, heat transfer in the evaporator is analysed. As fluid in the evaporator or condenser is under condition of phase transition, namely, its temperature is constant, which means the thermal capacity of fluid approaches infinity, the thermal capacity of air is smaller, namely, $(Mc_p)_{\min} = M_a c_{p,a}$.

The value of ε_e and NTU_e is defined in the conventional way as

$$\varepsilon_e = \frac{t_{e,ain} - t_{e,aout}}{t_{e,ain} - t_e} = 1 - e^{-NTU_e} \quad (1)$$

$$NTU_e = \frac{k_e A_e}{M_{e,a} c_{p,a}} \quad (2)$$

The thermal transfer in the evaporator can be noted as

$$Q_e = M_{e,a} c_{p,a} (t_{e,ain} - t_{e,aout}) \quad (3)$$

From Eq. (1) we get

$$t_{e,aout} = -\varepsilon_e (t_{e,ain} - t_e) + t_{e,ain} \quad (4)$$

From Eq. (3) and Eq. (4) we get

$$Q_e = M_{e,a} c_{p,a} \varepsilon_e (t_{e,ain} - t_e) \quad (5)$$

Marking that $c_1 = M_{e,a} c_{p,a} \varepsilon_e$, we have

$$Q_e = c_1 (t_{e,ain} - t_e) \quad (6)$$

Heat transfer in the condenser can be analysed in the same way as the evaporator shown as

$$Q_c = c_2 (t_c - t_{c,ain}) \quad (7)$$

where $c_2 = M_{c,a} c_{p,a} \varepsilon_c$, $\varepsilon_c = \frac{t_{c,aout} - t_{c,ain}}{t_{c,aout} - t_c} = 1 - e^{-NTU_c}$, $NTU_c = \frac{k_c A_c}{M_{c,a} c_{p,a}}$.

From Eq. (6) and Eq. (7), noting that $Q_e = Q_c$ and $t_e = t_c$, we get

$$t_e = t_c = \frac{c_1 t_{e,ain} + c_2 t_{c,ain}}{c_1 + c_2} \quad (8)$$

Taking Eq. (8) and putting it to Eq. (6) or Eq. (7), we have

$$Q_e = Q_c = \frac{c_1 c_2}{c_1 + c_2} (t_{e,ain} - t_{c,ain}) \quad (9)$$

Thus, the heat transfer quantity of the evaporator or condenser is linearly proportional to the inlet air temperature difference of the evaporator and condenser.

Secondly, above theoretical result has been also verified by the performance measurement of varying working condition experiment of a heat pipe exchanger (Li Qi-he et al., 2008). In this experiment, the filling rate and face velocity of the evaporator and condenser were both constant, and the inlet air temperature in the condenser was adjusted from 5℃ to 41.5℃ and the one in the evaporator varied from 20℃ to 55℃. The measured results showed that the heat transfer quantity was linearly proportional to the inlet air temperature difference of the evaporator and condenser, not related with the range of inlet and outlet air temperature in the evaporator or condenser, as Figure 2 (Li Qi-he et al., 2008) shown.

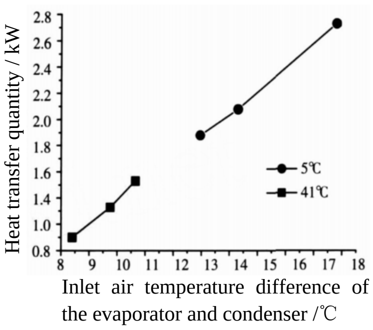

Figure 2 The curve of the dispersed performance with different temperature of inlet air of the condenser

Above the theoretical and experimental results, on the condition of constant face velocity of the evaporator and condenser, the heat transfer model of SHP exchanger can be described as

$$Q = a \times (t_{e,ain} - t_{c,ain}) + b \quad (10)$$

On the other hand, the power-using model can be described as the indoor and outdoor fans' power consumption. Generally, the outdoor fan of SHP exchanger varies with high, medium and low air volume and the indoor fan keeps constant, in which we can give the respective value of a , b and fans' power consumption basing on the sample data.

THE COUPLING CALCULATION OF THE MODEL OF DYNAMIC THERMAL PROCESS IN BUILDING AND SHP EXCHANGER

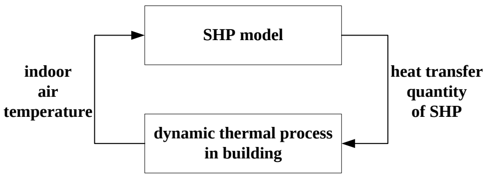

Figure 3 The coupling relationship of indoor air temperature and heat transfer quantity of SHP

After modelling, the combination and calculation of the two models are required. According to Eq. (10), the heat transfer quantity of SHP exchanger is linearly proportional to the inlet air temperature difference of the evaporator and condenser. The inlet air temperature of the evaporator can be regarded as room temperature and the inlet air temperature of the condenser is the outdoor air temperature. Because room temperature and heat transfer quantity of SHP exchanger at the present moment are interplayed as Figure 3 shown, and the real room temperature is varying, the solution of room temperature requires decoupling or iterating, which is the key problem of this study. In order to decouple, t_{bz} is introduced and then room temperature at the present can be divided as (DeST team of Tsinghua University, 2006)

$$t_a(\tau) = t_{bz}(\tau) + \sum_j \Phi_{j,0} t_j(\tau) + \Phi_{hvac} q_{hvac}(\tau) + \Phi_{hvac} c_{p,a} \rho_a G_{out}(\tau)(t_{out}(\tau) - t_a(\tau)) + \sum_j \Phi_{hvac} c_{p,a} \rho_a G_j(\tau)(t_j(\tau) - t_a(\tau)) \quad (11)$$

From Eq. (10) and Eq. (11), we can calculate the room temperature directly as

$$t_a(\tau) = [t_{bz}(\tau) + \sum_j \Phi_{j,0} t_j(\tau) + \Phi_{hvac}(a t_{out}(\tau) - b) + \Phi_{hvac} c_{p,a} \rho_a G_{out}(\tau) t_{out}(\tau) + \sum_j \Phi_{hvac} c_{p,a} \rho_a G_j(\tau) t_j(\tau)] / [1 + \Phi_{hvac} a + \Phi_{hvac} c_{p,a} \rho_a G_{out}(\tau) + \sum_j \Phi_{hvac} c_{p,a} \rho_a G_j(\tau)(t_j(\tau)] \quad (12)$$

When SHP exchanger working, power consumption can be calculated according to fan power; when spilt air-conditioner working, it can be calculated basing on the cooling load and coefficient of performance (COP) of air-conditioner.

Furthermore, control strategy of SHP exchanger is required, as Figure 4 shown. The setting value of room temperature is t_{set} , and the operating temperature difference of SHP exchanger is 5℃. When room temperature is higher than t_{hp_on} , SHP exchanger starts to work and it stops when room temperature is lower than t_{hp_off} .Besides, when SHP exchanger is working，the indoor fan keeps at the maximum air volume while the outdoor fan can vary with high, medium and low air volume according to the present and previous room temperature.

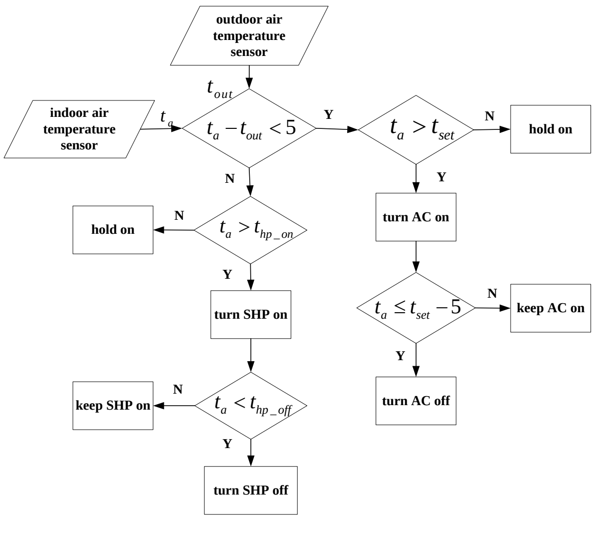

Figure 4 Control logic of SHP exchanger

In the software DeST, an annual energy-using simulation module of SHP exchanger has been added as a new type of air-conditioning and its calculating time step is one hour, in which SHP exchanger's library has been also built according to sample data supplied by manufacturers. Besides, users can also set the parameters to define the performance of SHP exchanger by themselves.

MODEL VERIFICATION

This part compared the measured and simulated results of SHP exchanger in a real base station to verify the reliability of coupling calculation of the model of dynamic thermal process in building and SHP exchanger.

INFORMATION OF THE BASE STATION

The measured base station is a 3 meter high room located in Guangdong province, in China, with 5.5 meter long east-west and 4.5 meter wide north-south, on the top floor of a three-floor building. It has walls of 100 millimetre colour-steel plate, no window and an outside door in the north wall. The measured power using of communication equipment was about 4.5 to 6.0kW. The setting temperature of the base station was 28℃, and alarm temperature of room and equipment was 33℃ and 35℃ respectively. The detail information of its air-conditioning system is as Table1 shown.

Table 1
Information of air-conditioning system

EQUIPMENT	PARAMETER
Split-unit air conditioner	brand：Haier mitsubishi；number：2；rated refrigerating capacity：7.5kW；rated power：2.7kW
SHP exchanger	brand：SIS；number：1；type：SHP4500；rated refrigerating capacity： 1.83 kW when 5℃ temperature difference of indoor and outdoor inlet air，4.20 kW at 10℃；largest air volume：5750 m^3/h；highest power：0.44kW

MEASURED RESULTS

The testing content included air dry-bulb temperature and equipment's accumulative power consumption. There were six testers measuring air temperature every 10 minutes, including outdoor and indoor inlet air of SHP exchanger, indoor outlet air of SHP exchanger, indoor inlet air of two spilt air-conditioners and communication equipment. Accumulative power consumption of communication equipment, split-unit air conditioners and SHP exchanger is measured every 10 minutes respectively.

The results of hourly average air temperature and power consumption during Jan.5th 00:00 a.m.to Jan.10th 16:00 p.m. in the year 2011 were as Figure 5 and Figure 6 shown. The hourly power consumption of communication equipment ranged from 4.5 to 6.0 kW and its regular pattern of different days was nearly the same, showing that it consumed less power before dawn and more during afternoon and evening. SHP exchanger and split-unit air conditioners worked in turn, but they worked at the same time on Jan.5th. Besides, the indoor fans of the split-unit air conditioners operated all the time even they did not turn on.

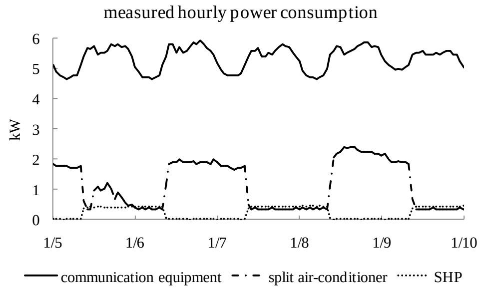

Figure 5 Measured hourly power consumption of equipments

During the test, SHP exchanger was controlled to operate during fixed time (from 09:00 a.m. this day to 08:00 a.m. of the next day) in order to evaluate the energy-saving effect of SHP exchanger, as Figure 6 shown. Besides, the inlet air temperature of two air-conditioners during their working was relatively stable and its average is 27.03℃.

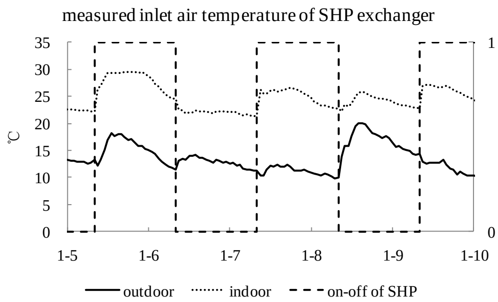

Figure 6 Measured inlet air temperature of SHP exchanger

SIMULATION SETTINGS

The building model of the measured base station in DeST is as Figure 7 shown, and the model settings are as Table 2 shown.

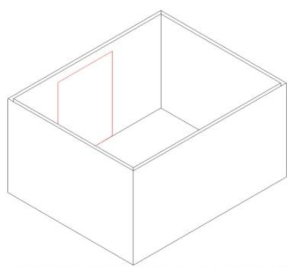

Figure 7 The building model of base station in DeST

Table 2

Settings of base station in DeST

ITEM	SETTING
Wall	100mm colour-steel plate，coefficient of heat transfer = 0.438 W/(K m^2)
Roof	Insulation roofing，coefficient of heat transfer= 0.804 W/(K m^2)
Door	1m×2m double wooden outside door
Occupancy	None
Lighting	None
Ventilation rate between indoor and outdoor	0.1 h^{-1}
Room temperature	15～28℃

Heat-release equipment in the base station included communication equipment, indoor fans of split-unit air conditioner and SHP exchanger, power using of which finally turned heat into air. The total power using of heat-release equipment on Jan.5th of 2011 was as Figure 8 shown, from which we can get heat-release schedule of equipment used in software DeST.

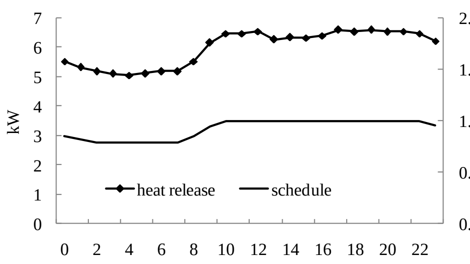

Figure 8 The total heat release of equipment and its schedule

The setting of SHP exchanger and split-unit air conditioners in simulation were the same as Tabel1. In order to compare the measured and simulated results, the outdoor inlet air temperature uses the measured one, the operating time of SHP exchanger is set the same as the measured one. During the split-unit air conditioner operating, the room temperature is set as 27℃. Besides, the annual room temperature of the first and second floor is kept at the range of 20℃ to 26℃.

COMPARISONS OF MEASURED AND SIMULATED RESULTS

The indoor inlet air temperature of SHP exchanger (or air-conditioner, if both are working, it is also SHP exchanger) during its working is regarded as the room temperature of the base station. The simulated and measured room temperature is as Figure 9 shown. We can see that the simulated one is higher than the measured one on the day of Jan.5th because SHP exchanger and split-unit air conditioner are working at the same time. If excluding these hours, the absolute error of simulated and measured temperature is less than 0.7℃. The simulated and measured power consumption of SHP exchanger is as Figure 10 shown. The average power consumption of SHP exchanger during working is 427.7W, and the simulated one is 440W. So the absolute error of them is 12.3W and relative one is less than 3%, which are good enough for the simulation results in the engineering application.

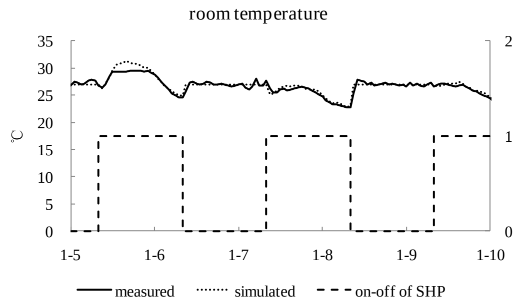

Figure 9 Comparison of the simulated and measured room temperature

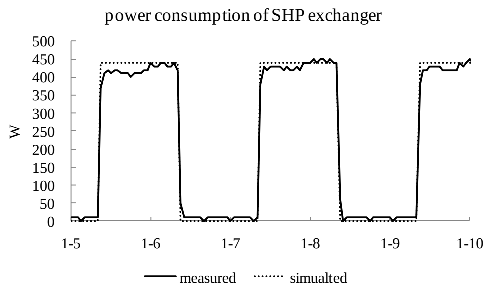

Figure 10 Comparison of the simulated and measured power consumption of SHP exchanger

CASE STUDY

In order to illuminate the application of annual energy-using simulation module of SHP exchanger in assisting to design air-conditioning system in base station, the performance of SHP exchanger in all condition in Guangzhou and Beijing is simulated by the software DeST.

SIMULATION SETTINGS

The base station is a one-floor building and model's setting is the same as Table 2. Besides, total heat release of equipment is 5kW continuously. The annual average COP of split-unit air conditioner is set as 2.5. The control strategy of SHP exchanger is the same as Figure 4, where starting and stopping temperature of SHP exchanger is set as 19℃ and 17℃ respectively. Furthermore, when the outdoor air temperature is extremely low, SHP exchanger working an hour would make room temperature below 17℃ while it would rise above than 19℃ if SHP exchanger stops, resulting in SHP exchanger turning on and off frequently. Therefore, during one hour time step, SHP exchanger can work only 10, 20, 30, 40 or 50 minutes in which the heat transfer quantity is calculated according to Eq. (10). For example, if it works only 10 minutes an hour, the heat transfer quantity is one-six quarter of the one an hour.

SIMULATED RESULTS

The simulated results of the annual hourly room temperature in Guangzhou and Beijing are as Figure 11 and 12 respectively shown. As the outdoor air temperature in Guangzhou is relatively high, the room temperature of base station varies from 21℃ to 28℃, while that in Beijing is from 17℃ to 28℃ due to relatively low outdoor air temperature. Besides, the room temperature is fluctuant when SHP exchanger operating while it is set as 28℃ during split-unit air conditioner on.

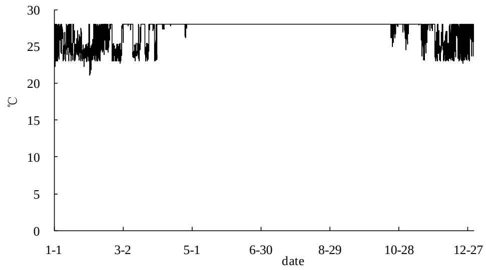

Figure 11 The simulated room temperature in Guangzhou

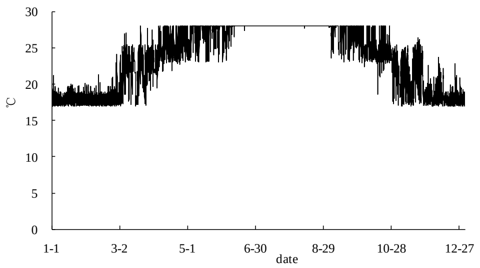

Figure 12 The simulated room temperature in Beijing

The simulated results of the annual hourly power consumption of SHP exchanger and split-unit air conditioner are as Figure 13 and 14 shown. As we see, split-unit air conditioner uses much more power than SHP exchanger hourly. From the full year, SHP exchanger work regularly during winter or transition season while air-conditioner has to be working in summer. Comparing the base station in Guangzhou and Beijing, the number of annul working hours of SHP exchanger in Beijing is more than in Guangzhou.

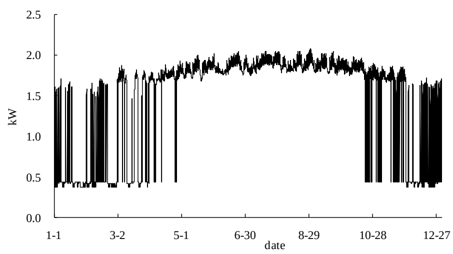

Figure 13 The simulated power consumption of SHP exchanger in Guangzhou

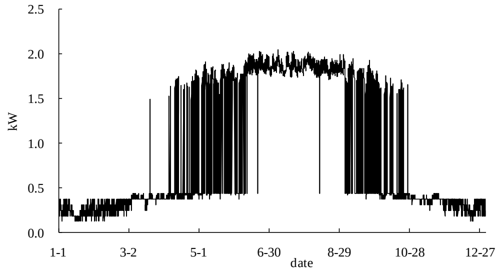

Figure 14 The simulated power consumption of SHP exchanger in Beijing

If there are two air-conditioning methods, one is using air-conditioning only (ACO), another is using both SHP exchanger and air-conditioner (SHPAC). The annual power consumption comparison of two methods in Guangzhou and Beijing is as Figure 15 and 16 respectively shown. We can see that the annual power consumption of SHPAC is less than ACO whether in Guangzhou or Beijing. Besides, the annual hourly outdoor temperature in Beijing is lower, which is good to the working of SHP exchanger, so SHPAC is more efficient in Beijing. Considering the economy, although SHPAC invests a new device (SHP exchanger) compared with ACO, SHPAC uses 2896 kWh in Guangzhou and 5975 kWh in Beijing less than ACO yearly, the recovery period is about one to two year.

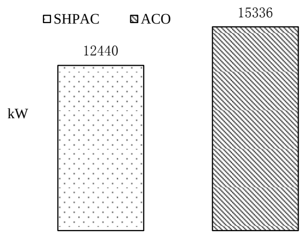

Figure 15 The power consumption comparison of two air-conditioning methods in Guangzhou

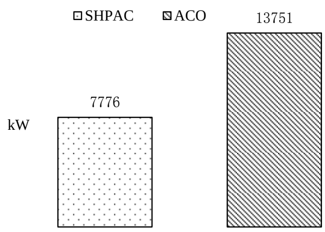

Figure 16 The power consumption comparison of two air-conditioning methods in Beijing

CONCLUSION

In order to study the performance of SHP exchanger in all condition used in base station, this study built the grey-box model of SHP exchanger basing on the theoretical and experimental analyses. In the building simulation software DeST, the model of SHP exchanger and dynamic thermal process in building is coupling calculated by introducing t_{bz} to divide the room temperature at the present moment, and after that the annual energy-using simulation module of SHP exchanger was built.

Besides, in this study, the measured and simulated operating results of SHP exchanger in a real base station were compared, showing that the absolute error of room temperature was less than 0.7℃ and the relative one of the power consumption was less than 3%, so the simulation results are good enough for the engineering application.

Finally, this study discussed the application of SHP exchanger simulation module by two cases. By comparing the simulated results of SHP exchanger working, we can conclude that SHP exchanger with air-conditioner was more efficient than air-conditioner only whether in Guangzhou or Beijing, which supplied a new method for air-conditioning system design in base station.

NOMENCLATURE

t_{ain} Inlet air temperature，℃

t_{aout} Outlet air temperature，℃

t Temperature of working fluid in heat pipe，℃

k Heat transfer coefficient，$W/(K \cdot m^2)$

A Heat transfer surface，m^2

M_a Air volume，kg/s

$c_{p,a}$ Air heat capacity，$J/(K \cdot kg)$

Q Heat transfer quantity，W

a Model parameter，$W/℃$

b Model parameter，W

t_a Room temperature，℃

t_{bz} Room temperature without the influence of air-conditioning, ventilation and heat transfer among other rooms at the present moment ，℃

t_j Temperature of adjacent room named j ，℃

t_{out} Outdoor air temperature，℃

q_{hvac} Heating quantity sent into the targeted room，W

G_{out} Ventilation between indoor and outdoor, m^3/s

G_j Ventilation between targeted room and adjacent room named j ，m^3/s

$\Phi_{j,0}$ Impact factor of adjacent room named j affecting on targeted room temperature

Φ_{hvac} Impact factor of heating by air-conditioning affecting on targeted room temperature

SUBSCRIPT

e Evaporator

c Condenser

τ Time

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