

# Performances of an air thermal energy utilization system developed with fan-coil units in large-scale plastic tunnels covered with external blanket

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**Abstract:** To improve the problem of low temperature at night in winter due to the lack of thermal storage in large-span plastic tunnels, an air thermal energy utilization system (ATEUS) was developed with fan-coil units to heat a large-scale plastic tunnel covered with an external blanket (LPTEB) on winter nights. The ATEUS was composed of nine fan-coil units mounted on top of the LPTEB, a water reservoir, pipes, and a water circulation pump. With the heat exchange between the air and the water flowing through the coils, the thermal energy from the air can be collected in the daytime, or the thermal energy in the water can be released into the LPTEB at night. On sunny days, the collected thermal energy from the air in the daytime ( $E_c$ ) and released thermal energy at night ( $E_r$ ) were 0.25-0.44 MJ/m<sup>2</sup> and 0.24-0.38 MJ/m<sup>2</sup>, respectively. Used ATEUS as a heating system, its coefficient of performance (COP), which is the ratio of the heat consumption of LPTEB to the power consumption of ATEUS, ranged from 1.6-2.1. A dynamic model was also developed to simulate the water temperature ( $T_w$ ). Based on the simulation,  $E_c$  and  $E_r$  on sunny days can be increased by 60%-73% and 38%-62%, respectively, by diminishing the heat loss of the water reservoir and increasing the indoor air temperature in the period of collecting thermal energy. Then, the COP can reach 2.6-3.8, and the developed ATEUS can be applied to heating the LPTEB in a way that conserves energy.

**Keywords:** large scale plastic tunnel, air thermal energy utilization system, energy conservation, COP

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## 1 Introduction

Chinese solar greenhouse (CSG) is a type of mono-slope horticultural facility widely applied in China for the overwinter production of vegetables. It could maintain high interior air temperature without or with a little amount of heating<sup>[1,2]</sup>. However, this type of greenhouse has the flaws of high construction cost, low land utilization efficiency, narrow space, etc<sup>[3,4]</sup>. As a result, a large-scale plastic tunnel with an external thermal blanket (LPTEB) has been employed in recent years to address the above issues. However, auxiliary heating in the winter is necessary for the LPTEB to satisfy the temperature requirement of the plants inside<sup>[5]</sup>.

Greenhouse heating is an important measurement to achieve optimal interior temperature and high yield in cold weather<sup>[6,7]</sup>.

Nevertheless, the traditional heating technologies in greenhouses consume huge amounts of fossil energy resources such as coal and natural gas, which easily cause environmental pollution and contribute to the global climate change and energy crisis<sup>[8]</sup>. Moreover, the heating cost could account for 30% of the overall greenhouse operational cost, according to Aramyan et al.<sup>[9]</sup> and Heidari et al.<sup>[10]</sup> Thus, heating technologies using solar energy, which is abundant and clean, have attracted considerable attention.

One popular method to use solar energy is to gather excess solar energy with a collector and store it in water<sup>[11-13]</sup>, a phase change material<sup>[14-16]</sup>, a rock-bed<sup>[17]</sup>, etc. At night, the stored thermal energy can be released to heat the greenhouse. Attar et al.<sup>[18]</sup> employed a solar water heating system using two solar collectors to gather solar energy and a capillary tube as heat exchanger. It was found that the inner air temperature in the greenhouse under Tunisian condition was increased by 5°C. Fang et al.<sup>[19]</sup> developed a system to collect and store solar energy into greenhouse soil. In the nighttime, this energy could be recovered and released into greenhouse via the capillary radiators. As a result, 27.8 kW·h/(m<sup>2</sup>·a) of the energy for greenhouse heating could be saved. Zhou et al.<sup>[20]</sup> applied the active heat storage-release system (AHS), which could collect solar energy with the panels made of polyethylene film and insulation board, for mono-span greenhouse heating. Considering that the stored solar energy can hardly meet the heating requirements alone, a heat pump was later used to improve the heat collection and release performances of the AHS. Hassaniena et al.<sup>[12]</sup> found that the air temperature and relative humidity of a greenhouse can be increased by 2°C-3°C and decreased by 10%, respectively, by heating a

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greenhouse with an evacuated tube solar collector as a solar water heater assisted by an electric heat pump. Additionally, this system covered 35% of greenhouse heating energy. However, those technologies require a large area of collectors and can cause the problems of occupying large amounts of land and blocking the sunlight for the plants.

The solar radiation that enters the greenhouses can increase the indoor air temperature, because of the greenhouse effect. A part of the solar energy becomes thermal energy in the air. If the indoor air temperature is greater than the optimum level, ventilation must be conducted to exclude that energy. Technologies such as earth-to-air heat exchange systems (EAHE), rock-bed system<sup>[21]</sup>, etc. were developed to heat the greenhouses with those types of energy. An EAHE is to store the thermal energy in soil in the daytime and recovers the stored energy in the night time to heat the greenhouse by circulating air between greenhouse and underground pipes. In this case, the greenhouse itself served as a solar collector and avoided the above shading problems. Ghosal et al.<sup>[22]</sup> increased the air temperature of a greenhouse by 7°C-8°C with the usage of EAHE in India. This effect can be further improved by increasing the pipe length and its buried depth to 4.0 m, decreasing pipe diameter, mass flow rate of air, etc. By using EAHE in combination with a thick brick wall, the air temperature in greenhouse increased by 8°C<sup>[22]</sup>. Ozgener et al.<sup>[23]</sup> developed an EAHE system using U-bend buried pipe as heat exchanger. Based upon the measurements made in the heating mode, the average heat extraction rate to the soil was 3.77-80.21 W/m of pipe length and the daily average maximum COP for the system reached 6.42. Yang et al.<sup>[24]</sup> indicated that, compared to the traditional heat-pump system in an agricultural greenhouse, EAHE could reduce the initial equipment costs by 35.3% and save 67.3% of energy in winter. On the other hand, a rock-bed system is similar to EAHE, but uses rocks buried in the ground to store heat. Its positive effects on rock beds also had been confirmed by Bouadila et al.<sup>[25-27]</sup>

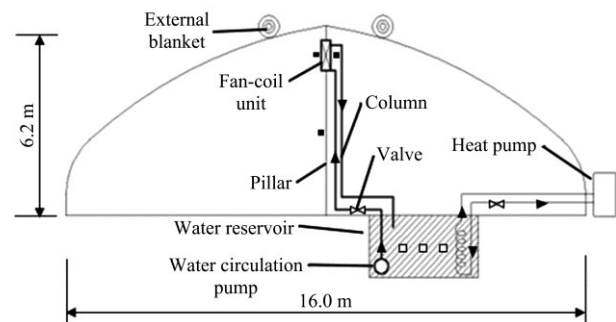
Apart from those technologies mentioned above, Yang et al.<sup>[28]</sup> developed an air thermal energy utilization system with fan-coil units mounted in the greenhouses. The surplus air thermal energy could be gathered with the system and stored in the water reservoir. A heat pump was also employed to control the water temperature. The daily COP of the system on a cold day was 3.01. Sun et al.<sup>[29]</sup> combined fan-coil units with heat pump to provide heat for the solar greenhouse at night, which raised the average nighttime temperature by 2.8°C-4.4°C and reduced the relative humidity by 8%-11.5%. Li et al.<sup>[30]</sup>, aiming at the plastic tunnel covered with thermal blanket, used thermal collecting and releasing system developed with fan-coil units to raise the indoor temperature by (2.5±0.4)°C and (1.1±0.3)°C respectively on sunny days and cloudy days. In those studies<sup>[28-31]</sup>, the thermal energy from the air was gathered or released with the fan-coil unit, which has high heat exchange efficiency and small sectional area. It is usually mounted in the greenhouses and hardly affects the plant lighting. In previous studies, researchers focused on the influence of system configuration parameters such as fan-coil unit performance, water velocity, and wind speed on system performance, but the heat loss of the water reservoir was usually ignored. In addition, the vents were habitually opened when the solar radiation was pretty to prevent excessive air temperature in the shed. However, the influence of the decrease in the maximum temperature in the shed caused by ventilation on the system performance has not been

discussed. And the higher the maximum indoor air temperature, the more conducive to the heat collection of the system. It was necessary to control the air temperature to be conducive to heat collection without causing high temperature stress to crops, the influence of the maximum indoor air temperature on the system performance was of great significance to the solar greenhouse airtight management. So in this study, an air thermal energy utilization system is developed with fan-coil units to adjust indoor air temperature of the LPTEB. The objectives of this study are evaluating the performance of this system and analyze the effects of the thermal insulation performance of the water reservoir and the maximum indoor air temperature on the system performance.

## 2 Material and methods

### 2.1 The tested plastic tunnel with external blanket

The experiment was conducted in an LPTEB in Yinchuan city of Ningxia Hui Autonomous Region, China (38.4°N, 106.4°E). The LPTEB was north-south oriented, 80 m long, and 16 m wide (Figure 1). The steel tube column was built every 4.0 m to improve the structure stability of the LPTEB. Its ridge height was 6.2 m. The gable wall was built with a 200 mm polystyrene board. The roof was covered with a polyethylene film with a thickness of 0.1 mm. The external blanket is made with spray-bonded cotton and has a heat transfer coefficient of 0.9 W/(m<sup>2</sup>·K).



Notes: ■ and □ are locations of the air temperature and humidity recorders and thermocouple, respectively. (Dec. 29, 2016 to 09:20 Jan. 01, 2017)

Figure 1 Schematic diagram of LPTEB and ATEUS structure and location of measuring points

During the experiment, the LPTEB was used to grow tomatoes. The external thermal blanket on the east roof of the LPTEB was retracted in the morning to enable solar radiation to enter the LPTEB. The west roof was covered with an external thermal blanket to prevent heat loss and increase indoor air temperature. For the same reason, the external thermal blanket on the east roof of the LPTEB was extended after 12:00 and that on the west roof was simultaneously retracted to enable solar radiation to enter the LPTEB. At 16:00, the external thermal blanket on the west roof was extended due to low solar radiation.

The meanings and units of all symbols used in this article are listed in Table 1.

### 2.2 Air heat utilization system

The developed air thermal energy utilization system (ATEUS) consisted of nine fan-coil units, a water reservoir, a water circulation pump and pipes. The fan-coil units were mounted under the ridge and 5.5 m to the ground. Each fan-coil unit contained two fans of 180 W. Every two adjacent fan-coils were separated by 6.0 m. The water reservoir was located at the center of the LPTEB and contained 22.8 m<sup>3</sup> of water. The electric power of the water circulation pump was 900 W and placed under water in the reservoir. Driven by the water circulation pump, the water

could circulate in the system at a speed of 12.4 m<sup>3</sup>/h. An air-source heat pump was installed to heat the water reservoir by collecting the outdoor air thermal energy. The heat pump's rated heating and cooling capacities were 12 and 10 kW, respectively, with the refrigerant of hydrochlorofluorocarbon. It only operated in the daytime of cloudy days, when  $T_{in}$  was so low that the ATEUS could not be started.

**Table 1** Definitions of the symbols used in this article

Symbol	Meaning	Unit
$\Delta t$	The calculation time step	h
$T_{in}$	Indoor air temperature	°C
$T_{out}$	Outdoor air temperature	°C
$T_w$	Water temperature of the water reservoir	°C
$T_{in2}$	Outlet air temperature of fan-coil units	°C
$T_{w2}$	Outlet water temperature of fan-coil units	°C
$T_{w,m+1}$	Water temperature at the time of $(m+1) \cdot \Delta t$	°C
$k_m$	The decrease rate of water temperature in reservoir at the time of $m \cdot \Delta t$	J/h
$t_d$	The time required for a decrease of 0.5°C	h
$k$	The decrease rate of $T_w$	°C/h
$\eta$	Efficiency of fan-coil unit	—
$n$	The number of fan-coil units in LPTEB	pcs
$G$	Air velocity of fan-coil unit	kg/s
$\rho_w$	The density of water	kg/m <sup>3</sup>
$c_p$	The isobaric heat capacity of air	J/(kg·°C)
$c_w$	The specific heat of water	J/(kg·°C)
$v$	The water circulation rate in system	m <sup>3</sup> /h
$V$	Volume of water reservoir	m <sup>3</sup>
$E_s$	Thermal energy stored in water of reservoir in the daytime	MJ
$E_c$	Air thermal energy collected by ATEUS	MJ
$T_{w,ic}$	$T_w$ at the beginning of heat-collecting process	°C
$T_{w,ec}$	$T_w$ at the end of heat-collecting process	°C
$E_L$	Total thermal energy lost by reservoir at night	MJ
$E_r$	Thermal energy released into LPTEB at night by ATEUS	MJ
$T_{w,ir}$	$T_w$ at the beginning of heat release process	°C
$T_{w,er}$	$T_w$ at the end of heat release process	°C
$E_p$	Electricity consumption of water circulation pump	MJ
$E_f$	Electricity consumption of fan-coil units in the day	MJ
$q_p$	Electric powers of water circulation pump unit	W
$q_f$	Electric powers of fan-coil unit	W
$t_c$	The operation periods of ATEUS to collect the surplus air thermal energy in the daytime	h
$t_r$	The operation periods of ATEUS to release the thermal energy into LPTEB at night	h

The water circulation pump and fans of the fan-coil units worked synchronously. In the daytime, when  $T_{in}$  was over 15°C, and it was 4°C higher than the water temperature in the reservoir ( $T_w$ ), the ATEUS operated. The water flowing through the coils absorbed thermal energy from the air via heat convection with air under the driving of the fans. Then, that energy was stored in the water of the reservoir, the system was switched off until  $T_i$  was below 10°C or  $T_i$  is 2°C higher than  $T_w$ . At night, when  $T_{in}$  was below 8.5°C, and it was 4°C lower than  $T_w$ , the ATEUS operated to release the thermal energy in the water and increased  $T_{in}$ . If  $T_{in}$  increased to 10°C, or the difference between  $T_w$  and  $T_{in}$  was less than 2°C, ATEUS was switched off. To prevent the heat release rate was too fast to cause no heat released in the second half of night, only 5 fan-coil units were operated during the heat release stage.

### 2.3 Measurements

The indoor and outdoor air temperatures ( $T_{in}$  and  $T_{out}$ ) were measured with the temperature and humidity recorder (HOBO

temperature/humidity data logger UX100-00, Onset Co., USA, accuracy:  $\pm 0.2^\circ\text{C}$ ).  $T_w$  was measured by using the T-type thermocouple at three points, which was in the middle depth of the water in the reservoir, and there was also a measuring point at the backwater outlet to measure the outlet water temperature of fan-coil units (measuring range:  $-180^\circ\text{C}$  to  $350^\circ\text{C}$ ; accuracy:  $\pm 0.5^\circ\text{C}$ ) (Figure 1).

The efficiency of fan-coil unit ( $\eta$ ) was determined with  $T_w$ , the air temperatures, and the relative humidity at the wind inlet and outlet of the fan-coil units. Two fan-coil units in the central part of the LPTEB were tested from Jan. 01 to 03, 2019. The air temperatures and relative humidity were measured with the aforementioned temperature and humidity recorder. In this period, the ATEUS automatically operated as described above. All instruments were recorded every 10 min. Meanwhile, the water was left to cool from Dec. 27 to 31, 2018 to evaluate the heat loss of the water reservoir. The time ( $t_d$ ) required for a decrease of 0.5°C in  $T_w$  was investigated. Then, the ratio of 0.5°C to  $t_d$  was defined as the decrease rate of the water temperature in the reservoir ( $k$ , °C/h).

The heat-collecting and heat-release performances of the ATEUS were performed from Jan. 03 to 30, 2019 with the measured  $T_{in}$ ,  $T_{out}$ , and  $T_w$ . All instruments were recorded every 10 min. The data from six consecutive days (from 09:00, Jan. 05 to 09:00, Jan. 10) were used for the analysis.

### 2.4 Model and calculation

The following assumptions were made to complete the simulation of the water temperature in the reservoir.

- 1) The inlet air temperature of the fan-coil units was identical to  $T_{in}$ .
- 2) The inlet water temperature of the fan-coil units was identical to that in the water reservoir.

The efficiency of fan-coil unit ( $\eta$ ) is defined as follows:

$$\eta = \frac{T_{in} - T_{in2}}{T_{in} - T_w} \quad (1)$$

The heat balance between air and water can be described as follows:

$$n \cdot G \cdot c_p (T_{in} - T_{in2}) = -\rho_w \cdot c_w \cdot v (T_w - T_{w2}) \quad (2)$$

$T_w$  can be calculated as follows:

$$T_{w,m+1} = \frac{(V - v \cdot \Delta t) \cdot T_{w,m} + v \cdot \Delta t \cdot T_{w2,m}}{V} - \frac{k_m}{3600} \cdot \Delta t \quad (3)$$

By substituting  $T_{w2}$  in Equation (3) with Equations (1) or (2), Equation (3) can be rearranged as follows:

$$T_{w,m+1} = T_{w,m} + \frac{n \cdot G \cdot c_p \cdot \eta (T_{in} - T_w)}{\rho_w \cdot c_w \cdot V} \cdot \Delta t - \frac{k_m}{3600} \cdot \Delta t \quad (4)$$

When the system is not operating,  $T_w$  can be calculated as follows:

$$T_{w,m+1} = T_{w,m} - \frac{k_m}{3600} \cdot \Delta t \quad (5)$$

$E_s$  and  $E_c$  can be calculated using the flowing equations:

$$E_c = \rho_w \cdot c_w \cdot V \cdot (T_{w,ic} - T_{w,ec}) \quad (6)$$

$$E_c = E_s + \sum_{m=0}^j k_m \cdot \Delta t \quad (7)$$

$E_L$  and  $E_r$  can be calculated as follows:

$$E_L = \rho_w \cdot c_w \cdot V \cdot (T_{w,ir} - T_{w,er}) \quad (8)$$

$$E_r = E_L - \sum_{m=i+1}^j k_m \cdot \Delta t \quad (9)$$

Used ATEUS as a heating system, its coefficient of performance (COP) was the ratio of the heat consumption of LPTEB to the power consumption of ATEUS, and in this study, it was the ratio of the heat released by ATEUS to the total power consumption of the water pump and fans (Not discussed the use of heat pump on cloudy day), The COP was calculated as follows:

$$COP = \frac{E_r}{E_p + E_f} \quad (10)$$

$E_p$  and  $E_f$  can be calculated as follows:

$$E_p = q_p \cdot (t_c + t_r) \cdot 3600 \cdot 10^{-6} \quad (11)$$

$$E_f = n \cdot q_f \cdot (t_c + t_r) \cdot 3600 \cdot 10^{-6} \quad (12)$$

### 3 Results and discussion

#### 3.1 Indoor and outdoor air temperatures

A day was defined as running from 09:00 a.m. to 09:00 a.m. of the next day. The daytime was defined as the period when the external blanket on the east or west roof was retracted. The nighttime was defined as the period when the external blanket on both roofs was extended and covered the roof of the LPTEB. The variations in outdoor air temperature ( $T_{out}$ ) and indoor air temperature ( $T_{in}$ ) are shown in Figure 2. These six days included five sunny days (Jan. 05/06, 06/07, 07/08, 09/10, and 10/11) and one cloudy day (Jan. 08/09) with low temperatures, which is normal for Yinchuan city at this time of year. The average  $T_{out}$  during the days and nights ranged from  $-0.45^\circ\text{C}$  to  $2.33^\circ\text{C}$  and from  $-9.00^\circ\text{C}$  to  $-13.40^\circ\text{C}$ , respectively. The lowest  $T_{out}$  was at night and ranged from  $-13.0^\circ\text{C}$  to  $-18.40^\circ\text{C}$ .

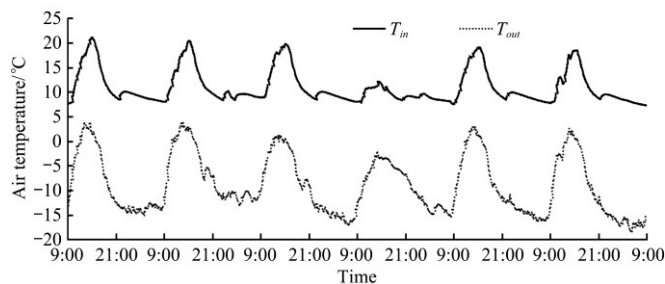


Figure 2 Daily courses of the indoor and outdoor air temperature

$T_{in}$  in the daytime of sunny days increased after retracting the east external thermal blanket and decreased after reaching the largest  $T_{in}$ . The average and maximal  $T_{in}$  during this period were  $13.5^\circ\text{C}$ - $15.8^\circ\text{C}$  and  $18.6^\circ\text{C}$ - $20.5^\circ\text{C}$ , respectively. The difference between  $T_{in}$  and  $T_{out}$  ( $T_{in}-T_{out}$ ) was  $15.4^\circ\text{C}$ - $19.6^\circ\text{C}$ . After covering both east and west external thermal blankets,  $T_{in}$  continuously decreased due to the large ( $T_{in}-T_{out}$ ) until the ATEUS started. On the nights of Jan.05/06, 07/08, 09/10, and 10/11, the ATEUS continuously operated after switching on. On the night of 06/07, the ATEUS was switched on twice and operated for 7.0 h in all. Then,  $T_{in}$  first increased and subsequently decreased. The average and minimal  $T_{in}$  on those nights changed from  $9.5^\circ\text{C}$  to  $10.3^\circ\text{C}$  and from  $7.3^\circ\text{C}$  to  $8.5^\circ\text{C}$ , respectively. The value for ( $T_{in}-T_{out}$ ) reached  $19.3^\circ\text{C}$ - $22.8^\circ\text{C}$ .

In the daytime of 08/09, which was a cloudy day,  $T_{in}$  slowly increased after retracting the east external thermal blanket. Then,  $T_{in}$  decreased after it reached  $12.2^\circ\text{C}$ . The average  $T_{in}$  and ( $T_{in}-T_{out}$ ) in the daytime was  $10.4^\circ\text{C}$  and  $16.4^\circ\text{C}$ , respectively. At night, the ATEUS was switched on since 20:00. The biomass briquettes were ignited at 01:30. Thus,  $T_{in}$  at 20:00, Jan. 08 and 01:30, Jan.09 increased slightly. Finally,  $T_{in}$  at night of the cloudy day was maintained at  $8.9^\circ\text{C} \pm 0.7^\circ\text{C}$ .

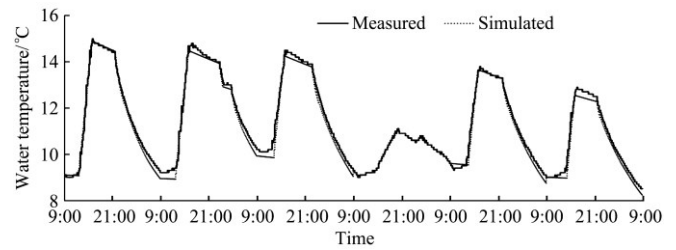


Figure 3 Measured and simulated water temperature in the water reservoir

#### 3.2 Water temperature in the reservoir

The water temperatures in the reservoir during the six-day period are presented in Figure 3. In the daytime of sunny days, the ATEUS operated to collect air thermal energy if  $T_{in}$  was over  $15^\circ\text{C}$  and was  $4^\circ\text{C}$  higher than  $T_w$ . Then, the air thermal energy in the LPTEB was collected and stored in the water reservoir.  $T_w$  increased as a result. In this experiment, the ATEUS was operated for 2.5-3.3 h in the daytime due to low  $T_{in}$  in the LPTEB. Finally,  $T_w$  increased by  $3.3^\circ\text{C}$ - $5.7^\circ\text{C}$  in the daytime of sunny days. The water reservoir was not fully insulated and continuously lost heat. As a result,  $T_w$  decreased by about  $0.7^\circ\text{C}$  in the period from 16:00 until the start time of the ATEUS at night. After the ATEUS started at night, the thermal energy stored in the reservoir was recovered to heat the LPTEB.  $T_w$  rapidly decreased in those periods. In this experiment, ATEUS was operated for 7.2-11.3 h on the night of sunny days.  $T_w$  decreased by  $4.0^\circ\text{C}$ - $5.7^\circ\text{C}$ . On the cloudy day, the ATEUS was not operated to collect the air thermal energy due to low  $T_{in}$ , but it was switched on at 20:20 to release heat into the LPTEB. The heat pump was operated to increase  $T_w$  from 09:00, 08 Jan. to 09:00 on the next day. As a result, the maximum  $T_w$  was  $11.1^\circ\text{C}$ , which was achieved at 20:20. After that,  $T_w$  slowly decreased. The ATEUS cannot collect sufficient thermal energy on a cloudy day. Thus, the heat collection performance of ATEUS on cloudy days will be optimized in future research.

#### 3.3 Heat collect and release performances of the ATEUS

Considering that the ATEUS was operated to collect air thermal energy on cloudy days, the heat-collecting and release performances of the ATEUS on sunny days were analyzed. In the daytime, the collected thermal energy was partly stored in the water of the reservoir and partly lost due to the heat loss of the water reservoir. According to the estimation, the ATEUS stored 316.4-445.8 MJ of heat in the water reservoir, which accounts for 94.6%-96.8% of what was collected in the daytime (Table 2). In the nighttime of sunny days, the thermal energy in the water reservoir was recovered to heat the LPTEB. In this experiment, the water reservoir of ATEUS transferred 383.0-545.8 MJ of thermal energy, of which 76.2%-85.6% was recovered to heat the LPTEB (Table 2).

Up to now, only the active heat systems had been applied to heat the LPTEB at night<sup>[5,20]</sup>. It is reported that the active heat storage-release system assisted with a heat pump (AHS-HP) released 0.14-0.30 MJ/m<sup>2</sup> of thermal energy at night<sup>[20]</sup>. The COP of the AHS-HP system was 3.2. In this experiment, the released thermal energy by ATEUS released 0.24-0.38 MJ/m<sup>2</sup> of thermal energy at night. This value is higher than the AHS-HP system. However, the estimated COP of the ATEUS under the experimental conditions was 1.6-2.1 and lower than the AHS-HP system (Table 2). Considering that the system is usually considered energy conservation if the COP is higher than 2.5, the developed system should be further improved<sup>[20]</sup>.

**Table 2 Heat collecting and releasing performances of the ATEUS**

Date	$E_c$ /MJ	$E_r$ /MJ	$E_p$ /MJ	$E_f$ /MJ	COP
05 Jan.	563.2	468.7	46.5	176.8	2.1
06 Jan.	541.4	303.9	32.9	125.2	1.9
07 Jan.	431.5	395.3	42.7	162.1	1.9
09 Jan.	398.3	368.1	44.3	168.3	1.7
10 Jan.	324.4	337.9	44.8	170.3	1.6

**3.4 Improvements of the ATEUS**

$k$  was calculated and plotted against  $T_w$  and is shown in Figure 4.  $k$  is linearly correlated with  $T_w$  and can be calculated with the regression equation ( $k = 1.21T_w + 10.51$ ,  $R^2 = 0.99$ ,  $n = 4$ ). The measured ( $T_{in} - T_{in2}$ ) is also linearly correlated with ( $T_{in} - T_w$ ) (Figure 5). Hence, the relationship between ( $T_{in} - T_{in2}$ ) and ( $T_{in} - T_w$ ) can be described with the regression equation ( $T_{in} - T_{in2} = 0.487(T_{in} - T_w)$ ,  $R^2 = 0.98$ ,  $n = 90$ ). Then, the slope of the regressed line can be recognized as the efficiency of the fan-coil unit ( $\eta$ ) according to Equation (1). In different conditions,  $\eta$  was different. For the convenience of calculation,  $\eta$  was taken as the average efficiency of the fan-coil unit, that is,  $\eta$  was 0.487 in this experiment.

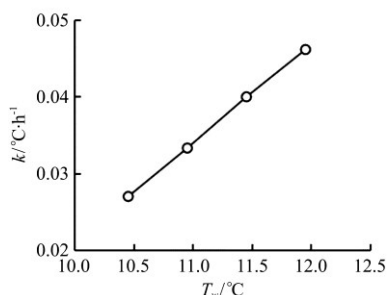


Figure 4 Decrease rate of the water temperature in the reservoir

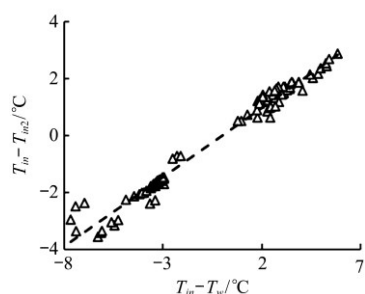


Figure 5 The efficiency of the fan-coil unit ( $\eta$ )

Based on the estimated  $k$ ,  $\eta$ , and  $T_{in}$ ,  $T_w$  in the experimental period was simulated based on the dynamical model except for the period from Jan. 8, 9:00 to Jan. 9, 9:00, since the heat pump was applied during this period. The results show that the measured  $T_w$  fitted well with the simulated  $T_w$ . The average error and average percentage error are 0.12°C and 1.1%, respectively. The maximum error was 0.8°C. Thus, the developed model can be used to describe the variation of  $T_w$ .

In this study, a constant  $\eta$  was used to simulate  $T_w$ . During the period of air thermal energy collection, the air temperature at the outlet of the fan-coil units may be lower than the dew point. The water vapor in the air can be condensed. Then, both sensible and latent heat of the air can be collected by the fan-coil unit. When there is no condensation in the heat collection process,  $\eta$  of a given fan-coil unit is a function of the wind speed and water speed<sup>[32]</sup>. In this experiment, both wind speed and water speed were constant. The condensation was also not observed. Thus, it is feasible to apply the constant  $\eta$  to simulate  $T_w$ . If condensation occurs, the energy released due to the condensation of

water vapor in air should be involved. Otherwise,  $T_w$  in the heat collecting process is underestimated.

In addition, the simulated  $T_w$  more quickly increased and decreased in the heat-collecting and releasing processes than the measured value. As a result, the percent errors between the calculated  $E_c$  and  $E_r$  with the measured  $T_w$  and those calculated with the simulated  $T_w$  were 1%-7% and 4%-11%, respectively. This difference may be caused by the assumption that all nine fan-coil units had identical  $\eta$ . Some fan-coil units may have smaller  $\eta$  and made the actual heat exchange of the fan-coil units lower than the simulated value. To avoid the estimation, the calculated  $E_c$  and  $E_r$  with the simulated  $T_w$  were multiplied by 96% and 93%, respectively, and applied for further analysis.

Based on the above analysis, the heat loss of the water reservoir decreases both  $E_r$  and COP. According to the developed model, the decrease in  $T_w$  in the early night of sunny days can be eliminated by making  $k$  equal 0 (Figure 6). With the simulated  $T_w$ , the calculated  $E_c$  was not improved due to the consideration of the simulating error. However, the calculated  $E_r$  was increased by 6%-22%. Then, the COP was 1.7-2.4. Thus, by improving the heat insulation performance of the water reservoir, more heat can be recovered to heat the LPTEB at night.

**Table 3 Heat-collecting and -releasing performances of the ATEUS under different conditions**

Conditions	Date	$E_c$ /MJ	$E_r$ /MJ	COP
$k=0$	Jan. 05	542.7	496.21	2.2
	Jan. 06	512.4	371.2	2.4
	Jan. 07	397.9	443.3	2.2
	Jan. 09	381.9	410.1	1.9
	Jan. 10	320.3	362.9	1.7
$T_{in}=25^\circ\text{C}$	Jan. 05	846.1	647.5	2.5
	Jan. 06	812.2	491.2	2.7
	Jan. 07	645.6	559.9	2.4
	Jan. 09	640.6	540.2	2.2
	Jan. 10	535.1	486.7	2.0
$k=0$ and $T_{in}=25^\circ\text{C}$	Jan. 05	870.8	746.4	3.3
	Jan. 06	828.7	597.5	3.8
	Jan. 07	644.4	670.6	3.3
	Jan. 09	659.1	622.7	2.9
	Jan. 10	552.4	548.6	2.5

According to Equation (4), a higher  $T_{in}$  in the daytime of sunny days corresponds to a larger achievable  $E_c$ . If  $T_{in}$  in the period of air thermal energy collection can be increased to 25°C,  $T_w$  can increase in both daytime and nighttime of sunny days (Figure 5). The maximum  $T_w$  can be 3.3°C higher than that in the experiment. Then,  $E_c$  and  $E_r$  can increase to 535.1-846.1 MJ and 486.7-647.5 MJ, which are 50%-65% and 38%-62% higher than those under experimental conditions, respectively. The COP can reach 2.0-2.7. Nevertheless, the increased  $T_w$  can encourage the heat loss of the water reservoir. A decreasing  $k$  will further improve the heat-collecting and releasing performances of the ATEUS. By making  $k$  equal 0 and increasing  $T_{in}$  in the period of collecting thermal energy from the air to 25°C,  $E_c$  and  $E_r$  can reach 552.4-870.8 and 548.6-746.4 MJ, which are 49%-70% and 59%-97% higher than those under experimental conditions, respectively. Then, the COP is 2.6-3.8, and the developed system can efficiently save heating energy.

By maintaining  $T_w$  at a low level in the daytime or a high level at night, it is helpful to enlarge the difference between  $T_w$  and  $T_{in}$  and benefit the heat collection or heat release of the ATEUS. Thus, a heat pump can be employed to control the temperature  $T_w$ .

However, this measurement will increase the investment and operation costs<sup>[31]</sup>.

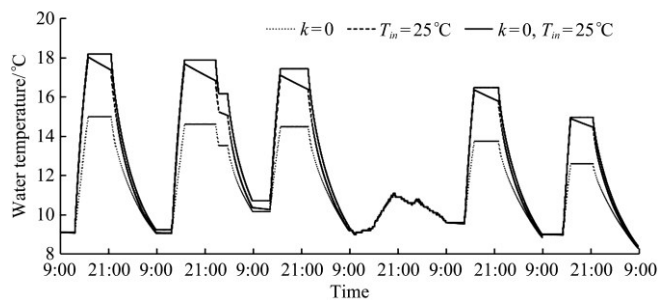


Figure 6 Effects of different conditions on water temperature

### 3.5 Economic analysis

In this experiment, the total cost of establishing ATEUS was 38 000 CNY (CNY is abbreviated of Chinese Yuan), including the fan-coil cost was 14 000 CNY, the water reservoir construction cost was 20 000 CNY, the supply and return water pipe and accessories cost was 2000 CNY, the cost of water pump and electrical control equipment was 2000 CNY. The operation of the heat pump was not taken into account, so its cost was not included. The total electricity consumption of ATUES was 281.7 kW·h in the experiment. According to the local agricultural electricity price of 0.473 CNY/(kW·h), the total operating cost of ATUES was 133.2 CNY. The total heating capacity of ATUES at night was 1873.9 MJ, which was equivalent to burning natural gas at 71.2 m<sup>3</sup>. Under the same test conditions, the heating cost of burning natural gas was 140.3 CNY, and the operating cost of ATUES was slightly lower.

The use of the system requires a certain cost of construction and operation, but the operation effect is still obvious, in addition, to avoid the use of non-renewable energy.

## 4 Conclusions

In this study, the heat collecting and release performances of the ATEUS developed with fan-coil units were tested in an LPTEB. The ATEUS could collect the air thermal energy in the daytime on sunny days and store it in the water reservoir. It could also recover the stored heat at night to heat the LPTEB. Based on the test and simulation results, the following conclusions were obtained:

1) On sunny days, the ATEUS collected 324.2-563.2 MJ of air thermal energy in the daytime and released 303.9-468.7 MJ of thermal energy at night. The COP of the ATEUS was 1.6-2.1. However, the ATEUS failed to collect air thermal energy on cloudy days.

2) The water temperature model constructed in this paper has high accuracy. Based on this model, the collected air thermal energy in the daytime and the released thermal energy at night on sunny days can be increased by 49%-70% and 59%-97%, respectively, by diminishing the heat loss of the water reservoir and increasing  $T_{in}$  in the period of collecting thermal energy from the air to 25°C. The COP reached 2.6-3.8.

3) In terms of economy, the construction cost of ATEUS was relatively high. The whole system cost 38 000 CNY under the test conditions, but its operating cost was lower than the heating cost of burning natural gas under the same conditions. The operation effect of ATEUS was obvious and avoided the use of non-renewable energy.

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