# PERFORMANCE OF SOLAR HOT-WATER INSTALLATIONS FROM ROOF-CONSTRUCTED SOLAR COLLECTORS INTEGRATED WITH A CENTRAL HEATING SUPPLY FOR TOBACCO CURING

by

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*In view of the abundant solar energy available during the tobacco curing season, a solar hot-water installation to provide auxiliary heating for bulk tobacco-curing operations was developed, based on the original concept of a boiler-driven central heating supply that transported hot water over short distances by pipeline, using solar collectors connected in parallel and installed on the unoccupied flat roofs of 20 curing barns. The results showed that daily solar conversion efficiency ranged from 65% to 67%. During the tobacco curing period from 10:00 hours to 14:00 hours each day, in sunny or partly cloudy weather, heating water temperatures exceeding 75 °C were automatically derived for use in the bulk curing barns needed. Use of solar energy as a substitute for coal fuel in tobacco curing, in conjunction with precise automatic control, enabled solar energy to account for 18.4% of the total curing energy consumption in this study. Through comparative analysis, the use of solar hot-water installations can help the local tobacco industry to reduce absolute carbon emissions by more than 10% at the experimental location in the pay-back period.*

Key words: *agriculture drying, auxiliary heating energy, bulk curing barn, heat exchanger, dry- and wet-bulb temperatures*

## Introduction

Bulk curing barn is the place where flue-cured tobacco is cured. To reduce the use of building materials in China, a single building unit of bulk curing barns comprises five barns built together in parallel as a single connected unit (15.12 m long × 11.44 m wide) [1]. Their construction, which is funded by local tobacco companies, is of bricks and timber, with flat steel-bar reinforced-concrete rooftops. A single bulk curing barn group typically comprises four to six single building units [2].

Curing energy consumption in tobacco production is high, with farmers using fuels such as coal or firewood to cure flue-cured tobacco leaves [3, 4]. To address these high consumption costs, a boiler-driven central heating supply that transports hot water over short distances by pipeline is widely applied [5, 6]. The potential use of the unoccupied flat rooftops of the barns is currently being developed.

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One of the most attractive and promising applications of solar energy for cash crops is the use of solar-assisted drying systems [7] first developed two types of solar greenhouse designs and investigated the technical feasibility of using hot air produced by solar energy for curing tobacco in a single bulk barn. Despite providing a relatively small percentage of total global energy supply, solar energy systems generally receive enthusiastic support from technologists' groups [8, 9]. Later, Indian and Chinese tobacco researchers built a solar heating air system on the unoccupied roof of a single barn that was used only in the yellowing period of tobacco curing (TC) [10, 11]. For the last few years, the development of computer microtechnology provides the feasibility for controlling agricultural production exactly by using controller [12]. At the same time, the concept of a dryer powered by solar energy is becoming increasingly feasible because of the gradual reduction in the price of solar collectors ordered [13]. Appling mature microcomputer technology, Wang *et al*. [14] precisely controlled a new device that heat pump associated with solar-energy heat supply using hot air for TC in a single bulk curing barn, and the curing cost saving of 21% per kilogram of dry tobacco leaves is achieved. However, the type of solar hot-water installations (SHI) for TC is not reported.

In view of the abundant solar energy available during TC season, the objective of this work were to develop and investigate the performance of SHI, using hot water as the transfer fluid from rooftop-constructed solar collectors, to provide auxiliary heating energy to assist the original hot-water boiler of the central heating system for TC.

## Materials and methods

### *Equipment description of principle and structure*

The working principle of the solar-energy integrated central heating supply system is shown in fig. 1, which has two separate heating systems with the existing boiler equipment and newly added SHI. Using an automatic hot-water controller, the heat is automatically distributed by pumping to heat exchangers in the heating chambers of the bulk curing barns.

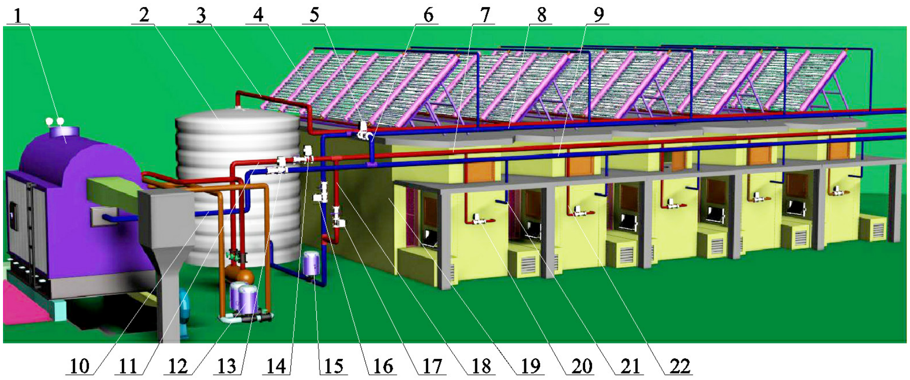


**Figure 1. Components of solar energy integrated central heating supply system for bulk tobacco curing;** *1 – boiler equipment, 2 – hot-water storage tank (HST), 3 – water return pipe for solar-energy collecting and water-heating array (SC) to HST, 4 – SC, 5 – electric water-control valve 1 (V1), 6 – shift pipe of cool water (between the boiler and SHI), 7 – main inlet pipe for hot water, 8 – water inlet pipe for HST to SC, 9 – main return pipe for cool water, 10 – special cool water pipe for boiler, 11 – special hot water pipe for boiler, 12 – electric water recycling pump 1 for heat supply of boiler (P1), 13 – V2, 14 – V5, 15 – electric water recycling pump 2 for inner water circulation or heat supply of SHI (P2), 16 – V3, 17 – V4, 18 – shift pipe of hot water (between the boiler and SHI), 19 – a single building unit, 20 – electric water-control sub-valve for barn, 21 – branch return pipe for cool water (out of bulk curing barn), 22 – branch inlet pipe for hot water (into bulk curing barn)*

### *Solar hot-water installation*

The SHI includes SC, electronic water-control valves, a power-driven water pump, a HST, water return pipe for SC to HST, water inlet pipe for HST to SC, and sub-pipeline. The SC equipment specified was an evacuated collecting and water-heating array (Haier Q-B-J-1-130, China) with 78% average collector efficiency. The array was installed on the roofs of the bulk curing barns, facing due south and oriented at an angle of 45° from the horizontal in order to increase solar energy collecting area. Each barn had six arrays, measuring 2200 mm × 1500 mm (height × width), which were connected in series through their water inlet and return pipes. The arrays were then connected in parallel with those on the neighboring rooftop. The study of one bulk curing barn group therefore involved a total of 20 barns and 120 solar-energy collecting and water-heating arrays, which gave a total solar-energy collecting area of 396 m$^2$.

### *Atmospheric-pressure hot-water boiler*

The boiler is a key component in the integrated central heating supply. The boiler had a capacity of 2 tons, a combustion ratio of 99%, and a water heat-exchange rate of 80.2%, which was capable of heating water to a temperature of 75-95 °C at atmospheric pressure.

### *Energy supply and utilization for a single barn during tobacco curing*

For good heat exchange, the temperature of the hot water entering the heat exchanger must be at least 6 °C higher than 68 °C [5]. Depending on the water temperature in the HST, SHI or boiler provide independent heating systems controlled by the automatic hot-water controller for their hot-water cycles: when the water temperature in the HST exceeds 75 °C, which represents about 1 °C of heat loss in the pipeline, the solar cycle preferentially uses only the solar thermal energy systems and when the water temperature in the HST is below 75 °C, the boiler cycle applies, in which case heat energy is supplied only by the boiler systems. The two cycles can be switched on or off using the electric water-control valves and the pumps opens or closes automatically as determined by the automatic hot-water controller. When hot water moves through the heat exchangers of the barns requiring curing heat, heat is transferred to the air of the heating chambers, and the water temperature will decrease to the point that it maybe not meet the required curing temperature and needs to be reheated to 75 to 95 °C. After reheating, the same cycles are repeated.

As shown in fig. 2, each barn is a basic curing unit that is equipped with a water-air-type heat exchanger in the heating chamber where curing energy carried by the hot water is exchanged with flowing air driven by a circulating fan: hot air rose to the upper section of the barn, flowed downward for curing in the loading chamber, and then returned to the heat-exchange chamber. According to the dry-bulb temperatures of the air in the loading chamber of a barn,

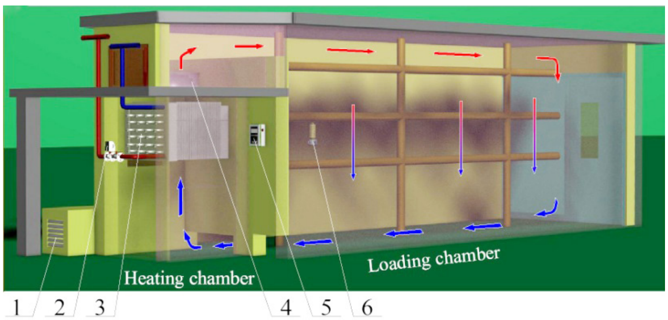


**Figure 2. Diagram of interior structure of a single bulk curing barn;** *1 – moisture-expelling louver for each barn, 2 – electric water-control sub-valve for each barn, 3 – heat exchanger (water-air-type), 4 – circulating fan, 5 – automatic tobacco-curing controller, 6 – sensors of dry-bulb and wet-bulb temperatures. Note: The arrow indicates the direction of the cyclic air*

the automated tobacco-curing controller managed by the special curing technician, governed via the water-control sub-valve for barn, allowed hot water to move into the heat exchanger and also regulated the flow rate. When the heat requirement of a barn was met, its own automated tobacco-curing controller switched off the electric water-control sub-valve for barn, stopped the heated water from entering the heat exchanger, and the hot water passed forward through the main inlet pipe for hot water.

*Auxiliary equipment and facilities*

The auxiliary equipment and facilities to distribute hot water from SHI or the boiler equipment to each barn included two electric water pump (P1 and P2) that provided power for outer or inner hot-water circulation (1-DG series boiler feed pump with a capacity of 11 kWh), five high-temperature solenoid valves (V1, V2, V3, V4 and V5) (ZCZG-D115), water inlet and return pipeline (main trunks of 110 mm diameter and branches of 60 mm diameter), and heat-insulating material to insulate the water pipes. The major ancillary supporting equipment was the HST, which had a capacity of 50 m$^3$.

***Test calculations***

The HST received solar heating of water per day $Q_w$ [J] given:

$$Q_W = \mathrm{c}_w V \rho_{hw} (T_{en} - T_{ST}) \tag{1}$$

where $C_w$ is the specific heat capacity of water, 4180 J/kg°C, $V$ [m$^3$] – the volume of the water storage tank, $\rho_{hw}$ [kgm$^{-3}$] – the density of hot water, $T_{en}$ [°C] – the temperature of hot water, and $T_{st}$ – [°C] the initial water temperature.

The daily efficiency of the SC $\eta_{cd}$ was given:

$$\eta_{cd} = \frac{Q_w}{A_c J_D} \tag{2}$$

where $A_c$ [m$^2$] is the total solar energy-collecting area and $J_D$ [Jm$^{-2}$] – the average daily solar radiation received by per unit area.

The curing energy received from solar heating or the boiler $Q_{\text{solar or boiler}}$ [J] given:

$$Q_{\text{solar}} = \sum_{i=1}^{n} [G_i c_w (T_{sui} - T_{rei}) \tau_{in}] \tag{3}$$

where $G$ [kgs$^{-1}$] is the flow rate specific heat of the hot water, $T_{su}$ [°C] – the temperature of the hot water supply through the main inlet pipe for hot water, $T_{re}$ [°C] – the return water temperature through the main return pipe for lower temperature hot water, and $\tau_{in}$ [s] – the time interval used for which the solar heater or boiler operated on by the automatic hot-water controller in the integrated central heating supply.

The solar water heating system provided the percentage of total curing energy $P_{\text{solar}}$ given:

$$P_{\text{solar}} = \frac{Q_{\text{solar}}}{Q_{\text{solar}} + Q_{\text{boiler}}} \tag{4}$$

***Materials***

The study was carried out in Jiaxian of Pingdingshan, Henan (33°00 N, 113°06 E), China, a region where tobacco has been grown for more than 100 years. The study was conducted between July 5 and September 21 in 2014 and 2016, which is the sunny dry period of the year from July to September when tobacco leaves are harvested and cured.

The study farms planted Zhongyan 100, a standard tobacco production variety, and chose normally maturing leaves as its test materials. The bulk curing barns, described in fig. 2, had a fresh-leaf loading capacity of about 4000-4500 kg per batch per barn. The leaves were cured following local practices: harvested fresh leaves were tied to tobacco hanging clips, with about 130 leaf bundles per clip, and were hung on the carrying beams of the bulk curing barns.

### *Measurement instruments*

To investigate effects of environmental and operating parameters on the performance of SHI, various measuring devices were employed. On the three days before the first and after the last curing day, solar radiation was measured using a radiometer (TBQ-2-B, Beijing Hsc Measurement Technology Co., Ltd., China) placed beside the solar array. A thermocouple temperature data logger (KTT 310, Shenzhen BoRui Instrument and Meter Co. Ltd., China) was employed, using a measurement interval of 10 minutes, to synchronously measure the water temperatures of the HST and points V1, V2, V3, V4, and V5 marked in fig. 1. When SHI or boiler began to providing heat for TC, the hot-water flow rate of the shift pipe of cool water and hot water (between the boiler and SHI) and the special hot water pipe for boiler was measured using a digital flow meter (LDBEKY-DN80; Tianjing YouYi Co. Ltd., China). GraphPad Prism 5.0 software analysed the experimental data.

## Results and discussion

### *Daily and curing temperature changes of hot water in the solar system*

A plot of daily temperature changes of hot water in the HST and the shift pipe of cool water (between the boiler and SHI), during the curing season on days with sunny or partly cloudy weather is shown in fig. 3. Temperature fluctuations of the ambient air were in the ranges of 23-32 °C and 17-27 °C from June to September. The maximum temperature of 80 °C occurred around 12:00 hours and the minimum temperature of 69 °C was reported at 4:00 hours. The SHI provided hot water for TC for about 4-5 hours working time per day. As the water moved through the heat exchangers, it was heated to above 75 °C in the shift pipe of hot

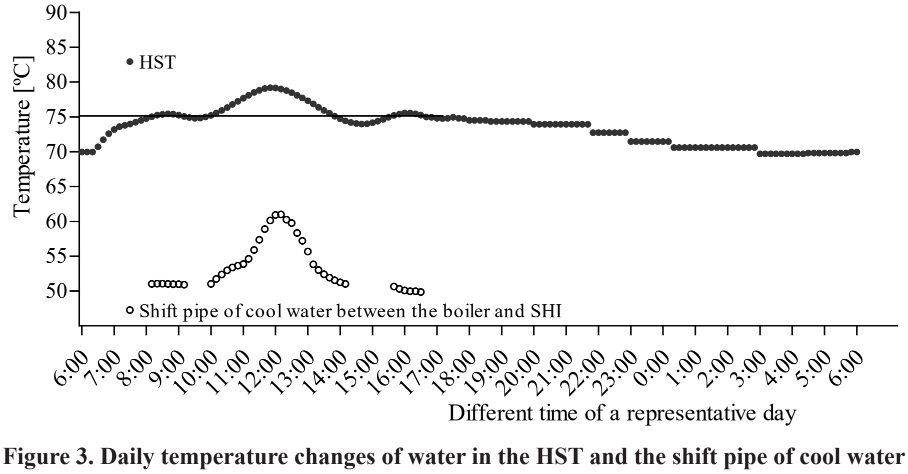


**Figure 3. Daily temperature changes of water in the HST and the shift pipe of cool water**

water and would fall to 49-61 °C in the shift pipe of cool water, giving a temperature difference of 18-26 °C between them when SHI was being used for TC in the different barns.

### *Efficiency of solar hot-water installation*

The variations in the temperature of the hot water in the HST during the three days before and after the tobacco-curing period and the efficiency of SHI are shown in fig. 4. The slope of the curve of temperature of the stored water decreased with time, indicating that, as the temperature of the stored water rose, the solar arrays converted solar energy into thermal energy at a decreasing rate. As the curing period shifted from July to September and the seasonal temperatures dropped, the efficiency of SHI tended to decline. The temperature of water moving out of the heat exchangers of the bulk curing barns generally ranged within 49-61 °C, fig. 3. Using this as a baseline temperature, the average daily efficiency $\eta_{cd}$ of the solar system for TC ranged within 65-67%.

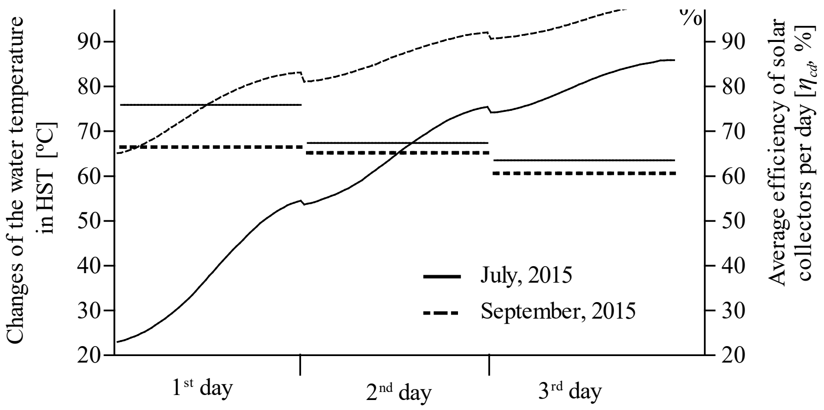


**Figure 4. Temperatures changes in HST of the three-day periods before and after curing and average efficiency of SHI**

Solar collecting area and irradiation are the two main factors effecting solar-energy collection efficiency [15]. Increasing the collecting area using idle land close to the curing barn groups can also directly increase the proportion of solar energy available for curing in the resource-rich regions. On the thermal efficiency of the solar-self collector with hot water, the collection efficiencies above 94% have recently been achieved by [16]. Many environmental policies that encourage use of solar energy have been issued by the government [4]. These have great significance for fossil-fuel energy savings in the TC industry in the near future.

### *Proportion of solar-generated energy consumed by curing*

The proportions of energy used for TC relative to total consumed energy were calculated according to eq. (4). The SHI provided 18.4%, while the boiler provided more than 81.6% of the total energy required for curing.

### *Economic evaluation*

To evaluate the economics of the roof-constructed SC, the dryer was assumed to be used for more than two months (July to September) for flue-curing of tobacco, with six batches being treated per bulk-curing group. An additional electricity cost for SHI is required for internal recycling of hot water. The economic benefit of the collectors functioning as heat insulators for the roof was not taken into account. Based on current Chinese data, the costs and economic parameters are shown in tab. 1. The pay-back period, calculated using the method described by Thuesen *et al.* [17], was 11.6 years. Glass and metal are the main raw materials of the SHI, which have a thermal efficiencies of energy consumption of 60-68% and 69.9% during their production process from raw materials to finished products, respectively [18, 19]. Their thermal efficiency is higher than that of coal when used as a fuel for TC with typically less than 36.2% for a single bulk barn [20]. Excluding labor costs for construction and financing costs, this suggests that, additionally, such a solar-energy integrated central heating supply subsystem itself for TC could reduce $CO_2$ emissions over the life span of the SC by more than 10%.

**Table 1. Cost and economic parameters**

| Economic parameters | Cost |
|---|---|
| Material cost for the construction of SC | US$ 11,400 |
| Cost of HST | US$ 2,540 |
| Pump, pipes, valves, and heat-insulating material | US$ 13400 |
| Labor cost for the construction | US$ 2400 |
| Interest rate | 4.2% |
| Electricity cost | US$ 0.10 kWh |
| Cost of coal fuel (Combustion value of 22 844 kJ) | US$ 0.10 kg |
| Salvage value of SHI | US$ 1,300 |
| Life span of SC | 15 years |
| Obtaining solar energy for TC | 387.6 GJ |

## Conclusion

A solar energy-collecting and water-heating array was developed and tested as an auxiliary heat source for TC. Compared with the original central heating system, solar energy accounted for 18.4% of the total curing energy consumption that could be supported by the boiler heating system alone. Use of the experimental solar heat as a substitute for fuels burning can help the local tobacco industry to reduce absolute carbon emissions by more than 10% at the experimental location in the pay-back period. Considering the pay-back period of the SHI, the duration of the curing season is relatively short, so such an integrated central heating supply could be made more competitive for warming houses for local residents or for drying of other local cash corps out of the tobacco-curing season.

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