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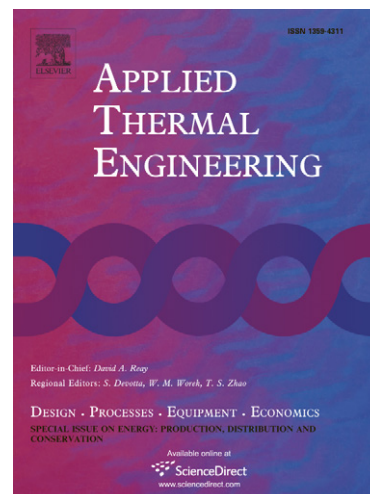
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**Experimental study of the temperature field in a solar chimney power setup**

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**Abstract**

A pilot experimental solar chimney power setup consisted of a 5m-radius air collector and an 8 m-height chimney has been built. The temperature distribution in the solar chimney power setup was measured. Temperature difference between the collector outlet and the ambient usually can reach 24.1°C, which generates the driving force of airflow in the setup. This is the greenhouse effect produced in the solar collector. It is found that air temperature inversion appears in the latter chimney after sunrise both on a cool day and a warm day. Air temperature inversion is formed by the increase of solar radiation from the minimum and clears up some time later when the absorber bed is heated to an enough high temperature to break through the temperature inversion layer and make air flow through the chimney outlet.

**Keywords:** Solar chimney; Collector; Temperature field.

**1. Introduction**

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The concept of solar chimney power technology was first conceived in 1931 by a German author, Hanns Gunther, and has been proven with the successful operation of a pilot plant constructed in Manzanares, Spain in the early 1980s by Professor Schlaich with the support of both the German government and a Spanish electric company [1]. The project works on the principle that in the collector, solar radiation is used to heat an absorber (ordinarily soil or water bags) on the ground, and then a large body of air, heated by the absorber, rises up the chimney, due to the density difference of air between the chimney base and the surroundings, driving large turbines to generate electricity. The collector had a radius of 122 meters while the chimney was 194.6 meters tall with a diameter of 5.08 meters. The plant produced an upwind velocity of 15m/s under no load conditions [2]. The highest power output reached 41 kW from July to September in 1982 [3].

Since then, more and more researchers have been strongly interested in and studied this solar power technology which has huge potential applications world-wide [3-10]. In 1983, the American scientist Krisst built a courtyard solar chimney power setup with a power output of 10 W. Its collector had a diameter of 6 meters while the chimney was 10 meters tall [4]. In 1997, three different power demonstration models of solar chimney were built in the campus of the University of Florida, and both theoretical and experimental research on their performance was done [5]. Bernardes et al presented a thermal and technical analysis by computer-aided calculation [6]. In 2000, Von Backström and Gannon developed a one-dimensional compressible flow approach to

calculate all the thermodynamic variables depending on chimney height, wall friction, additional losses, internal drag and area change [7]. In 2003, they also carried out an investigation of the performance of a solar chimney turbine [8]. In 2005, Schlaich described the design of a commercial solar updraft chimney power system, presenting theory, practical experience, and economic analysis of solar updraft towers [9]. A program [10], to construct a solar chimney power plant with a power output of 100MW in a desert, in Rajasthan, India, was scheduled, but then was aborted owing to the potential danger of nuclear competition between India and Pakistan. Recently, the Australian government decided to support a proposed solar chimney power plant with a 1000m chimney in Mildura, Australia, which can produce 200 MW of electric power, and is expected to be constructed in 2006 [11].

The above work mainly focused on structure models, efficiency of energy conversion and other related problems for solar chimney power technology. However, a detailed analysis of the measured temperature fields for solar chimney power systems has never been reported.

We have undertaken research on the performance of solar chimney power plants with the support of the local government, in China. A pilot solar chimney power setup was designed and built in 2003. This paper reports a detailed analysis of the measured temperature field in the experimental setup.

## **2. Experimental procedure**

### **2.1 Building of a pilot setup**

In order to perform a detail investigation into the measured temperature field in solar chimney power system, a pilot experimental setup shown in Fig.1 consisted of a 5m-radius air collector and an 8 m-height chimney was built in HUST, in China.

The slope angle of the conical collector is chosen to maximise absorption of solar radiation when the slope angle of the collector is equal to local latitude [5]. Wuhan is 30° north [12]. If the slope angle of collector is 30°, the height from the collector outlet to the ground level would be  $5 \times \tan 30^\circ$  m. Because of construction costs, the actual slope angle of the collector was chosen as 8°, and the height from the collector outlet to the ground level was therefore 0.8m.

The size of the opening at the periphery of the collector was chosen as 0.05m, and was constructed to be readily adjustable.

Optimising cost and strength, standard PVC drain-pipes were used as a chimney. The maximum size of a PVC drain-pipe was 0.3 m diameter  $\times$  4m in the market. The diameter was not big enough so that frictional loss during airflow in the chimney was sufficient to reduce final power output and therefore the chimney should not be too high. The chimney was made of two connected PVC pipes, giving 8 m height and 0.3 m diameter.

The main parameters of the solar chimney power setup shown in Fig.2 are listed in Table 1.

Since a building space of more than 10m in diameter is needed, and to avoid the shadow of buildings on the collector, the solar chimney power setup was built on the

roof of a building in HUST, in China.

The 10 m diameter collector was a single layer of transparent glass. The framework was constructed of angle iron (0.03×0.03m and 0.05×0.05m) to ensure enough strength to resist strong winds, heavy rain and snow because the experimental setup was located outdoors. In order to produce a greenhouse effect, transparent material was used to cover the framework of the collector. The function of the absorber bed on the ground under the collector is the absorption and storage of solar energy. So it is necessary to lay insulation materials below the absorber bed to reduce heat losses through the building roof. On top of the insulation materials 25 cm of mixed asphalt and black gravel was placed as the absorber. Black materials can collect most solar energy and maximise the conversion efficiency from solar energy to heat energy [13]. A heat insulator was packed round the steel-frame structure of the collector to avoid heat diffusion through the steel-frame.

The whole experimental setup with a design power of 5 W, shown in Fig.1 (a), was built in January in 2003. At the base of chimney was installed a removable cylinder with a flange, shown in Fig.1 (b), within which in turn were installed a multiple-blade turbine and a generator. The turbine, the blades of which were about 0.14 meters length, was designed and manufactured by ourselves according to the operating principles of turbine blades [14]. The generator, commercially available, was a permanent magnetism motor with direct current. The updraft drives the turbine at the base of the chimney, and thus drives the generator to generate electricity.

## 2.2 Measuring the temperature distribution

Platinum resistance thermometer sensors (Pt 100) were used to measure air temperatures.

We chose 12 typical points in the north-south section through middle axis, as shown in Fig.3. In the Figure, for that the heights of sensors can be freely adjusted, the points of 1#-8#, distributed in the collector, were used to measure air temperatures at different heights in the collector. While, the points of 9#-12#, distributed in the chimney, were used to measure the temperatures of air in the center of the chimney. Further, a mercury thermometer with an accuracy of  $\pm 0.5^{\circ}\text{C}$  was fixed outside the setup to measure the ambient temperature. A thermal anemometer with the accuracy of  $\pm 0.01$  m/s is used to measure the velocity of airflow.

Measurements were transferred automatically to a data collecting device every ten minutes.

## 3. Results and discussion

### 3.1 Temperature field

In the course of experimental measuring, the turbine-generator is under no load conditions

Taking the experimental results obtained in the solar chimney power setup on May 1st, 2003 at 15:30 as an example, the distribution of air temperatures at different heights above ground level in the setup are shown in Fig.4 and Fig.5.

Fig.4 gives the variations of air temperature within the collector both near the ground

and at one third of the height of collector roof above the ground level. From Fig.4, some conclusions can be drawn as follows:

(1) The variations of air temperatures in the northward and the southward collector are basically similar. However, the air temperatures at points of 5#-8# in the south are a little greater than those at points of 1#-4# in the north because the setup is located in the Northern Hemisphere where the southward sloping surfaces of the collector will obviously absorb solar radiation with higher efficiencies than northward sloping and southward sloping surfaces of the collector. Further, the temperatures usually increase from the periphery to the center. The temperatures at point of 5# are usually the highest, since that the point of 5# is located in the south and near the center of the collector. In contrast, the results at point of 1# are the lowest, because point 1# is located in the north and close to the collector opening.

(2) Air temperatures decrease with increase in height above ground level, which is induced by the greenhouse effect. The variation of air temperature is in agreement with those in refs 15 and 16. Solar radiation firstly heats the absorber bed, and cool air obtains heat from the heated absorber bed mainly by free convection and infrared radiation.

(3) The ambient temperature on May 1st, 2003 at 15:30 was 25.1 °C. Point 9# is in the center of the chimney inlet, which is also the collector outlet. Associated with the results in Fig.5, the temperature difference between the collector outlet and the ambient air can reach 24.1 °C, which generates the driving force of airflow in the solar chimney

power setup. This is the greenhouse effect produced in solar collector.

(4) As shown in Fig.5, air temperature decreases with increase in height up the chimney. As hot air rises up the chimney, the heat of air is mainly lost in succession to ambient through the chimney walls in the effect of heat convection of stronger wind on the building roof.

### 3.2 Daily variation

Taking the experimental results obtained on January 12th, 2003 as an example, distributions of air temperature in the setup at different times of day from 09:45 to 17:00 were measured, and are shown in Fig.6-Fig.8.

During a typical day, air temperatures in both collector and chimney increase from sunrise, reach a maximum at about 13:30, and then decrease with time as solar radiation becomes increasingly weak.

This mainly depends on the fact that before dawn the absorbing bed has released almost all heat stored in it the day before, and is first heated by solar radiation after sunrise, and its temperature thereafter keeps increasing. In the afternoon, as solar radiation becomes weaker, the heated absorber bed, storing large quantity of heat, releases heat to the air by free convection and infrared radiation, resulting in continuous reduction of its temperature with time.

Fig.7 shows the distributions of air temperatures in the chimney on a typical cool day. Fig.8 shows distributions of air temperatures in the chimney on May 1st, 2003 from 09:20 to 13:40, a typical sunny day (the ambient temperature: 28 °C). As seen from

Fig.7 and Fig.8, the distributions of chimney air temperatures on both days are similar. As can be seen from Fig.7, on the typical cool day, air temperature inversion in the chimney appears in the morning and clears up in the afternoon. It's also seen from Fig.8 that air temperature inversion in the chimney appears before 09:50 and clears up after 09:50. Nevertheless, the temperature distribution in the vertical direction in the collector keeps normal, even if air temperature distribution is inversed in the latter chimney, proved by an example of air temperature distribution in the vertical direction in the collector obtained at 09:25 on May 1st, 2003 as shown in Fig.9.

Without doubt, the indoor air in the pilot setup is nearly equal to the ambient before sunrise. When sunrise, the main function of the absorber bed on the ground is the absorption and storage of solar radiation. Its temperature is usually low, only generating a small driving force, but the air can hardly flow out from the chimney outlet due to the heat loss through the chimney walls and along the chimney. In the small driving force, the air rises along the chimney with its temperature decreasing, and then recirculates with lower velocity according to the mass conservation. Most of energy loss around recirculation is used to heat air inside the latter chimney. So, the air inside the latter chimney is in succession heated by the energy loss of the updraft to form the temperature inversion, whose temperature is usually 2-5 °C higher than that at the point of 11#, shown in Fig.7-Fig.8.

Naturally, temperature inversion appears which to some extent restricts the flowing of air in the chimney. So air is heated mainly by heat conduction and infrared radiation from the

absorber bed. Temperature inversion to some extent restricts the flowing of air in the chimney. Only when indoor air is heated to a high enough temperature to generate an upward driving force strong enough to break through the temperature inversion layer and make air flow through the chimney outlet, temperature inversion will clear up. After that, air, continuously heated mainly by free convection and infrared radiation from the heated ground, normally flows from the collector opening to the chimney outlet. Outflow of air from the top of the chimney is also the reason why the variation of collector air temperatures from the periphery to the center in the afternoon is smaller than that in the morning, as shown in Fig.6.

It's found that the temperature inversion is produced due to the increase of solar radiation from the minimum. As seen from Fig.7 and Fig.8, the temperature inversion clears up at the earlier time of 09:50 on the warm day than that on the cool day. This depends on the fact that the stronger solar radiation heats the absorber bed faster in summer.

#### **4. Conclusion**

In order to investigate the temperature field as well as to examine the effect of time of day on the temperature field, a pilot experimental setup was built in HUST, in China. The glass collector with a 10 m diameter was built on a steel-frame structure. The chimney, 8m height, was made from two PVC drain pipes with a diameter of 0.3m. In this paper, on the basis of the experimental temperatures measured in the solar chimney power setup, we analyzed the temperature distribution in solar chimney power system.

Temperature difference between the collector outlet and the ambient usually can reach 24.1°C, which generates the driving force of airflow in the setup. This is the greenhouse effect produced in the solar collector. It is found from the analyses of temperature distribution in the solar chimney that air temperature inversion appears in the latter chimney after sunrise. Air temperature inversion in the chimney appears first thing due to the increase of solar radiation and clears up when indoor air is heated to a high enough temperature to generate an upward driving force strong enough to break through the temperature inversion layer and make air flow through the chimney outlet.

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**Fig. 1 Picture of the experimental solar chimney power setup**

**(a) Overall picture of solar chimney**

**(b) Turbine - generator installed at the base of solar chimney**

**Fig.2 Schematic diagram of solar chimney power setup**

**Fig.3 Distribution of temperature - measuring points in solar chimney power setup**

**Fig.4 Distributions of air temperatures at different heights above the ground level in solar collector on a typical warm day (ambient temperature at 15:30: 32.5 °C, updraft velocity in the chimney at 15:30: 2.13 m/s)**

**Fig.5 Distribution of air temperatures at different heights in solar chimney on a typical warm day (ambient temperature at 15:30: 32.5 °C, updraft velocity in the chimney at 15:30: 2.13 m/s)**

**Fig.6 Distributions of air temperatures in solar collector at the different daytime from 09:45 to 17:00 on a typical cool day (average ambient temperature: 9 °C, maximum updraft velocity in the chimney: 1.22 m/s)**

**Fig.7 Distributions of air temperatures in solar chimney at the different daytime from 09:45 to 17:00 on a typical cool day (average ambient temperature: 9 °C, maximum updraft velocity in the chimney: 1.22 m/s)**

**Fig.8 Distributions of air temperatures in solar chimney at the different daytime from 09:20 to 13:40 on a typical warm day (average ambient temperature: 28 °C, maximum updraft velocity in the chimney: 2.81 m/s)**

**Fig.9 Air temperatures at different heights above the ground level in the**

northward solar collector on a typical warm day (ambient temperature at 09:25:

23 °C)

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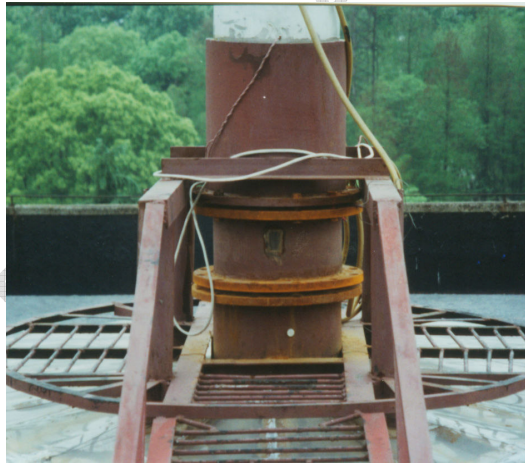
**Table 1** Main parameters of the solar chimney power setup

<b>Parameter</b>	<b>Symbol</b>	<b>Value/m</b>
<b>Collector diameter</b>	<i>D</i>	<b>10</b>
<b>Height from collector outlet to ground level</b>	<i>H</i>	<b>0.8</b>
<b>Size of the opening at the periphery</b>	<i>H<sub>p</sub></i>	<b>0.05</b>
<b>Chimney diameter</b>	<i>d</i>	<b>0.3</b>
<b>Chimney height</b>	<i>H<sub>c</sub></i>	<b>8</b>

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(a)



(b)

**Fig. 1 Picture of the experimental solar chimney power setup**

**(a) Overall picture of solar chimney**

**(b) Turbine-generator installed at the base of solar chimney**

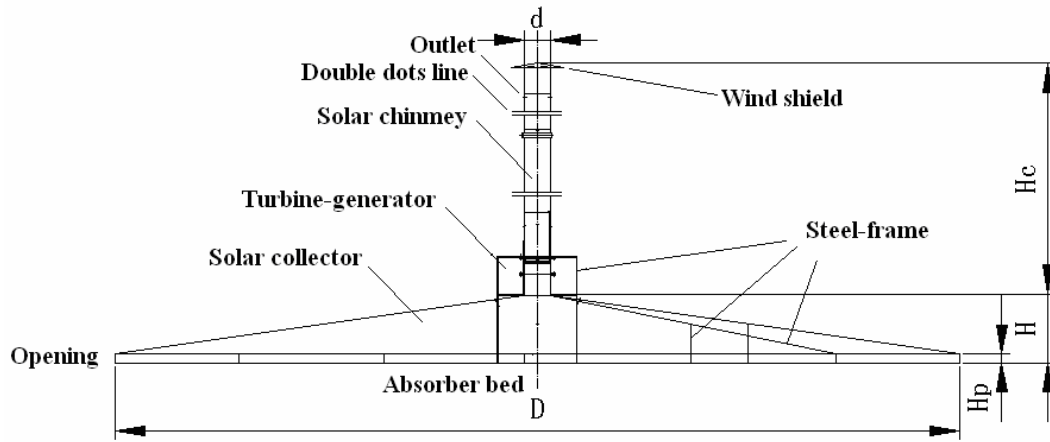
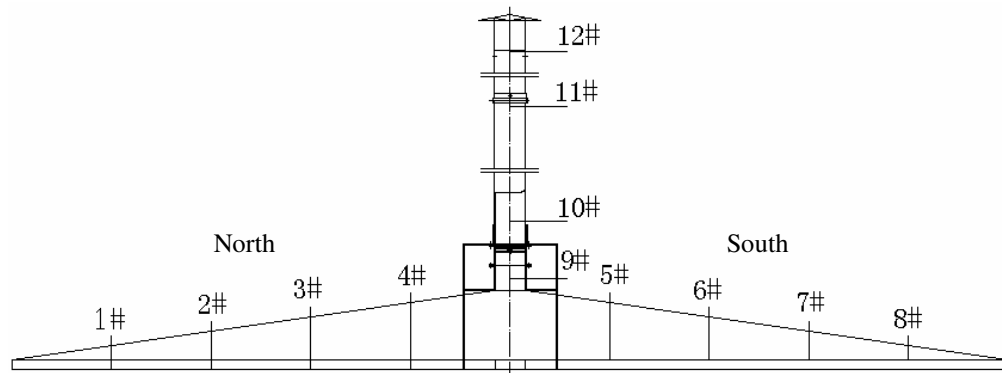
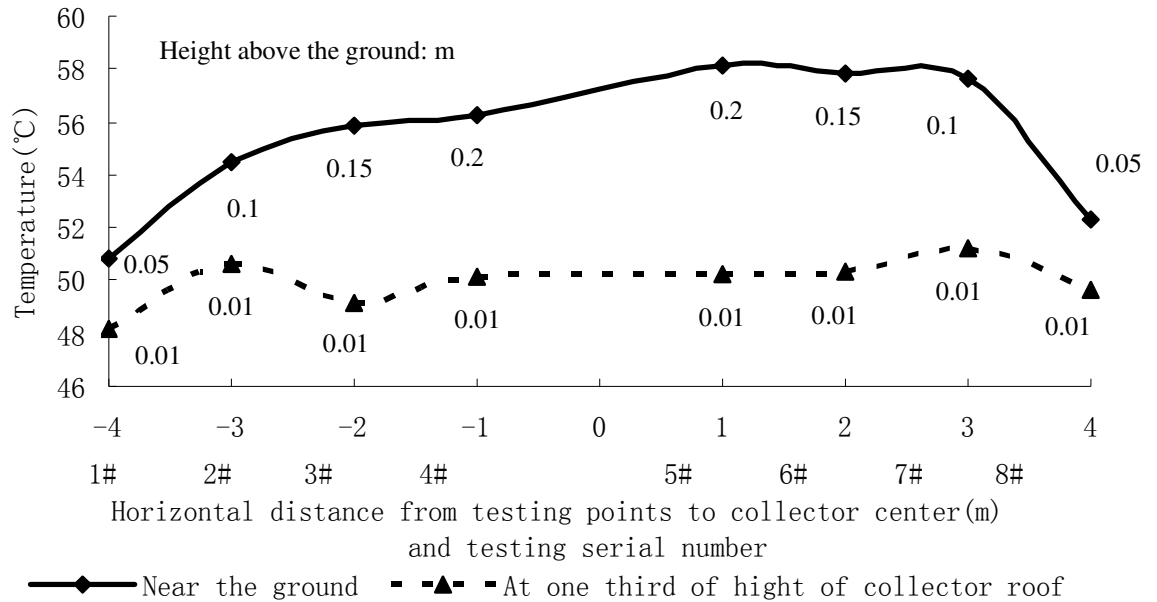


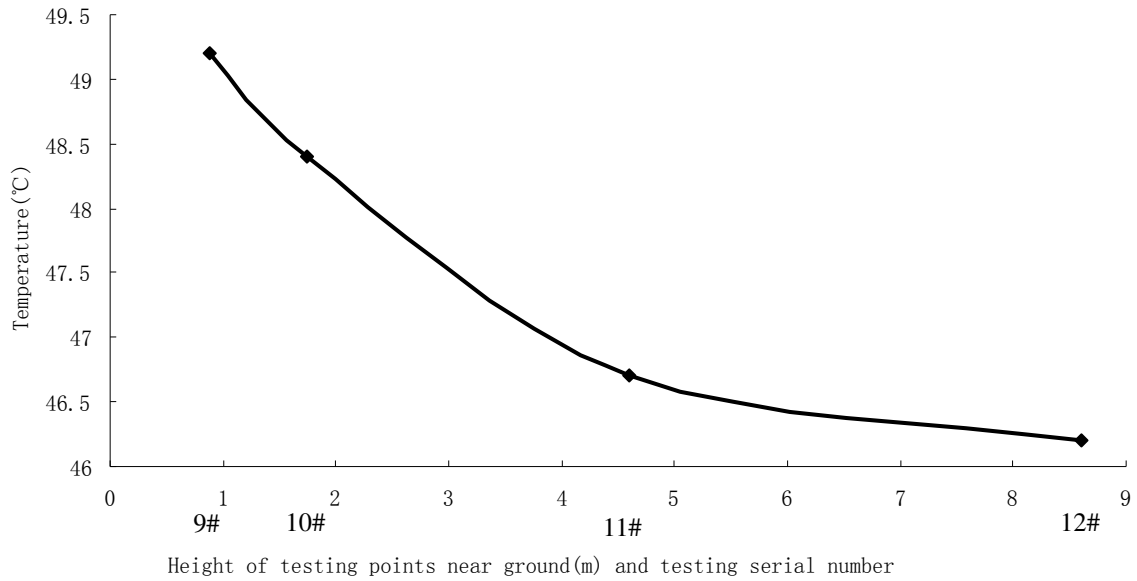
Fig. 2 Schematic diagram of solar chimney power setup



**Fig.3 Distribution of temperature- measuring points in solar chimney power setup**



**Fig.4 Air temperatures at different heights above the ground level in the solar collector on a typical warm day (ambient temperature at 15:30: 32.5 °C, updraft velocity in the chimney at 15:30: 2.13 m/s)**

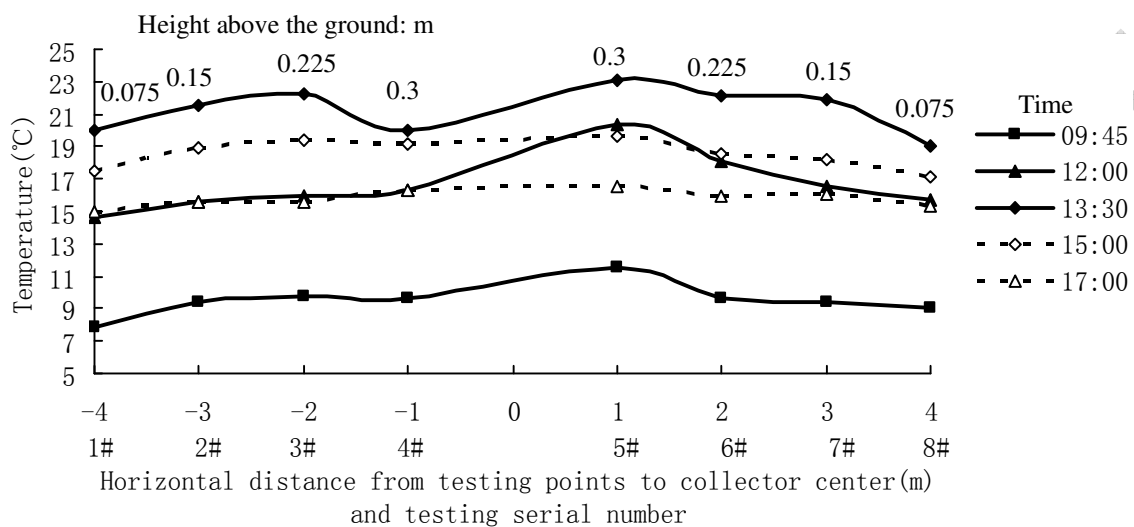


**Fig.5 Air temperatures at different heights in the chimney on a typical warm day**

**(ambient temperature at 15:30: 32.5 °C, updraft velocity in the chimney at 15:30:**

**2.13 m/s)**

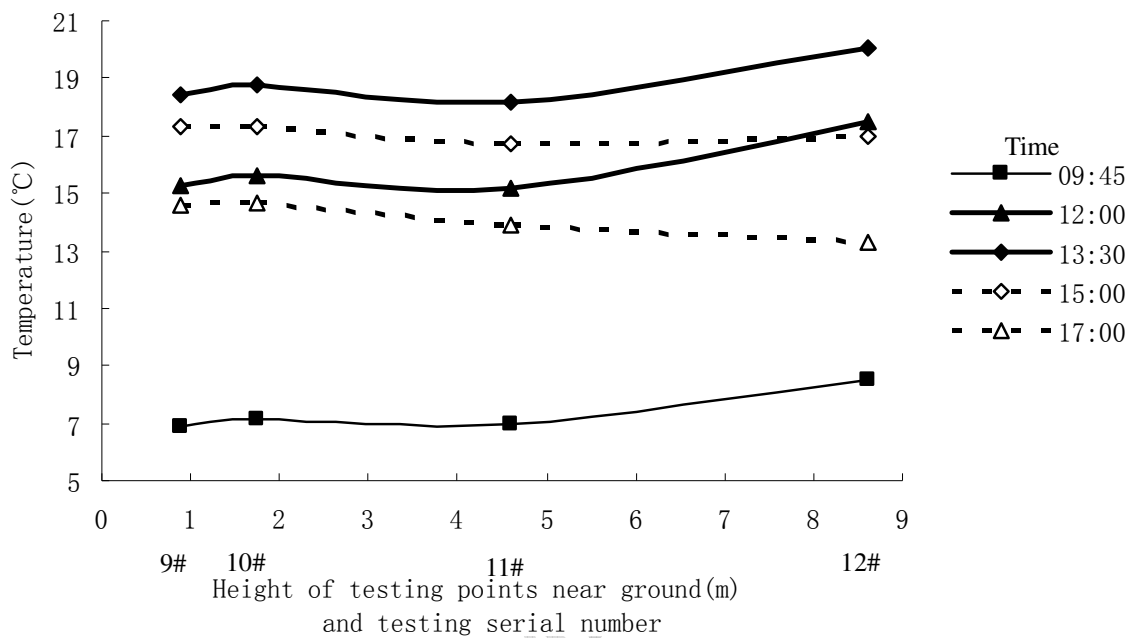
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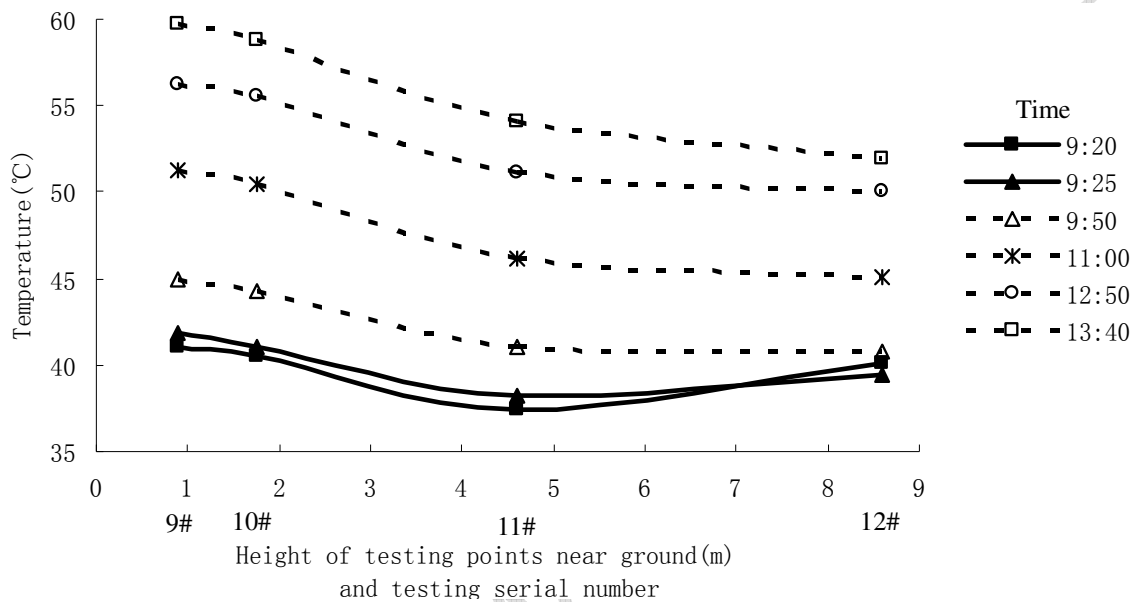
**Fig.6 Air temperatures in the solar collector at the different times during the day**

**from 09:45 to 17:00 on a typical cool day (average ambient temperature: 9 °C,**

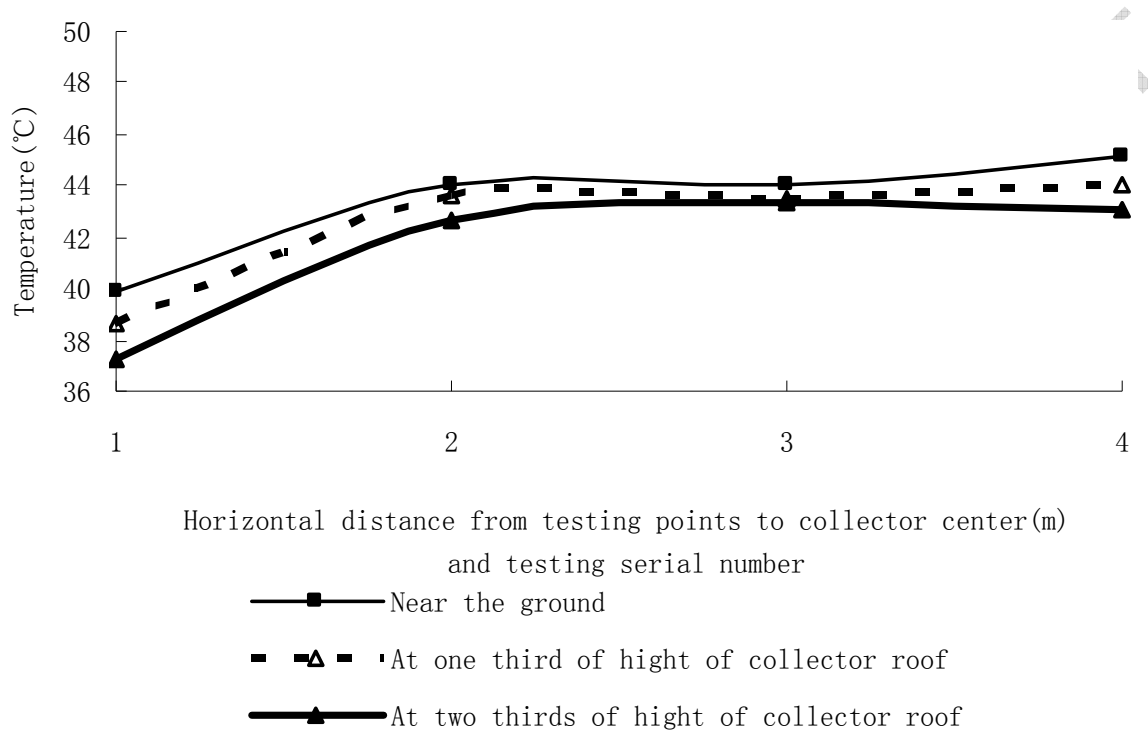
**maximum updraft velocity in the chimney: 1.22 m/s)**



**Fig.7 Air temperatures in the chimney at different times during the day from 09:45 to 17:00 on a typical cool day (average ambient temperature: 9 °C, maximum updraft velocity in the chimney: 1.22 m/s)**



**Fig.8 Air temperatures in the chimney at different times of the day from 09:20 to 13:40 on a typical warm day (average ambient temperature: 28 °C, maximum updraft velocity in the chimney: 2.81 m/s)**



**Fig.9 Air temperatures at different heights above the ground level in the northward solar collector on a typical warm day (ambient temperature at 09:25: 23 °C)**