Thermal Storage Comparison for Variable Basement Kinds of a Solar Chimney Prototype in Baghdad - Iraq Weathers

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Abstract

A solar updraft tower power plant 'solar tower' is a solar thermal power plant utilizing a combination of solar air collector and central updraft tube to generate an induced convective flow which drives pressure staged turbines to generate electricity. The issue of this paper is to present practical results of prototype of a solar chimney with thermal mass, where the glass surface is replaced by transparence plastic cover. The study focused on chimney's basements kind effect on collected air temperatures. Three basements were used, concrete, black concrete and black pebbles basements. The study was conducted in Baghdad from August to November 2010.

The results show that the best chimney efficiency attained was 49.7% for pebbles base. The highest collected air temperature reached was 49ºC when using the black pebbles basement. Also, the maximum basement temperature measured was 59ºC for black pebbles. High increments in collected air temperatures were achieved compared to ambient air temperatures for the three basements kind. The highest temperature difference reached was 22ºC with the pebble ground.

Keywords: Solar Chimney, Basement Effect, Concrete, Pebbles, Storage Efficiency.

1. INTRODUCTION

Sun is the principal source of almost all kinds of energy, both conventional and non-conventional. The sun is approximately 1.4 million km in diameter and 150 million km from the earth. Its temperature is close to 5500°C at its surface and emits radiation at a rate of 3.8×10^{23} kW. This power is supplied by nuclear fusion reactions near its core which are estimated to continue for several billion years [1].

The input of solar radiation to the biosphere is the source of energy which drives our weather systems and so in turn, winds, hydroelectric and biomass energy systems. Solar radiation can be used directly for photovoltaic energy conversion and for solar thermal conversion [2].
Electricity can be generated from solar radiation through the following methods:
- Photovoltaic cells
- Solar thermal power
- Solar tower / chimney [3].

A recent development in solar energy is a solar tower/chimney. It is a method used for large-scale generation of electricity from solar radiation. The principle is very simple [4]. A solar chimney is an air-heating solar collector that runs automatically, on sun power alone. It is based on the well known principle of greenhouse effect, chimney updraft effect, and wind turbine. Air is heated by

solar radiation under a low circular transparent or translucent roof opened at the periphery; the roof and the natural ground below it form a solar air collector [5]. In the middle of the roof a vertical tower is installed with large inlet at its base. The joint between the roof and the tower base is airtight. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter [6], [14]. Due to greenhouse effect the air is warmed in the solar collector. The warm air is moving from the periphery of the solar collector towards its center, in order to ''escape'' to upper layers of atmosphere through the solar chimney (fig.1). This moving stream of warm air leaves part of its thermodynamic energy to the air turbines that are geared with appropriate electric generators.
An indicative diagram for a Solar Chimney Power Plant is shown in fig.1.

In 1903, Spanish Colonel Isidoro Cabanyes first proposed a solar tower power plant in the magazine La energia electrica. One of the earliest descriptions of a solar tower power plant was written in 1931 by a German author, Hanns Gunther. Beginning in 1975, Robert E Lucier applied for patents on a solar tower electric power generator. These patents were granted in Australia, Canada, and the USA between 1978 and 1981.

The first studies on solar chimneys have been reported in 1993 by reference [17]. They present a stationary state model to describe a solar chimney, consistent by a conventional chimney linked to an air solar heater. Hirunlabh et al. report on 1999 the results of an experimental solar chimney, composed by a glass surface, air channel and a metallic black wall as collector surface. Reference [7] make a comparative study among different configurations of solar chimneys classified like; roof solar collector, modified Trombe wall, Trombe wall and metallic solar wall. On 2003 reference [8] report the experimental and theoretical results of a solar chimney similar to the Hirunlabh one.

Solar towers have a number of special features:
1. The collector can use all solar radiation, both direct and diffuse. This is crucial for tropical countries where the sky is frequently overcast [9].
2. Due to the soil under the collector working as a natural heat storage system, updraft solar towers can operate 24 hours on pure solar energy, at reduced output at night time. If desired, additional water tubes or bags placed under the collector roof absorb part of the radiated energy during the day and releases it into the collector at night [8].
3. Solar towers are particularly reliable and not liable to break down, in comparison with other power plants. Turbines and generators - subject to a steady flow of air - are the plant's only moving parts. This simple and robust structure guarantees operation that needs little maintenance and of course no combustible fuel [4].
4. Unlike conventional power stations (and also some other solar-thermal power station types), solar towers do not need cooling water. This is a key advantage in the many sunny countries that already have major problems with water supply [10].
5. The building materials needed for solar towers, mainly concrete and glass, are available everywhere in sufficient quantities. In fact, with the energy taken from the solar tower itself and the stone and sand available in the desert; they can be reproduced on site. Energy payback time is two to three years [11].
6. Solar towers can be built now, even in less industrially developed countries. The industry already available in most countries is entirely adequate for solar tower requirements. No investment in high-tech manufacturing plants is needed [12].
7. Even in poor countries it is possible to build a large plant without high foreign currency expenditure by using local resources and work-force; this creates large numbers of jobs while significantly reducing the required capital investment and thus the cost of generating electricity [2].
Nevertheless, solar towers also have features that make them less suitable for some sites:
A. They require large areas of flat land. This land should be available at low cost, which means that there should be no competing usage, like e.g. intensive agriculture, for the land [9].
B. Solar towers are not adequate for earthquake prone areas, as in this case tower costs would increase drastically [13].

C. Zones with frequent sand storms should also be avoided, as either collector performance losses or collector operation and maintenance costs would be substantial there [6].
The objective of this study was to examine the effect of basements type on the air temperatures of prototype solar chimney designed and constructed for this purpose, in Baghdad autumn days.

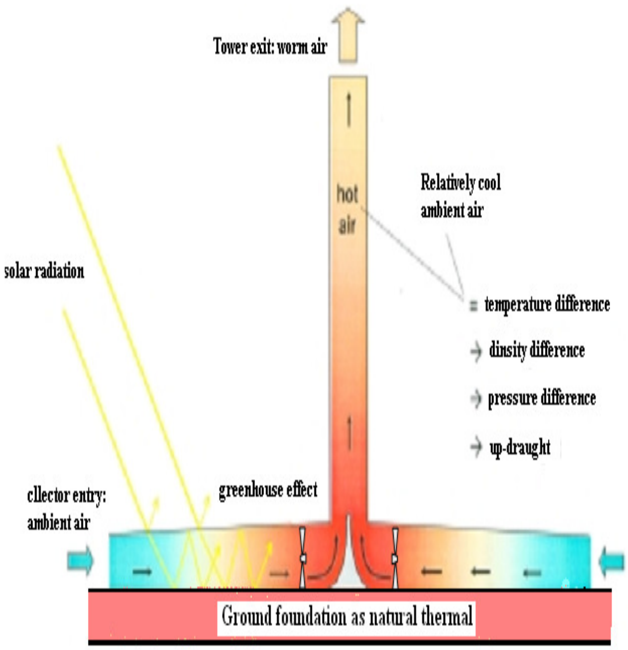

FIGURE 1: Solar tower working principles

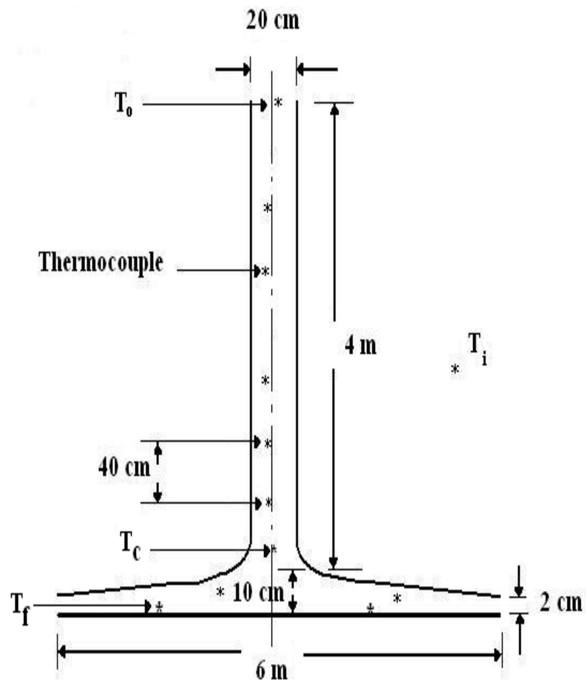

FIGURE 2: Schematic diagram of the solar chimney and thermocouples distribution

2. EXPERIMENTAL SETUP

The solar tower's prototype was build (shown in Fig. 2): Air is heated by solar radiation under a low circular transparent roof (6 meters diameter) open at the periphery (2 cm high from ground); the roof and the ground below it form a solar air collector. In the middle of the roof is a vertical (4 meters tall and 20 cm diameter) tower with large air inlets at its base (10 cm height from the ground). The joint between the roof and the tower base is airtight. As hot air is lighter than cold air it rises up the tower. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter. Continuous 24 hours- operation can be achieved by placing a thermal collector ground. For this purpose three kinds of grounds were studied, the first was an ordinary concrete ground, which heats up during day-time and releases its heat at night. The second was selective black colored concrete ground to absorb more heat at daylight. The third basement was selective black colored pebbles which known as heat storage substance and gave efficient air mixing by increasing its turbulence. The idea was to investigate the best basement material that makes solar radiation causes a daily constant updraft in the tower.
The temperature of air under the transpierce cover was measured by (6) six calibrated copper-constantan thermocouples distributed uniformly around the vertical chimney. Also, the rising air temperature through the chimney was measured by means of calibrated thermocouples. These thermocouples were fixed in variable manner, to give accurate analysis for moving air through the chimney. The first thermocouple in the group represents collected air temperature (T_c). The temperature of the air entering the chimney (T_a) was measured by thermometer fixed away from the chimney. The basements floor temperature (T_f) was measured by means of three thrmo-couples distributed in the west, south and east directions, with a distance of 1.5 meter from the

centre of the collector; the average of these thermocouples readings was taken as (T_f). Temperatures were red by calibrated digital electronic thermometer, through a selector switch. Fig. 2 represents prototype dimensions and thermocouple distribution, while Fig. 3 shows a photographic picture for tested prototype solar chimney.

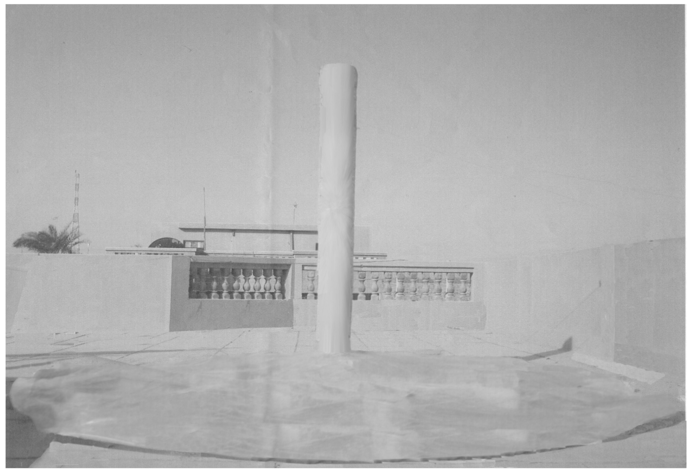

FIGURE 3: The solar tower's prototype

The experiments were conducted in Iraqi autumn days, started at the first of August and finished at the end of November 2010. The tests were conducted in Saydia city west of Baghdad. Three grounds were prepared, the first one was ordinary concrete ground, the second one was ordinary concrete ground painted with selective black color, and the third was selective black colored pebble ground. Table 1 represents the thermal properties for the used material. The prototype chimney was fixed in each ground for 10 days. Temperatures readings were taken, so for each ground there are readings for the three months, the resultant average were undertaken to compare between the three cases. Temperature readings operation began at sun shine and continued after sunset until the basement reached its starting temperature. These temperatures demonstrated the thermal storage in the basement.

3. SYSTEM EFFICIENCY CALCULATIONS

Solar tower system consists of three main parts: collector, tower and turbine. In this study there is no turbine used, and the concentration was on thermal energy gathered by solar chimney collector by its various basements.

In calculating system efficiency the procedure mentioned in (Schlaich et al, 2005) was used, for any further detail one can refer to. The basic function for solar chimney is to convert heat flow produced by the collector into kinetic energy. Then its efficiency can be calculated by:

Total system efficiency

$$= \eta_{coll} . \eta_{tower} . \eta_{turbines} \quad (1)$$

Where: η_{coll} - Collector efficiency. η_{tower} - Tower efficiency, and $\eta_{turbine}$ - Turbine efficiency.

In this study there was no turbine to complete this conversion, and the focus was on the collector efficiency which is calculated by:

$$\eta_{coll} = \frac{P_{tot}}{\dot{Q}} \quad (2)$$

P_{tot} - the pressure difference produced between collector outlet and ambient air, it depends on the density difference of air caused by the temperature rise in the collector area and calculated as follow:

$$P_{tot} = A_c.g.\int_0^{Hc}(\rho_a - \rho_c).dH \quad (3)$$

With: A_c- collector area, H_c- tower hight, ρ_a- air density in ambient temperature, and ρ_c- air density in the tower. Thus P_{tot} increase with the tower hieght.

$$\dot{Q} = G_h.A_c \quad (4)$$

where $\dot{Q}$ - The solar energy input, and G_h - Average solar intensity taken from Iraqi Meteorology organization for 24 hours of the tested period. This efficiency was used to compare between the three basements in this study.

The former equations illustrate for very important characteristic in solar chimney, which is the chimney efficiency depends mainly on chimney's tower height.

4. RESULTS AND DISCUSSION

Figures (4 to 6) represent the solar chimney behavior when concrete ground was used for the three studied months. The results show the air temperature increase with time, starting from the sun rise, this increase was associated with an increase in the collected air (T_c) and the basement (T_f) temperatures. The maximum temperatures were achieved at 2 PM. collected air was heated in this region (sun rise till 2 PM) by greenhouse effect, while the direct radiation heated the ground. In these hours the collected air was independent of the worm ground.

All temperatures reduced after 2 clock at noon, until they reached the starting temperature after sun set. In this region the collected air depends on the basement to worm up. The thermal storage for the concrete ground was very limited and achieved temperature differences for about two hours after sun set. This limited time is due to the prototype chimney dimensions. It is believed that bigger collector area will give more thermal storage heat, and will introduce more working hours to the chimney. The maximum difference between (T_c) and (T_a) was (19ºC). The maximum variation between air temperature (T_a) and ground temperature (T_f) for ordinary concrete case was about (25ºC) at 1 to 2 PM where the highest temperatures were achieved. The maximum (T_f) reached was (56ºC) in August days.

Figures (7 to 9) represent the solar chimney behavior when selective black colored concrete ground was used. The average temperatures for three months operation periods in these figures show that there were some improvements in temperature differences between ambient air and collected air, where it reached (20ºC) at peak time.

The black colored concrete ground absorbed more solar radiation, and heated more than ordinary concrete basement where (T_f) reached maximum temperature about (57.6ºC) in August days. Also at 7 AM (temperatures measurement starting point) there were differences between (T_c) and (T_f) more than other months. The effect of solar radiation is more efficient in hotter days, which means more system efficiencies will be obtained at summer months.

The thermal storage of black colored concrete basement managed to continue worming collected air for three hours after sun set, despite the limited collector size.

Figures (10 to 12) demonstrate the solar chimney behavior when black colored pebbles basement was used. The figures show that there are some improvements in temperature differences; the maximum temperature difference between (T_a) and (T_c) reached (22ºC) at the peak time. The black pebbles ground absorbed solar radiation, and heated more than ordinary concrete basement due to its higher specific heat. The maximum temperature obtained was (59ºC). This thermal storage managed to continue operating for five hours after sun set, despite the limited collector size.

These results give black pebbles priority on ordinary and black concrete basements. As well as it proves that a suitable basement combined with suitable solar chimney design manage to operate for 24 hours.

The results demonstrate that the storage capacity of black concrete improved about 50% compared with ordinary concrete, while black pebbles improved this capacity with about 250% due to its thermal properties.

Fig.13 shows the chimney's collector hourly efficiency variation for the three systems with operation time. Because the studied system depends on solar energy, then it's collecting time starts from sunrise and ends at sunset. The pebbles basement collecting efficiency surpasses the other cases. The thermal storage improved with this ground, and enables the chimney to work for more time. On the other hand, coloring the concrete ground with black upgrade the thermal storage and improve its efficiency. The results concluded that the efficiency of solar chimney depends highly on the thermal storage capacity of its basement material.

5. CONCLUSIONS

The practical prototype model of the solar chimney power plant was designed and constructed to investigate the influence of basement kinds on chimney's air temperatures, in the region of Baghdad city- Iraq. The effects of storage parameter, such as the solar radiation, the ambient temperature, and the heat storage capacity for ground materials on the power plant operation time are also investigated. According to the results obtained from the proposed model, the following conclusions can be drawn:

1- The solar chimney power plant have a suitable basement (black colored pebble ground in this work) can achieve air heating for many hours operation after sun set. With suitable design the solar chimney power plant will manage to act 24 hours / day.

2- The results show that black pebbles basement had better thermal storage quality than ordinary concrete or black concrete ground.

3- Although the chimney prototype size was limited, it gave high temperature difference between T_c and T_a reached 22^{o}C. Maximum T_f reached was 59 ^{o}C when using black pebbles. This indicates the convenient of Iraqi weathers for this type of plants.

4- Painting the basement with selective black color increase absorbed solar radiation, thereby improved the system efficiency.

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material	Density (ρ) kg/m3	Conductivity (k) W/m ºC	Conductance W/m2 ºC	Specific heat kJ/kg ºC
Concrete	2020-2180	-	3.0-3.5	0.92
Pebble	2080	0.92-1.12	-	5.28

TABLE 1: Typical thermal properties for tested materials (McQuiston et al).

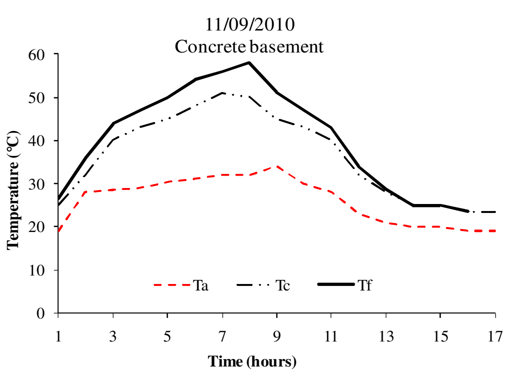

FIGURE 4: Concrete basement and air temperatures at 11/9/2010.

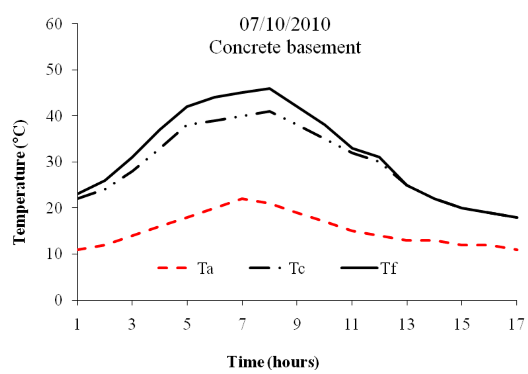

FIGURE 5: Concrete basement and air temperatures at 7/10/2010**.**

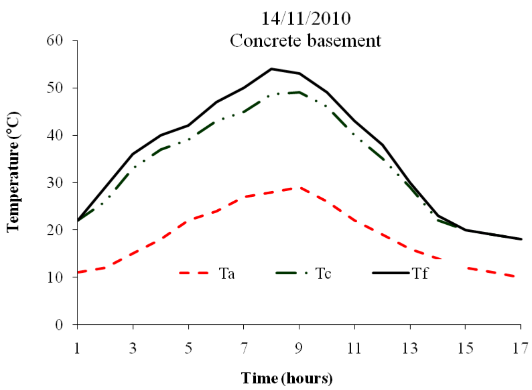

FIGURE 6: Concrete basement and air temperatures at 14/11/2010.

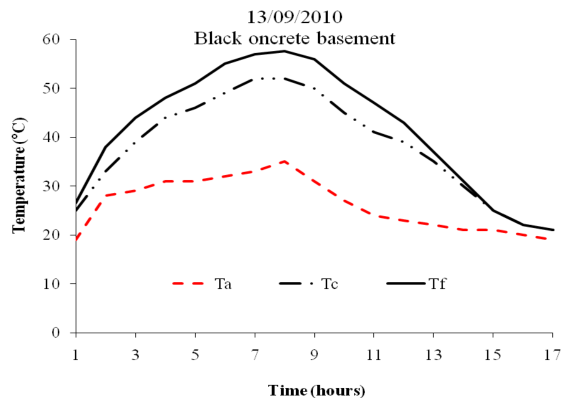

FIGURE 7: Black concrete basement and air temperatures at 13/9/2010**.**

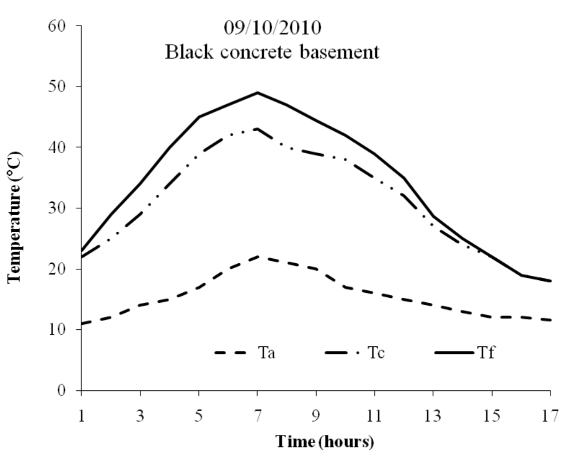

FIGURE 8: Black concrete basement and air temperatures at 9/10/2010.

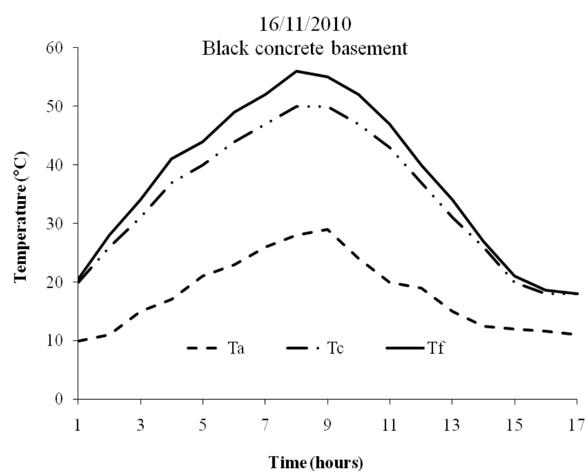

FIGURE 9: Black concrete basement and air temperatures at 16/11/2010.

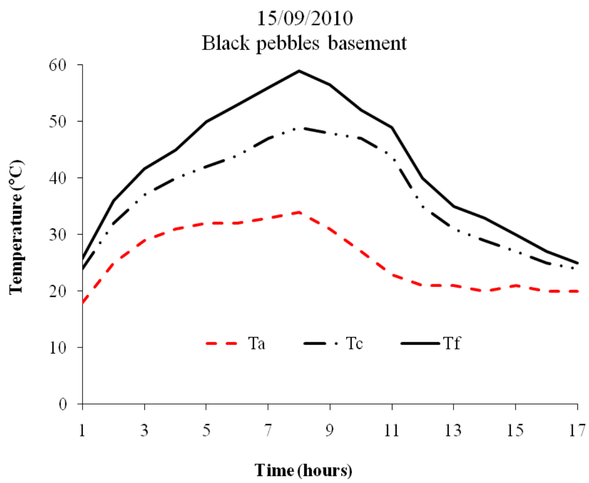

FIGURE 10: Black pebbles basement and air temperatures at 15/9/2010.

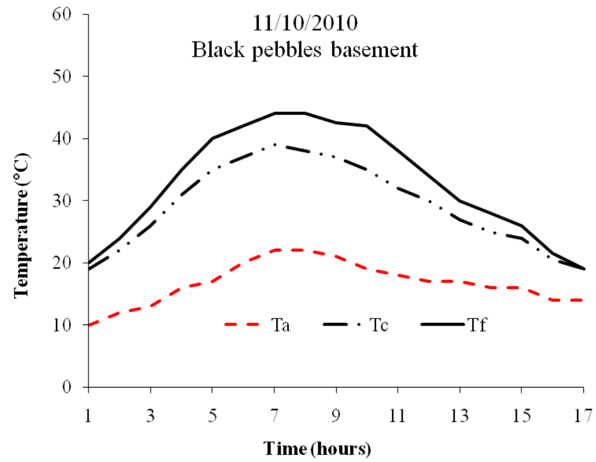

FIGURE 11: Black pebbles basement and air temperatures at 11/10/2010.

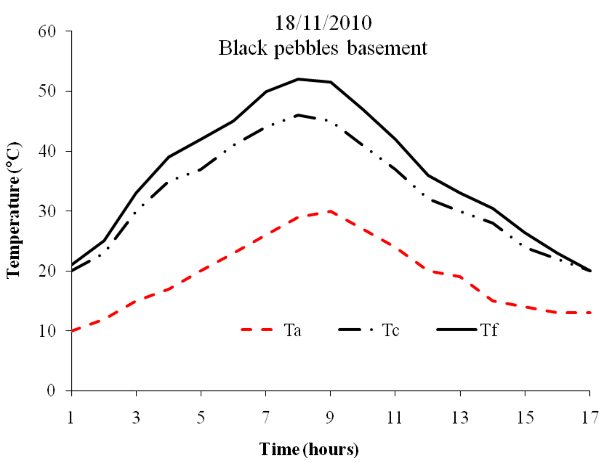

FIGURE 12: Black pebbles basement and air temperatures at 18/11/2010.

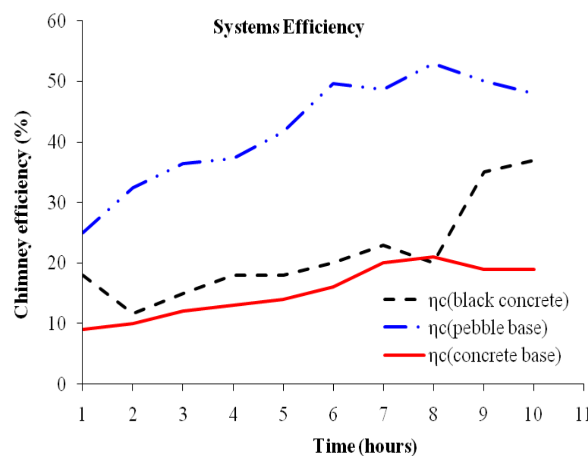

FIGURE 13: Average efficiency differences for day hour for basement systems.