RESEARCH ARTICLE

ScienceAsia 36 (2010): **237–243**

doi: 10.2306/scienceasia1513-1874.2010.36.237

A rock fills based solar thermal energy storage system for housing

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Received 20 Feb 2010
Accepted 14 Aug 2010

ABSTRACT: The efficiency of a solar thermal energy storage system using basaltic rock fills has been assessed using a scaled-down model. The proposed system is designed to operate without external electricity in cold areas. Solar energy is collected and stored in basalt ballasts filled in a shallow pit excavated above the groundwater table. The surrounding soil and an acrylic sheet cover serve as insulator. The stored thermal energy is released through a system of tubes to warm up housing at night. The thermal properties of ten rock types that occur widely in the north and northeast of Thailand were determined in the laboratory. A scaled-down model, simulating the storage system and housing, was constructed to monitor the temperature changes of the various system components and the results were compared with the predictions of mathematical models. Buriram basalt was selected for testing as it has the highest thermal conductivity and specific heat. The results indicate that throughout the night the system can increase the housing temperature to 4–6 °C more than the surroundings, depending on the packing density, tube size, and surrounding temperature. The efficiency of this storage system is about 35%. The gained heat energy in the housing is equivalent to the electrical energy of 203 kJ. The mathematical models developed here agree well with the measured results.

INTRODUCTION

Winter temperatures drop to nearly 0 °C in many areas of the north and northeast of Thailand[1]. Each year the Thai government and public agencies spend substantial funds (over 2.6 million US dollars) for blankets and temporary shelters to alleviate this problem[2]. A long-term solution in the form of new low-cost technology that relies only on the renewable sources of energy and on locally available materials is called for.

One possible solution is a solar thermal-energy storage system. It deals with a selecting medium that absorbs and stores heat during the day and releases it to warm the housing space during the night. This technology is not new. It has long been studied and developed successfully in many countries with a variety of system components. Solar cells or solar greenhouse domes have sometimes been used to collect thermal energy. It is then transferred by using a system of fans and tubing to rock fills[3–7]. The advantage of this technology is that the sun is the main source of energy and the rocks are relatively inexpensive, readily available in many areas, long-lasting, and safe. The existing alternative systems are expensive, difficult to install, and usually require external electricity to operate, and hence are not truly applicable for remote areas.

The objective of this study is to assess the performance of a solar thermal energy storage system using rock fills without an electricity supply. The research effort involves the determination of thermal properties of various rock types available in the north and northeast of Thailand, construction of a scaled-down model to demonstrate the system performance, derivation of a mathematical model to describe the temperature variation in the system, and development of guidelines for applying the proposed storage system.

ROCK AND SOIL PROPERTIES

Ten rock types commonly found in the north and northeast of Thailand were collected from the sites and tested in the laboratory to determine their mineral composition, specific heat, and thermal conductivity. The results indicated that Buriram basalt with the average density of 2810 kg/m^3 shows the highest specific heat (C_r) of 1174 kJ/kg K. It has a thermal conductivity (k_r) of 1.70 W/m K, thermal diffusivity (κ_r) of 5.15×10^{-7} m^2/s, thermal expansion coefficient (β_r) of 5.4×10^{-6} K^{-1}, and hence has a good potential for thermal storage. It therefore has been primarily selected for rock fills in the scaled-down model. A soil sample was collected from around

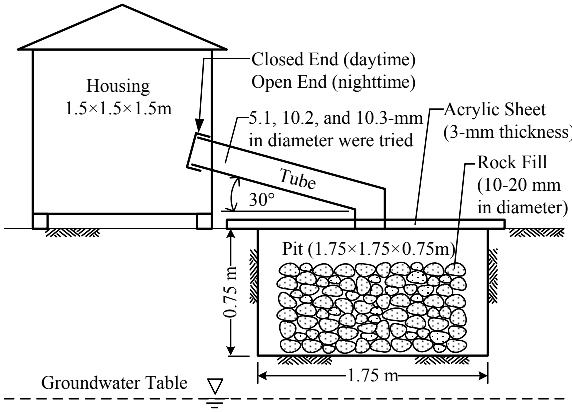

Fig. 1 Diagram of storage pit and housing model.

Suranaree University of Technology where the scaled-down model was constructed. From sieve analysis and hydrometer testing[8] the soil was 17% gravel, 34% sand, and 49% clay by weight and thus could be classified as classified as clayey sand[9].

SCALED-DOWN MODEL

A scaled-down model was constructed to assess the efficiency of the solar thermal storage system and to determine its optimum design parameters. The system consists of a storage pit and a housing model (Fig. 1). The storage medium absorbs the solar heat by exposing the basaltic rock fragments to direct sunlight through clear acrylic sheet. The solar thermal energy is accumulated and causes an increase in temperature in the storage pit. The stored energy is released during the night to warm up the air in the housing model.

The storage pit (1.75 m $\times$ 1.75 m $\times$ 0.75 m) was filled with four chain-link baskets (0.5 m $\times$ 0.5 m $\times$ 0.5 m) packed with pre-defined fragment-sized basalt (10–20 cm in diameter). Insulator sheets were placed around the pit walls and floor to prevent heat loss. The pit floor was excavated in the soil mass above the groundwater table. The top of the pit was covered with 3 mm thick transparent acrylic sheet. It has a specific heat of 1470 J/kg K, a thermal conductivity of 0.20 W/m K, and a density of 1150 kg/m^3. The housing model was made of wood and covered with a tile roof. The transparent acrylic sheets reinforced by steel frames were placed on top of the storage pit. This allows the solar energy to be transmitted to the rocks while preventing heat loss from convection by wind. The housing model (1.5 m $\times$ 1.5 m $\times$ 1.5 m) was constructed with plywood. The housing model and the pit were connected via a hot-air tube. Thermocouples were installed to monitor the changes of rock temperature at the centre of pit, the air in the pit, the air at the end of the tube in the hosing model, the air in the housing model, and the surrounding air. The temperature changes at these points were recorded every 30 min using an on-site data acquisition system (Digital Strain Meter TC-31K). The device can measure the temperature as a function of time to the nearest 0.001 °C. The stored data were uploaded daily to a computer.

Monitoring results

The temperatures were monitored during two cool seasons (Table 1). The hot-air tubes with diameters of 5.1, 10.2, and 20.3 cm were used. Initially rock fills of mass 743 kg were used and this was later changed to 370 kg to assess the impact of the storage mass. Table 1 summarizes the test series for the scaled-down model.

Fig. 2a shows the temperature as a function of time measured from the system with 5.1 cm diameter tube with 743 kg rock fragments. The pit was not covered by any insulator on the top. During the charging period (6:00 am–6:00 pm), the housing model was open and the hot-air tube was shut. After 6:00 pm, the housing model was closed and the hot-air tube was opened to allow the hot-air in the pit to flow to the housing model and the cool air in the housing model to circulate back to the pit. Results from the temperature measurements indicate that the heat flow through the pipe to the housing space is minimal, probably due to the excessive heat loss through the acrylic sheet, improper size of the tube, and leakage of heat energy of the housing model.

In an attempt to enhance the heat flow, the hot-air tube with a diameter of 10.2 cm was installed. The tube was covered with an insulator to reduce heat loss. The opening and closing times for the pit, tube, and housing was the same as for the previous testing. The housing model was opened and the tube was closed after 6:00 am. After 9:00 pm the housing was closed and the tube was opened. The measurement results were not different from the previous test. This is probably because there were significant energy losses from the top of the pit.

To reduce energy loss, the top of the pit was covered by gunny-bags after 3:00 pm. The temperature in the housing model increased to about 1 °C more than the surroundings. Then the housing walls, ceiling, and floor were sealed with 2 cm thick polyurethane foam sheets to minimize the heat loss and leakage. After the tube was opened, the temperature in the housing model rapidly increased within the first 60 min then

Table 1 Series of monitored results from scaled-down model.

Test series	Monitoring period	Rock weight (kg)	Tubing diameter and Inclination	Remarks
I	20 Nov 2005 – 14 Dec 2005	743	5.1 cm 0°	Not covered on top of pit OH, OP and CT – 6:00 am CP, CH, and OT – 6:00 pm
II	18 Dec 2005 – 4 Jan 2006	743	10.2 cm 30°	Covered on the top of pit OH, OP and CT – 6:00 am CP – 3:00 pm; CH and OT – 9:00 pm
III	6 Jan 2006 – 20 Apr 2006	743	20.3 cm 60° (first half) 20° (second half)	Covered on the top of pit OH, OP and CT – 9:00 am CP – 3:00 pm; CH and OT – 9:00 pm
IV	28 Nov 2006 – 21 Jan 2007	370	20.3 cm 60° (first half) 20° (second half)	Covered on the top of pit OH, OP and CT – 9:00 am CP – 3:00 pm; CH and OT – 9:00 pm

O = Open; C = Closed; P = Pit (rock fills); T = Hot-air tube; H = Housing

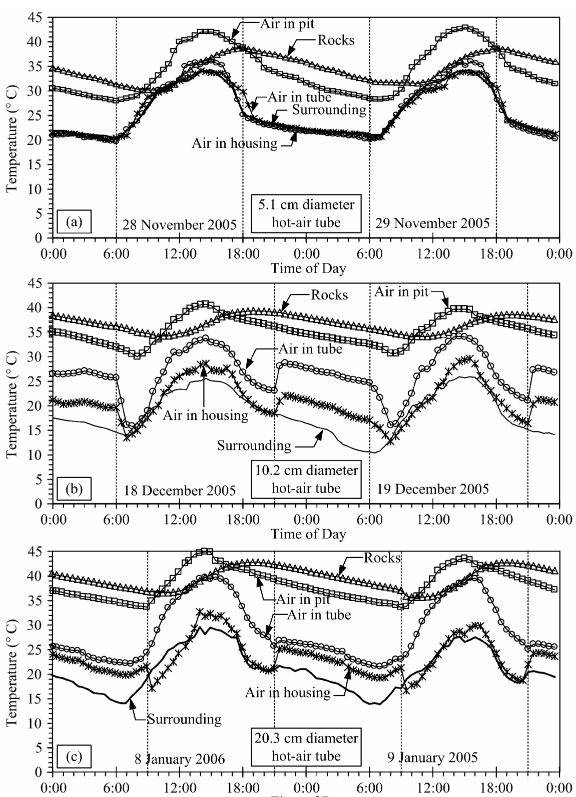

Fig. 2 Temperature as a function of time measured from various components using the hot-air tube with diameter of (a) 5.1 cm (b) 10.2 cm (c) 20.3 cm.

it slightly decreased. The results show that more heat energy is transferred to the housing model since the temperature in the housing model was nearly 5 °C more than the surroundings (Fig. 2b).

Fig. 2c shows the temperature as a function of time measured from the system using a 20.3 cm diameter hot-air tube with 743 kg of rock fragments. The tube was inclined at an angle of 60° on the first half and 20° on the second half. The elevation difference between the inlet and outlet was about 1.5 m. The temperature changes were similar to the results obtained from the system with a 10.2-cm diameter hot-air tube. The results indicated that the housing model was over 5 °C warmer than the surroundings.

To study the effect of rock fragments quantity for the system with a 20.3 cm diameter hot-air tube, the amount of rock fragments was reduced to 370 kg. The housing model and storage pit were opened at 9:00 am. At 3:00 pm the pit was closed and the hot-air tube was opened at 9:00 pm. This time the temperature in the housing model was found to be only around 2–3 °C higher than the surroundings (Fig. 3).

MATHEMATICAL MODEL

The system comprises of three volumes, namely, the rock fragments (V_{rf}), the air in the storage pit (V_{ap}), and the air in the housing model (V_{ah}). The solar energy absorbed by the air, air humidity, thermal gradient within solid particles, radiation effects, and heat losses to the environment are neglected. The heat flow is assumed to be one-dimensional and quasi-steady state.

Daytime equivalent model

The solar radiation (I_{s}) transmitted through the transparent acrylic sheet is absorbed by the rock fills. The ability of rock to store the energy depends on the thermal absorbability (α_{r}). After the temperature of

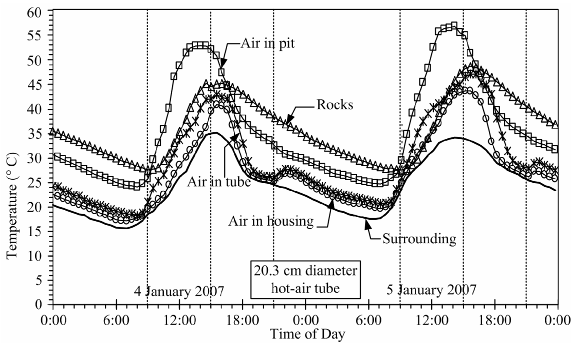

Fig. 3 Temperature as a function of time of various components when using a 20.3-cm diameter hot-air tube and 370 kg of rock fragments.

the rock bed increases, the heat is transferred to the flowing air by convection, and to the pit walls and floor by convection and radiation. The air is heated up along its path and loses through various heat transfer coefficients.

The energy gained in the mass of rock is by the rock fill absorbing the incident solar radiation. Heat is lost from the rock fill to the air in the pit by convection. Hence

$$m_\mathrm{r}C_\mathrm{r}\frac{\mathrm{d}T_\mathrm{r}}{\mathrm{d}t} = \alpha_\mathrm{r}I_\mathrm{s}A_\mathrm{r,top} - h_\mathrm{r}A_\mathrm{r}(T_\mathrm{r} - T_\mathrm{ap}), \quad (1)$$

where m_r is the mass of rocks in pit, C_r is the specific heat capacity of the rocks, α_r is the absorptivity coefficient of rocks, I_s is the solar radiation or heat flux, $A_\mathrm{r,top}$ is the solar collection area which is equivalent to the area of rocks on the top exposed to the air, T_r is the rock temperature, T_ap is the air temperature in the storage system, h_r is the convective heat transfer coefficient from rocks to air, and A_r is the area of all rock fragments. Assuming the rock fragments are spherical with diameter D, h_r is a function of Nusselt number (Nu), characteristic length ($\delta = \pi D/2$), and thermal conductivity (k) of the rocks:

$$h_\mathrm{r} = \frac{k\mathrm{Nu}}{\delta} \quad (2)$$

Nu can be determined from [10]

$$\mathrm{Nu} = 2 + \frac{0.589\,\mathrm{Ra}^{1/4}}{\left[1 + \left(\frac{0.469}{\mathrm{Pr}}\right)^{9/16}\right]^{4/9}},$$

where Pr is Prandtl number which is 0.71 for dry air at 0–300 °C and the Rayleigh number Ra is given by [11]

$$\mathrm{Ra} = \frac{g\beta_\mathrm{r}}{\nu\kappa_\mathrm{r}}\left(T_\mathrm{r} - T_\mathrm{ap}\right)\delta^3,$$

where g is the acceleration due to gravity, β_r is the thermal expansion coefficient of rock, ν is the kinematic viscosity of air, κ_r is the thermal diffusivity of rock.

Air in the storage system gains its heat energy from the solar heat reflected from the rock fill and the radiative and convective heat transfers from the rock fill. It loses energy by heat convection to the surrounding air above the acrylic sheet and to the pit wall. Hence

$$\begin{aligned} m_\mathrm{ap}C_\mathrm{a}\frac{\mathrm{d}T_\mathrm{ap}}{\mathrm{d}t} &= f_\mathrm{ab}(1-\alpha_\mathrm{r})I_\mathrm{s}A_\mathrm{r,top} \\ &\quad + h_\mathrm{r}A_\mathrm{r}\left(T_\mathrm{r} - T_\mathrm{ap}\right) \\ &\quad - U_1A_\mathrm{acr}\left(T_\mathrm{ap} - T_\mathrm{sur}\right) \\ &\quad - U_2A_\mathrm{w}\left(T_\mathrm{ap} - T_\mathrm{soil}\right), \end{aligned} \quad (3)$$

where m_ap is the mass of air in storage system, C_a is the specific heat capacity of the air (1012–1017 J/kg K), f_ab is the heat loss factor from the reflected radiation of rock, A_acr is the area of the acrylic sheet, A_w is the area of the pit wall, T_sur is the temperature of the air outside the housing, and T_soil is the temperature of soil (pit wall). U_1 and U_2 are the overall heat transfer coefficients from the pit to the surrounding air and from the air to the pit wall, respectively. They are given by

$$U_1 = \frac{1}{\dfrac{1}{h_\mathrm{ic}} + \dfrac{\Delta x}{k_\mathrm{acr}} + \dfrac{1}{h_\mathrm{exc}}}, \quad U_2 = \frac{1}{\dfrac{1}{h_\mathrm{ic}} + \dfrac{\Delta x}{k_\mathrm{acr}}},$$

where Δx is the thickness of acrylic sheet, k_acr is the thermal conductivity of acrylic sheet, and h_ic and h_exc are the convective heat transfer coefficients of the air in the pit and the air outside the pit, respectively, and can be evaluated using (2). The mass of air in the storage pit $m_\mathrm{ap} = \rho_\mathrm{air}V_\mathrm{ap}$ where ρ_air is the density of air which is taken as being a constant value (1.103 kg/m^3).

Night time equivalent models

At night, as there is no solar radiation but the lid of the hot tube is open so that hot air flows through the tube to the housing model, (1) and (3) can be re-written as:

$$m_\mathrm{r}C_\mathrm{r}\frac{\mathrm{d}T_\mathrm{r}}{\mathrm{d}t} = -h_\mathrm{r}A_\mathrm{r}(T_\mathrm{r} - T_\mathrm{ap}), \quad (4)$$

$$\begin{aligned} m_\mathrm{ap}C_\mathrm{a}\frac{\mathrm{d}T_\mathrm{ap}}{\mathrm{d}t} &= h_\mathrm{r}A_\mathrm{r}\left(T_\mathrm{r} - T_\mathrm{ap}\right) \\ &\quad - U_1A_\mathrm{acr}\left(T_\mathrm{ap} - T_\mathrm{sur}\right) \\ &\quad - U_2A_\mathrm{w}\left(T_\mathrm{ap} - T_\mathrm{soil}\right) \\ &\quad - \dot{m}C_\mathrm{a}\left(T_\mathrm{ap} - T_\mathrm{ah}\right), \end{aligned} \quad (5)$$

where $\dot{m}$ is the air mass flow rate from the storage pit to the housing under stack effect when the hotter air (in pit) flows to the cooler area (in housing), and T_{ah} is the temperature of the air in the housing. The mass flow rate is obtained from [12, 13]

$$\dot{m} = \frac{\rho_{\mathrm{a}} C_{\mathrm{D}} A_{\mathrm{o}}}{\sqrt{1 + (A_{\mathrm{o}}/A_{\mathrm{i}})}} \sqrt{2gH\left(\frac{T_{\mathrm{ap}} - T_{\mathrm{ah}}}{T_{\mathrm{ap}}}\right)},$$

with $\rho_{\mathrm{a}} = P/RT_{\mathrm{ap}}$, where P is the air pressure (= 101 300 Pa), C_{D} is discharge coefficient (= 0.60–0.75), R is gas constant (= 287 J/kg K), A_{o} and A_{i} are the outer and inner cross-sectional areas of the tube, and H is the difference between the elevation of tube entrance and exit.

The heat in the hot-air mass from the storage system flows to the housing space and causes an increase in the temperature of in the housing. At the same time, there is heat loss to the surroundings by convection and leakage of the air in the housing through the gaps. The energy leaks (L) are assumed to be 0–15% of the energy from the air mass flow from the storage system. The energy equations of air in the housing are therefore

$$m_{\mathrm{ah}} C_{\mathrm{a}} \frac{\mathrm{d}T_{\mathrm{h}}}{\mathrm{d}t} = (1 - L)\dot{m} C_{\mathrm{a}} (T_{\mathrm{ap}} - T_{\mathrm{ah}}) - U_{\mathrm{h}} A_{\mathrm{h}} (T_{\mathrm{ah}} - T_{\mathrm{sur}}) \quad (6)$$

where m_{ah} is mass of air in the housing, A_{h} is the area of housing wall for thermal loss, and U_{h} is the overall heat transfer coefficient of air in housing to the surroundings and is given by

$$U_{\mathrm{h}} = \frac{1}{\dfrac{1}{h_{\mathrm{i,h}}} + \dfrac{\Delta x}{k_{\mathrm{w}}} + \dfrac{1}{h_{\mathrm{ex,h}}}},$$

where $h_{\mathrm{i,h}}$ is the convective heat transfer coefficient of air in the housing, $h_{\mathrm{ex,h}}$ is the convective heat transfer coefficient of air outside housing, k_{w} is the thermal conductivity coefficient of housing wall, and Δx is the thickness of housing wall. The values of $h_{\mathrm{i,h}}$ and $h_{\mathrm{ex,h}}$ can be determined from (2).

Comparisons of the results

This section compares the temperatures measured from the scaled-down model with those calculated from the mathematical model. The objective is to assess the reliability, the agreement, and the variability of the results. The input parameters for the calculation include the constants and variables related to the characteristics of the storage pit, hot-air tube, and housing model. The constant parameters include the surrounding air obtained from the records of the Thai Meteorological Department [1], the soil mass temperature obtained from the measured results, the solar radiation calculated from the equation proposed by Exell and Kumar [14], the air properties [10] (density, Nusselt number, Prandtl number, specific heat, and thermal conductivity), the rock properties (a specific heat and thermal conductivity, absorption coefficient, effective diameter), and the acrylic sheet properties (specific heat and thermal conductivity, thickness, area). Table 2 summarizes the solar radiation, temperature of soil mass, and temperature of surrounding air as a function of time as used in the calculation.

Table 2 Input data for the calculation: solar radiation, temperature of soil mass and surrounding air.

Time of day	Solar radiation[a] (W/m^2)		Temperature (°C)		
			Surrounding air[b]		Soil mass[c]
	Avg.	Min	Avg.	Min	
06:00	58.4	19.5	19.2	10.4	28.5
07:00	185.2	133.7	20.2	10.7	28.4
08:00	323.8	258.4	22.4	12.8	28.8
09:00	457.3	364.9	24.6	15.9	29.3
10:00	567.0	450.8	26.8	18.8	29.8
11:00	636.2	496.0	28.9	21.3	30.3
12:00	653.8	493.8	31.0	23.9	30.8
13:00	617.2	446.2	32.7	25.9	31.3
14:00	532.1	361.9	33.7	26.9	31.9
15:00	411.9	256.5	33.9	27.3	32.3
16:00	274.5	147.8	32.3	26.8	32.4
17:00	138.3	51.8	29.4	25.1	32.2
18:00	21.2	0	26.0	22.5	31.9
19:00	0	0	23.5	20.2	31.7
20:00	0	0	22.4	18.5	31.4
21:00	0	0	22.0	17.0	31.1
22:00	0	0	21.6	15.6	30.8
23:00	0	0	21.3	14.6	30.5
24:00	0	0	20.9	14.0	30.2
01:00	0	0	20.6	13.4	29.9
02:00	0	0	20.1	12.8	29.6
03:00	0	0	19.7	12.2	29.4
04:00	0	0	19.4	11.6	29.1
05:00	0	0	19.0	11.3	28.8

[a] Using equation proposed by Exell and Kumar [14].
[b] Records from the Thai Meteorological Department [1].
[c] Measured from scaled-down model.

The variables include the characteristics of the storage pit (width, length, and depth), packed rock fragment properties (weight, collector surface, and thickness), characteristics of the hot-air tube (diameter, inclination, length, and elevation head between

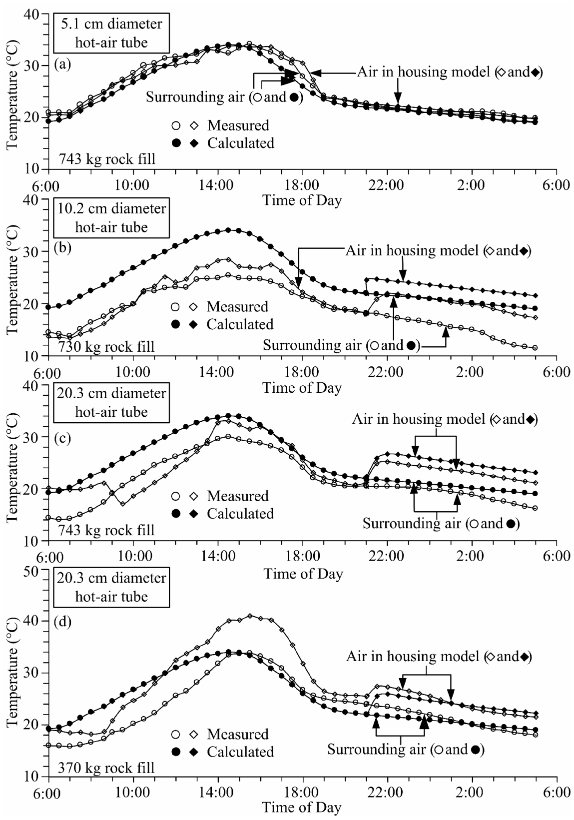

Fig. 4 Comparisons of temperature variation of the air in housing model (square dots) and the surrounding air (circle dots) from scaled-down model (light dots) with those the calculated results using mathematical model (solid dots).

inlet and outlet) and the volume of housing model. An unknown for this study is L, the proportion of heat energy leaking from the housing model. This unknown is determined from the measured results. The differential equations were integrated using Euler's method with MATLAB 7.0.

Fig. 4a–c compare the changes of air temperature in the housing model and the surrounding air using 5.1, 10.2, and 20.3 cm diameter hot-air tube with 743 kg of rock fragments. Fig. 4d compares the results using 20.3 cm diameter hot-air tube with 370 kg of rock fragments. The results from the two methods are similar. The larger hot-air tube provides a higher temperature at the housing model. The housing temperature is about 3–6 °C higher than that of the surrounding air. The calculation results suggest that about 10% of heat energy is leaked from the housing model.

Performance of storage system

An attempt is made here to assess the storage system efficiency and to determine the heat energy gained in the housing in the form of electrical energy. The housing model with the 10.2 cm diameter hot-air tube is considered here as an example. The amount of solar energy (Q_{r}) stored in the rock fill due to the direct gain of solar energy with the mass flow rate of air being zero, is given by:

$$Q_{\mathrm{r}} = m_{\mathrm{r}} C_{\mathrm{r}} \Delta T = [V_{\mathrm{bed}}(1-\varepsilon)\rho_{\mathrm{r}}] C_{\mathrm{r}} \Delta T,$$

where ΔT is the rock fragments temperature increase over a specified period of time, C_{r} is the specific heat of the rocks, m_{r} is the weight of the rock fragment, V_{bed} is the bulk volume of rock or the packed rock volume, ε is the void fraction of rock fill (= 0.50), and ρ_{r} is the density of rocks (= 2810 kg/m^3). The storage efficiency (η) of the rock fill is given by $\eta = Q_{\mathrm{r}}/I$, where I is the amount of solar radiation received over a specified period of time [15]. From the observations in the scale-down model, the average temperature increase of rock fragments is about 5 °C. The solar energy stored in the rock fill is estimated as 4.28 MJ. The amount of solar radiation received over a specified period of time (during 9.00 am–3.00 pm) is estimated as 12.4 MJ. The efficiency of this storage system is about 35%. By using the absorbed energy equation proposed by Sonntag et al [16], the heat energy gained in the housing is equivalent to 203 kJ of electrical energy.

DISCUSSION AND CONCLUSIONS

The results suggest that the efficiency of the storage system depends on the level of energy input, size and inclination of hot-air tube, heat losses from the pit, and the housing. The most suitable system seems to be a storage pit connected to the housing model using a 10.2 cm diameter hot-air tube inclined at about 30°. The top of storage pit should be covered with an isolator sheet (a textile, gunny-bags, or fabric sheet). This arrangement provides a temperature increase of up to 5 °C in the housing model. When the heat energy was allowed to be transferred to the housing model until 9:00 am, the temperature in the storage pit was still higher than that in the housing model. This implies that the efficiency of the heat transfer was not optimized. Further mathematical modelling is therefore needed to improve the efficiency of the system.

The mathematical equations are used to improve the system efficiency by producing comparable temperatures in the housing and storage pit during the heat transfer time. The heat transfer is simulated to compare with the actual temperature measured in the model. The calculated results agree with the measurements which can be concluded that the mathematical equations are reliable and suitable for the temperature predictions under different values of the physical parameters. The heat loss from the housing model is estimated at 10% of the total heat energy transfer. The variables from the sensitivity analysis including volume of the housing model, packed rock volume, collector area, and size of the hot-air tube are considered for the design recommendations.

From the observations on the scaled-down model it seems that the soil mass around the pit is not completely dry. The permeated water would evaporate and be transferred to the housing model. When the air in the housing cooled down in the morning, the vapour condensed on the ceiling. To solve this problem, the pit walls and floor should be covered with impermeable materials such as concrete, steel sheet, and rubber. This can increase the efficiency of rock fragments to store the heat energy since the heat loss to the soil mass would be reduced. The efficiency of the storage pit and the increase in housing temperature can be improved by several approaches such as the installation of a ventilator at the hot-air tube to increase the mass flow rate, putting double layers of acrylic sheet on top of the pit, and covering the pit walls and floor with impermeable material which can also reduce heat loss. Some housing with the walls made from bamboo should be covered with an insulator.

Acknowledgements: This research is funded by Suranaree University of Technology. Permission from this institute to publish this paper is gratefully acknowledged.

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