Characteristics of heat storage and release of gravel layer in solar collectors by hot air natural circulation

Moonki Jang
(1. College of Engineering, Shenyang Agricultural University, Shenyang 110161, China;
2. Chungbuk National University, Chungcheonbuk 361763, Korea)

Abstract: The thermal characteristics of heat storage and release of the gravel layer used in the solar collector in winter were analyzed. Air from the solar collector was expected to circulate through the gravel layer naturally without other energy consumption. The gravel layer consisted of river gravels with diameter from 50 mm to 100 mm. The temperature of the solar collector, gravel layer and cement mortar surface were measured respectively to analyze thermal characteristics of heat storage during daytime and heat release at night in the gravel layer. The horizontal and vertical heat characteristics of the gravel layer and cement mortar surface were analyzed. Results of the thermal characteristics of the gravel layer in the solar collector can be used as basic data for the thermal analysis of gravel layer.

Key words: solar collector; gravel layer; heat storage; heat release; hot air natural circulation
CLC number: S214 **Document code**: A **Article ID**: 1002-6819(2005)08-0126-06

Moonki Jang. **Characteristics of heat storage and release of gravel layer in solar collectors by hot air natural circulation** [J]. **Transactions of the CSAE**, 2005, 21(8): 126-131.

0 Introduction

Recently, for decreasing a fossil fuel use and environmental pollution, all countries are looking for other energy resources which can be applied to new architectures.

There are natural energy (solar energy, geothermal energy, biomass etc.), waste resource energy (chaff, waste wood, waste tire, waste oil, combustible trash etc.) and waste industry heat that can be used for reduction of fossil energy consumption. Considering resources, investment, environmental impact and economic performance, the method of heat storage of solar energy is the most desirable[1-5].

Sensible heat materials such as water, stone (gravel) and air are used for solar heat storage. Research materials for the heat storage at low temperature can be found easily, but the research materials about storing the heat of high temperature using the solar collector are limited. Therefore, river gravels which are safe and economical in use were used in this study.

The purpose of this study is to apply the solar collector and the gravel for floor heating of a solar house, based on analyzing past meteorological data, and measuring the solar radiation amount, temperature in the gravel layer and the surface temperature of cement mortar, as well as analyzing the thermal characteristics of heat storage and heat release in the gravel layer during daytime and nighttime.

Received date: 2005-04-05 Revised date: 2005-08-10
Biography: Moonki Jang (1971 -), Male, Born in Cheongju city, Chungbuk Province, Republic of South Korea, Ph. D candidate at Shenyang Agricultural University, Majoring in Agricultural Building Environment & Energy. College of Engineering, Shenyang Agricultural University, Shenyang 110161, China. Email: mkjang2000@yahoo.com

1 Mechanism of heat storage and heat release of the gravel layer

Sensible heat storage is based on temperature difference and heat capacity of materials. The heat exchanges are expressed by formula (1) and formula (2).

$$Q_s = m\int_{T_1}^{T_2} C_p \mathrm{d}t \quad (1)$$

$$Q_s = V\int_{T_1}^{T_2} \rho_p \mathrm{d}t \quad (2)$$

Where Q_s is the heat capacity, MJ; m is the mass of heat storage material, kg; V is the volume, m^3; C_p is the specific heat of the material, MJ/(kg·℃); T_1 is the initial temperature of heat storage, ℃; T_2 is the final temperature of heat storage, ℃; ρ is the density of the material, kg/m^3; t is the temperature at any time.

Therefore, heat capacity per unit volume of materials is,

$$q_s = \int_{T_1}^{T_2} C_p \mathrm{d}t \quad (3)$$

Where q_s is the heat capacity per unit volume, MJ/m^3.

2 Materials and methods for experiment

2.1 Materials and the equipment for experiment

2.1.1 Solar collector

The solar collector used was bought from Shenyang market. Table 1 shows its performance.

Table 1 Characteristics of the solar collector

Type of vacuum tube	Standard of vacuum tube /mm × mm	Capacity of heat tank /L	Number of vacuum tubes
Azul	D47×1500	157	28

2.1.2 Gravel

Gravel used as the heat storage material was picked in the Hun River situated in Shenyang city. And the diameter of the gravel ranges from 50 mm to 100 mm.

2.1.3 Pipe for connection

Material which connected solar collector and the gravel layer was a PVC tube. The outer diameter of the pipe is 110 mm, and the wall thickness is 3.2 mm.

2.1.4 Heating insulation panel

Heat insulation material which enclosed the gravel layer was polystyrene panel. Both sides of the polystyrene panel were steel plate. The thickness of the panel was 100 mm. Table 2 expresses the characteristics of the material.

Table 2 Characteristics of heating insulation panel

Mass /kg · m^{-2}	Electric heat coefficient K/W · (m^2 · K)	Soundproofing R/dB
11.93	0.330	23.0

2.2 Methods for experiment

The gravel layer and the heat tank were linked by PVC pipe to store heat of high temperature from the solar collectors. The gravel layer, which can store much heat as shown in figure 1, figure 2 and figure 3, has been wrapped by all heating insulation panel except the upper part. The upper part was constructed with the sand thickness of 10 mm and the cement mortar thickness of 30 mm on the gravel layer so that the stored heat can be emitted. Figure 1 shows the plane view of the gravel layer. Figure 2 shows the side view. Figrue 3 shows the positions of sensors measuring the temperature. Solar radiation data during the experimental period were from Shenyang Meteorological Observatory.

3 Results and analysis

3.1 Physical characteristics of gravel[10, 11]

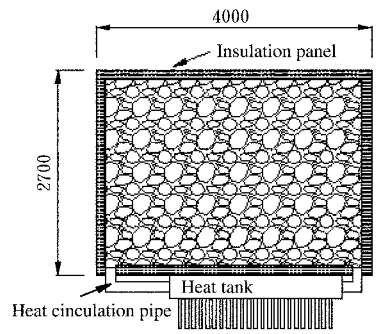

Fig. 1 Plane view of the gravel layer

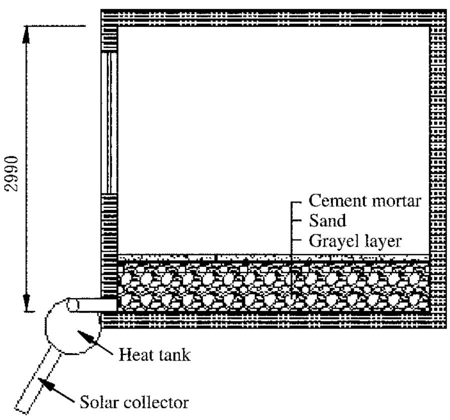

Fig. 2 Side view of the gravel layer

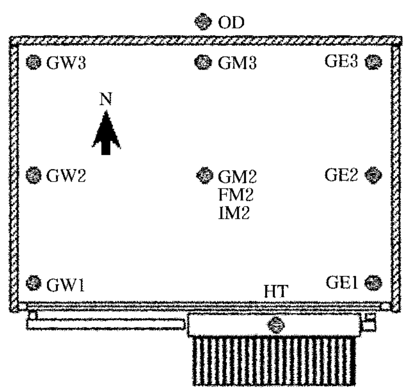

Fig. 3 Sensor positions of temperature measuring points

The density of the gravel used in the study as shown in Table 3 was 2.75 kg/cm^3. The porosity of the gravel layer was 45.7%. The bulk density of the gravel was 1438 kg/m^3. Table 3 shows its physical characteristics of the gravel which constitute the gravel layer. Figure 4 shows the grading curve of the gravel.

Table 3 Physical characteristics of gravel

Density /kg · cm^{-3}	Porosity /%	Size of gravel/mm	Bulk density /kg · m^{-3}	Fineness modulus
2.75	45.7	53～100	1438	2.58

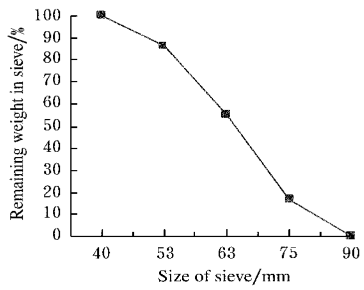

Fig. 4 Grading curve of the gravel

3.2 Experimental results

The temperatures of 1 point in the internal center of the heat tank, 8 points in the gravel layer, 3 points on upper surface of the cement mortar, 1 point outdoor and 1 point indoor were measured simultaneously to analyze the thermal characteristics of the gravel layer during daytime and nighttime. Table 4 shows the experimental result of each point during the experimental period.

Table 4 Maximum temperature and minimum temperature at measuring points*

	Maximum Temperature/℃	Time	Minimum Temperature/℃	Time
HT	48.6	14:26	-2.7	06:51
OD	1.4	13:22	-15.9	06:21
GE1	37.2	14:52	10.3	07:21
GE2	22.4	14:52	12.7	07:21
GE3	16.4	16:22	11.2	07:22
GM2	19.2	16:22	12.6	07:21
GM3	18.4	15:52	11.8	07:21
GW1	18.0	16:22	8.1	07:21
GW2	19.0	16:22	10.9	07:21
GW3	19.5	15:52	10.3	07:21
M2	33.0	13:22	11.0	06:51
FM2	17.6	15:52	12.3	07:21

* Average temperature from the 25th to the 26th, February.

The time of the maximum temperature of each point as given in Table 4 was between 1:00 PM and 5:00 PM and the maximum temperatures of the heat tank and the outdoor were 48.6℃ and 1.4℃, respectively. And the maximum temperatures of 8 points in the gravel layer and 3 points on the cement mortar surface were from 16 ℃ to 37 ℃ and 33.0℃, respectively.

The time of the minimum temperature was between 6:00 AM and 7:21 AM. The minimum temperatures of the heat tank and the outdoor were -2.7℃, and -15.9℃, respectively. And the minimum temperatures of the 8 points in the gravel layer and 3 points on the cement mortar surface were from 8.1℃ to 12.7℃ and 11.0℃, respectively.

Because the arrival time of the maximum temperature in the gravel layer was later than that of outdoor and the cooling speed of the gravel layer was slower than that of outdoor, the stored heat in the gravel layer in daytime was worth using at night. Also, because the arrival time of the minimum temperature in the gravel layer was about 1 hour later than that of outdoor, this time lag was worth utilizing to design a heating system for interior temperature estimation.

3.3 Changes of outdoor air temperature and heat tank temperature

To analyze the change of outdoor air temperature and heat tank temperature with time passing, outdoor air temperature and internal temperature of the heat tank were measured, respectively. As shown in figure 5, the changes of the outdoor air temperature and internal temperature of the heat tank had a similar inclination during daytime and nighttime. But, the change of internal temperature of heat tank during daytime and nighttime was greater than that outdoor. Specially, internal temperature of the heat tank fell down to 2.7℃ at dawn. Because the thermal capacity of air used as heat transfer medium was small, the internal temperature change of heat tank was great. As shown in figure 5, the maximum temperature of heat tank was 48.6℃ at about 2:00 PM and the maximum temperature of the outdoor was 1.4℃ at about 1:00 PM. Also, the minimum temperature of the heat tank was 15.9℃ at 6:21 AM and the minimum temperature of outdoors was -2.7℃ at 6:51 AM. The time interval between the outdoor air maximum temperature and the internal maximum temperature of the heat tank was about 1 hour. In case of using the solar collector of air circulation, the temperature of the heat collection with solar collector came up to about 47℃ according to experiment results. If the optimum temperature indoor is postulated by 16℃, the heat storage in the gravel layer from 9:00 AM to 7:00 PM can be used. The influence of temperature change in the heat tank on outdoor air temperature

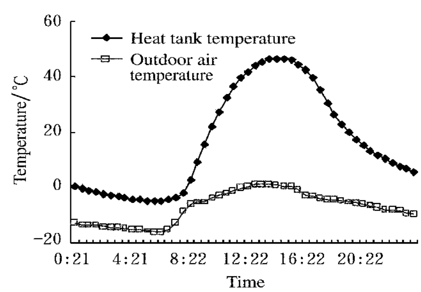

Fig. 5 Changes of outdoor air temperature and heat tank temperature

change was not significant in the daytime, but the influence of internal temperature change of the heat tank on outdoor air temperature was significant at night. Figure 5 shows the temperature changes of outdoors and the heat tank inside with time passing.

3.4 Temperature changes of gravel layer

The temperature change of the gravel layer was relatively small and stable during daytime and nighttime. As shown in figure 6, the temperature change of the heat tank was significant during daytime and nighttime, but the temperature change of the gravel layer was smaller than that of heat tank. Also, the temperature changes of the gravel layer can be seen as sensitive reflection in temperature change of outdoor at night. The maximum temperature of the gravel layer was on average 21.3℃ between 2:00 PM and 4:00 PM, and the minimum temperature was on average 11.0℃ between 7:00 AM and 8:00 AM. The heat storage period of the gravel layer was about 9 hours (between 7:00 AM and 4:00 PM), and the heat release period of the gravel layer was about 15 hours (between 4:00 PM and 7:00 AM next day). The temperature rising rate of the gravel layer was 1.26℃ per hour and the descending rate was 0.48℃ per hour. The temperature rising rate was greater than that of the descending rate.

Thus, because the temperature changes of the gravel layer in the daytime was greater than that at night, the practical use of house heating system which uses gravels and solar collectors may be regular. Figure 6 shows the temperature change of the gravel layer with time passing.

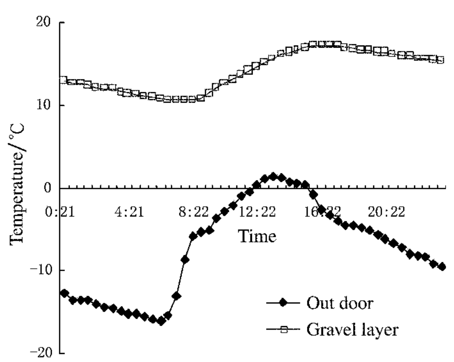

Fig. 6　Temperature changes of outdoor air and gravel layer

3.5 Temperature changes of heat tank, inlet and outlet of gravel layer

The temperature changes of the inlet and outlet in the gravel layer were similar to the internal temperature change of the heat tank. The temperature change of the gravel layer inlet was greater than that of outlet of the gravel layer, and it appeared similar to the inside of the heat tank. As shown in figure 7, the temperature rising rate of the gravel layer inlet was 4.18℃ per hour in the daytime, and the temperature descending rate of the gravel layer outlet was 2.28℃ per hour. In the daytime, because the temperature difference between the inlet and outlet of the gravel layer existed continuously, the natural circulation of air was possible without other energy consumption in the gravel layer inside. The temperature rising period of the gravel layer was about 9 hours from 7:00 AM to 4:00 PM and the temperature descending period was about 15 hours from 4:00 PM to 7:00 AM next day. Because the outlet in the gravel layer was situated in the farthest place from the solar collector, the temperature change of outlet in the gravel layer was smaller than that of the inlet of gravel layer caused by the outdoor air temperature and the heat loss of the solar collector. Figure 7 shows the temperature change of heat tank, inlet and outlet of the gravel layer, respectively.

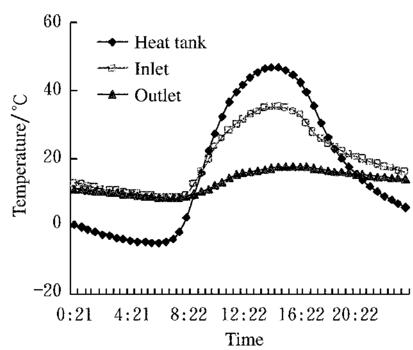

Fig. 7　Temperature changes of inlet and outlet of gravel layer and heat tank

3.6 Vertical temperature changes of gravel layer and cement mortar surface in heat storage element

To analyze the vertical temperature change of the heat storage element, the temperatures of the gravel layer and the cement mortar surface were measured. The temperature change of the gravel layer and the upper temperature of the cement mortar were almost similar. Because the solar collector was used as heat collection for high temperature unlike the typical solar heat collection, the temperature changes of the gravel layer and the cement mortar surface during daytime were greater than those at night. As shown in figure 8, the surface temperature of the cement mortar where the cement mortar and the indoor were in contact was not greater than that of the gravel layer. During daytime and nighttime, because the surface temperature of the cement mortar was lower than that of the gravel layer, the heat of gravel layer can be delivered to indoor without additional energy consumption. Figure 8 shows the vertical temperature changes of the heat storage element.

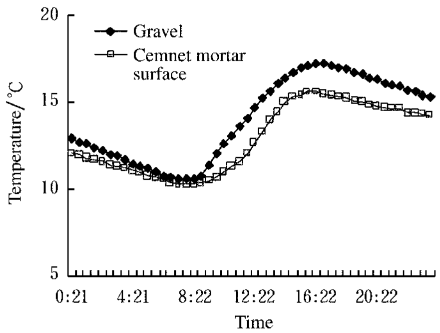

Fig. 8 Vertical temperature changes of heat storage element

3.7 Horizontal temperature changes of heat storage gravel layer

To analyze the horizontal temperature distribution of the heat storage element, the temperatures of the gravel layer and the upper surface of the cement mortar which constitutes the heat storage element were measured. The temperature changes of 8 points in the gravel layer were in similar inclination with time. When the positions of the inlet and outlet in the gravel layer are on a straight line, the temperatures of E1, M2 and W3 located on the straight line or located around the straight line were close somewhat or were higher than those of other points. The temperatures of E3 and W1 situated on the straight line and the one faraway place were relatively low. Specially, the reason that the temperature of W1 is low is a construction cause where the outlet pipe of the gravel layer was linked to outdoor. Figure 9 shows the horizontal temperature changes of the heat storage element with time passing.

4 Conclusions

The thermal characteristics of the gravel layer which uses the solar collector and the gravel were analyzed, the results are as follows:

1) The temperature of the heat storage element with the solar collector increased by 1.26℃ per hour, and decreased by 0.48℃ per hour. The inner temperature of the solar collector was 47℃.

2) The time of heat storage and heat release for the storage element was 9 hours (from 7:00 AM to 4:00 PM), and 15 hours (from 4:00 PM to 7:00 AM next day) respectively.

3) When the minimum temperature of outdoor air

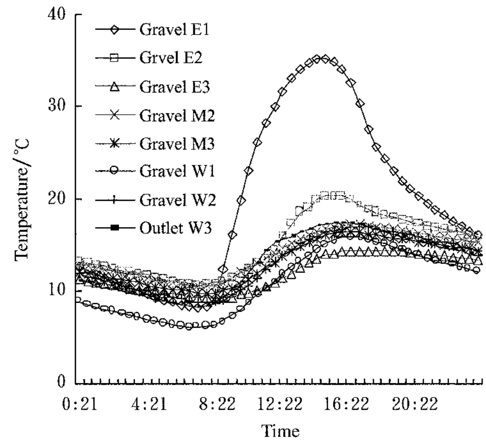

Fig. 9 Horizontal temperature changes of heat storage element

was -15.9℃ at 6:21 AM, the minimum temperature of the heat tank was -4.7℃ at 6:51 A.M. Because there were a lot of heat losses by heat transfer in the solar collector, heat storage of the solar collector is needed when common solar collectors are used.

4) Because the temperature differences between the heat collection element and heat storage element, between the gravel layer inlet and outlet, and between the heat storage element and using element were significant in this study, the natural circulation of air for heating was possible without other energy consumption.

[References]

[1] Lu Nan. Integrated Energy Systems in China[M]. FAO, 1994: 179-209.

[2] Liu Ronghou. Practical Technologies of Integrated Energy [M]. Shenyang: Liaoning Science and Technology Press, 1999: 110-150.

[3] Seong-bok Lee. A comparative study of proportional flux-modulation and various types of temperature-modulation approaches for radiant floor heating systems control[J]. ASHRAE Transactions, 1994, 100, Part. 1, 74-80.

[4] Lee, Seung-Soo. A study on the characteristics of the thermal environment in the using radiant floor jointly with convection cooling and heating at living room [D]. Kyongil University, 2001: 5-23.

[5] Kwang Seop Chung. A study on the experiments and transient simulations of ondol heating floor by varying pipe embedding depths and hot water supply conditions [D]. Hanyang University, 1991: 41-46.

[6] KM GB. Effect of a geometrical shape on steady-state natural convection in a cavity[D]. KAIST, 1998: 10-15.

[7] KM GB. Buoyant convection heat transfer of a realistic viscous fluid in a confined, space[D]. KAIST, 2003: 28-54.

[8] Park, Min Young. A study on analysis of the sensible heat storage wall and the paraffin's latent heat storage

wall[D]. Dong-A University, 1998: 7- 16.
[9] Lee Suk-Gun. Saving methods of cooling and heating energy in the solar heated underground rock storage greenhouse[R]. Ministry of Agriculture, 2001, 9, 35- 53.
[10] Method of Test for Sieve Analysis of Aggregates[S]. KS F 2502, 1996.
[11] Testing Method for Specific and Absorption of Coarse Aggregate[S]. KS F 2503, 1996.

太阳能集热器的热流气体对砾石的蓄放热特性研究

张文基[1,2]
(1. 沈阳农业大学工程学院, 沈阳 110161;　2. 韩国忠北大学农业生命环境学院, 清州 361763)

摘　要: 太阳能的蓄放热特性的研究对清洁能源太阳能的开发和利用具有重要意义。该文利用冬季太阳能集热器的热流气体, 对砾石的蓄放热特性进行了研究。以居民居住的标准房间(4 m ×2. 7 m)为依据进行了模拟; 利用太阳能集热器的热能与直径为 50～ 100 mm 的砾石铺设成 150 mm 厚度的地下蓄热系统进行蓄热和放热试验, 研究昼夜之间室内砾石的蓄热和放热特性; 通过测试太阳能集热器的内部温度、砾石层内部及室内地表面的温度, 研究了太阳能集热器的蓄热效率和转换效率, 同时分析了蓄热层及室内地表面的热传递特性; 为进一步开拓针对冬季寒冷地区太阳能蓄热型居民建筑物内部热环境方面的基础研究提供了科学的依据。
关键词: 太阳能集热器; 砾石层; 蓄热; 放热; 热流气体自然循环