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Hirasawa, Shigeki
Tsubota, Ryohei
Kawanami, Tsuyoshi
Shirai, Katsuaki

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Reduction of heat loss from solar thermal collector by diminishing natural convection with high-porosity porous medium

Shigeki Hirasawa*, Ryohei Tsubota, Tsuyoshi Kawanami, Katsuaki Shirai

Department of Mechanical Engineering, Kobe University
1-1 Rokkodai, Nada, Kobe, Hyogo 657-8501 Japan

***Corresponding Author:**
Shigeki Hirasawa
Department of Mechanical Engineering, Kobe University
1-1 Rokkodai, Nada, Kobe, Hyogo 657-8501 Japan
Tel: +81-78-803-6153
E-mail address: hirasawa@kobe-u.ac.jp

Abstract

We studied the reduction of natural convection heat loss from a solar thermal collector by placing a high-porosity porous medium above the collector plate in a solar thermal collector system. It is known that natural convection can be diminished in a porous medium. In order to use a porous medium in a solar thermal collector, it is necessary to minimize the shading effect of solar radiation caused by the porous medium. In this work, we used a series of offset wire screens made of fine nylon fishing lines of 0.05 mm in diameter with 2-mm pitch and a porosity of 0.999. The experimental apparatus consisted of a copper 300 mm × 300 mm collector plate with a selective absorption film on the surface. We measured the reduction rate of the convection heat loss from the collector plate and the shading effect for actual sun radiation by changing the condition of the porous medium, the temperature of the collector plate, and the inclined angle of the collector plate. Experimental results of the Nusselt number of natural convection in the high-porosity porous medium agreed with the equation proposed by Gupta et al. The effect of the inclined angle on the Nusselt number was small. The net reduction rate of natural convection heat loss was 7% by placing the high-porosity porous medium above the collector plate when the temperature of the collector plate was 100°C.

Keywords: Solar thermal collector; Natural convection; Porous medium; Collector efficiency

1. Introduction

To reduce consumption of fossil energy and to decrease CO_2 emissions alternative energy systems are constantly being developed. Solar energy is one of the clean energies. If every house uses more solar energy as their primary heat source, much fossil energy could be saved. Currently, a solar thermal collector system to obtain hot water (42°C) for bath-use is widely used in Japan. In order to expand the usage of solar energy, it is important to develop a highly efficient solar thermal collector systems to obtain hot water closer to 100°C. The authors (Hirasawa et al., 2007, 2010, 2011) have been developing a high-performance flat-plate-type solar thermal collector system. This system is effective at collecting heat by boiling of water as a working fluid because the pumping power consumption of the working fluid is very small (Hirasawa et al., 2011). The collector efficiency of a flat-plate-type is higher than that of a tubular-type because there is no useless collector space between the tubes. An evacuated solar collector system has a higher efficiency than a non-vacuum system in terms of collecting hot water closer to 100°C (Hirasawa et al., 2010). Benz et al. (1999) reported that natural convection does not occur in collectors at pressures lower than 5 kPa and that thermal losses decrease by 30 % compared with that at atmospheric pressure. They also reported that thermal conduction loss significantly decreases at pressure lower than 0.1 Pa because of the free-molecular heat transfer in low-density gas. However, the glass plate needs sufficient strength (e.g., by using thick, curved glass) to withstand the vacuum pressure over the large area of a flat-plate-type solar thermal collector. Also, it is not easy to maintain the vacuum condition for a long time in such collectors. There is therefore a need for new technology to reduce the natural convection heat loss of a non-vacuum flat-plate-type solar thermal collector. Malhotra et al. (1980) and Hollands et al. (1983) have proposed technology to suppress natural convection in the collectors by placing transparent sheets between the collector plate and the glass plate. Platzer (1992), Hollands et al. (1993), and Ziyan et al. (1997) have proposed technology to suppress natural convection in the collectors by using honeycomb structure. In this work, we propose reducing natural convection heat loss by placing a high-porosity porous medium above the collector plate.

There have been previous works on natural convection heat transfer performance in an enclosed space. It is well known that natural convection does not occur in a horizontal space with a higher temperature bottom plate when the Rayleigh number Ra is less than 1708 (Cooper, 1981; Churchill, 1983):

$$Ra_{critical} = \frac{g\beta\Delta T h^3}{\nu a} = 1708 \qquad (1)$$

Here, g is the acceleration of gravity, β is the volume coefficient of expansion, ΔT is the temperature difference of the top and bottom plates, h is the distance between the plates, ν is the kinematic viscosity, and a is the thermal diffusivity. The Nusselt number Nu of natural convection in the horizontal space is calculated with the following equation (Churchill, 1983).

$$Nu = \left\{ \left[1 + 1.446\left(1 - {}^{1708}\!/_{Ra}\right)\right]^{15} + \left[{}^{Ra\left[1 + \left(0.5/\Pr\right)^{9/16}\right]^{-16/9}}\!\Big/_{1420} \right]^{5} \right\}^{1/15} \tag{2}$$

Lapwood (1948), Katto et al. (1967), and Gupta et al. (1973) studied natural convection in an isotropic porous medium with spherical fillings with porosity near 0.5. They reported that natural convection does not occur in porous medium when the porous Rayleigh number Ra_s is less than $4\pi^2$:

$$Ra_{s\cdot critical} = \frac{g\beta\Delta T h^3}{\nu a}\frac{k}{h^2} = 4\pi^2 \tag{3}$$

where k is the permeability of the porous medium. The permeability is the property of a porous medium, which is an indication of fluid passage area (Collins, 1961). The Nusselt number Nu of natural convection in porous medium is calculated with the following equation (Gupta et al., 1973).

$$Nu = 1 + 2\left(1 - {}^{4\pi^2}\!/_{Ra_s}\right) + 0.016 Ra_s \tag{4}$$

In this work we try to use the critical porous Rayleigh number $Ra_{\mathrm{s\cdot critical}}$ to discuss experimental results of a high-porosity porous medium. Shiina et al. (2007, 2010) reported the equation of the critical porous Rayleigh number for the onset of natural convection in an anisotropic porous medium with thin vertical cylindrical rods. When we use a porous medium to reduce the natural convection heat loss of a solar thermal collector, it is necessary to minimize the shading effect of the solar radiation by the porous medium.

In this work, we study the reduction of natural convection heat loss from a solar thermal collector by placing a high-porosity porous medium above the collector plate. First we determined the experimental conditions near the critical factors to diminish natural convection in the porous medium. Next, we measured the reduction rate of natural convection heat loss and the shading effect with an experimental apparatus under actual solar radiation. These measurements were performed by changing the temperature of the collector plate and the inclined angle. Finally, we analyzed the effect of parameters on the net increase rate of the collector efficiency inserting the high-porosity porous medium in the flat-plate-type solar thermal collector.

Nomenclature

a	thermal diffusivity (m^2/s)
c	horizontal pitch of string (m)
D	shading effect of porous medium
d	diameter of string (m)
f	function of porosity
g	acceleration of gravity (m^2/s)
h	distance between collector plate and glass plate (m)
k	permeability (m^2)
Nu	Nusselt number of natural convection
n	Number of string net layers
p	vertical pitch of string net layers (m)

q_s inlet solar radiation (W/m^2)
q_1 absorbed solar radiation on collector plate (W/m^2)
q_2 upward convection and conduction loss (W/m^2)
q_3 upward radiation loss (W/m^2)
q_4 backward conduction loss (W/m^2)
q_5 collected heat to cooling water (W/m^2)
Ra Rayleigh number
$Ra_{critical}$ critical Rayleigh number
Ra_s porous Rayleigh number
$Ra_{s\cdot critical}$ critical porous Rayleigh number
α heat transfer coefficient (W/m^{2}K)
ε_1 absorptivity of selective absorption film on collector
ϕ porosity
λ thermal conductivity (W/mK)
ν kinematic viscosity (m^2/s)
θ inclined angle (°)
σ Stefan-Boltzmann constant (W/ m^{2}K^4)
τ_g transmissivity of glass plate for solar radiation
ψ transparency of string

2. Experiment

2.1 *Experimental apparatus and conditions*

Figures 1 and 2 show the model of the porous medium in a flat-plate-type solar thermal collector. This porous medium was a series of offset wire screens made of fine transparent strings, and the string net layers were placed parallel to the glass and collector plates. The transparent strings were nylon fishing lines with a diameter of d = 0.05 mm. Figures 3 and 4 show the experimental apparatus. The collector plate was a 300 mm × 300 mm copper plate with a thickness of 0.2 mm and a selective absorption film on the upper surface. The absorptivity of the selective absorption film for solar radiation was ε_1 = 0.95, and the emissivity of the selective absorption film for infrared radiation was ε_2 = 0.07 (BlueTec, 2009). A copper tube was soldered onto the back side of the collector plate to flow the cooling water. Above the collector plate there were a porous medium and a 3-mm thick glass plate. The transmissivity of the glass plate for solar radiation was τ_g = 0.9. There was a rock wool thermal insulator with a thickness of h_u = 0.05 m below the collector plate, and the thermal conductivity was λ_u = 0.05 W/mK. The side wall was a 2-mm thick Bakelite plate and the bottom wall was an aluminum plate. The enclosed space of the apparatus was completely sealed. There was a 50-mm thick rock wool thermal insulator outside the Bakelite plate. The T-type thermocouples were attached at 9 positions on the back side of the collector plate, 12 positions in the porous medium, and the inlet and outlet positions of the cooling water. Inlet temperature of the cooling water was changed to 20, 45, 60, and 90°C. The flow rate of the cooling water was about 1.3 × 10^{-6} m^3/s and the temperature change between the inlet and outlet was about 10°C. The inclined angle of the collector plate could be changed from the horizontal (inclined angle θ = 0°) to the normal direction of the solar radiation (about $\theta = 60°$ in December). Inlet solar radiation q_s was measured by the temperature rising speed of a small copper plate with a selective absorption film on the surface near the atmosphere temperature outside the apparatus. The small copper plate was a 10 mm × 10 mm plate with a T-type thermocouple soldered on the back side. There were a rock wool thermal insulator below the plate. When the temperature of the plate is near atmosphere temperature, the convection, conduction and radiation heat loss is negligibly small and all absorbed heat is used for the temperature rise of the plate. The solar radiation q_1 absorbed on the collector plate in the apparatus was measured by the temperature rising speed of the collector plate near atmosphere temperature without the flow of the cooling water. Using this method we can obtain q_s and q_1 simply without placing any obstruct sensors in the apparatus. Measuring errors of q_s and q_1 are estimated to be about ±3 %. The shading effect D of the porous medium was defined as the following equation using the inlet solar radiation q_s, the absorbed solar radiation on the collector plate q_1, the transmissivity of the glass plate for solar radiation $\tau_g = 0.9$, and the absorptivity of the selective absorption film on the collector plate $\varepsilon_1 = 0.95$.

$$D = 1 - q_1 / (q_s\ \tau_g\ \varepsilon_1) \tag{5}$$

The shading effect D is the reduction ratio of the inlet solar radiation by the porous medium. Collected heat q_5 was measured by the temperature change of the cooling water at a steady state of the collector plate heated with solar radiation. The upward convection and conduction loss q_2 from the collector plate was obtained by the following equations using the measured values of the absorbed solar radiation on the collector plate q_1, the collected heat by the temperature change of the cooling water q_5, the temperature of the collector plat T_p, and the surrounding air temperature T_a:

$$q_2 = q_1 - q_3 - q_4 - q_5 \tag{6}$$

$$q_3 = \sigma \cdot \frac{T_p^4 - T_g^4}{\frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_g} - 1} \tag{7}$$

$$q_4 = (\lambda_u / h_u)(T_p - T_a) \tag{8}$$

where q_3 is the upward radiation loss, q_4 is the backward conduction loss, ε_2 is the emissivity of the selective absorption film for infrared radiation ($\varepsilon_2 = 0.07$), ε_g is the emissivity of the glass plate for infrared radiation (glass plate is assumed to be opaque for infrared radiation $\varepsilon_g = 1$), σ is the Stefan-Boltzmann constant, λ_u is the thermal conductivity of a rock wool ($\lambda_u = 0.05$ W/mK), h_u is the thickness of the wool ($h_u = 0.05$ m), and T_g is the temperature of the glass plate assumed to be surrounding air temperature T_a. We also measured the upward convection and conduction loss q_2 at the steady state of the high-temperature collector plate in a room without solar radiation. The Nusselt number Nu of the upward convection and conduction loss from the collector plate was obtained from the following equation.

$$Nu = \frac{q_2 h}{\lambda_a (T_p - T_a)} \tag{9}$$

where λ_a is the thermal conductivity of air ($\lambda_a = 0.028$ W/mK) and h is the distance between the collector plate and the glass plate.

We set five experimental conditions for the porous medium as shown in Table 1. The structure of the porous medium is shown in Figs. 1 and 2. As the diameter of the string d is very small, heat conduction rate through the string is small and the heat transfer phenomena in the porous medium is assumed to be isotropic. The permeability of the porous medium k of these conditions is calculated with the following equation (Shiina et al., 2007, 2010) to calculate the porous Rayleigh number Ra_s:

$$k = d^2 f / 32(1-\phi) \tag{10}$$

$$f = \ln\frac{1}{1-\phi} - 1.476 + \frac{2(1-\phi) - 0.7959(1-\phi)^2}{1 + 0.4892(1-\phi) - 1.605(1-\phi)^2} \tag{11}$$

$$\phi = 1 - \frac{\pi d^2}{2cp} \tag{12}$$

where ϕ is the porosity of a porous medium. Equations (10) – (12) were obtained from the flow drag calculation with the Stokes equations of motion for a viscous fluid flowing perpendicular to the axes of cylinders arrays (Drummond et al., 1984). The shading effect D of the solar radiation by the porous medium is calculated by the following equation.

$$D = 1 - \left\{1 - \frac{2d(1-\psi)}{c}\right\}^n \tag{13}$$

where ψ is the transparency of a string. Equation (13) was obtained from that the shading ratio of each net layer is $\{2d(1-\psi)/c\}$. The transparency of a nylon string is assumed to be ψ = 0.88. Condition No. 1 in Table 1 is the case in which the diameter of the string d = 0.05 mm, the horizontal pitch of the string c = 2 mm, the vertical pitch of the string net layers p = 2 mm, the number of the string net layers n = 6, the distance between the collector plate and the glass plate h = 14 mm, and the porous Rayleigh number of Condition No. 1 was Ra_s = 25 while the average porosity was determined to be 0.999, which is less than the critical porous Rayleigh number $Ra_{s\cdot critical} = 4\pi^2$, which means there is no natural convection in the porous medium. Condition No. 2 is the case in which the number of the string net layers n = 8. The porous Rayleigh number of condition No. 2 is near $Ra_{s\cdot critical}$. Condition No. 3 is the case in which h = 34 mm by inserting 10 mm space between the glass plate and the top layer of the string net, and another 10 mm space between the collector plate and the bottom layer of the string net. Condition No. 4 is the case in which the vertical pitch of the string net layers p is 2 and 10 mm alternately. The porous Rayleigh number of conditions No. 3 and No. 4 are greater than $Ra_{s\cdot critical}$, meaning that natural convection might occur in the porous medium. Condition No. 5 is the case with no porous medium. The Rayleigh number of condition No. 5 is $Ra = 5.1 \times 10^5$ which is greater than $Ra_{critical}$ = 1708, so natural convection occurs in the space.

2.2 *Experimental results*

We measured the shading effect of the porous medium and the upward convection and conduction loss from the collector plate under five experimental conditions, as shown in Table 1. Experiments were performed under actual solar radiation on a sunny day at 10:00

– 14:00 in December 2012 in Kobe, Japan. We also measured the heat loss at steady state of the high-temperature collector plate in a room without solar radiation.

Figure 5 shows the experimental results of the shading effect D of the porous medium for conditions No. 1 – No. 4 measured with a 100°C inclined angle $\theta = 60°$ collector plate with solar radiation. The calculation result of Eq. (13) is shown as a black line. Experimental results and the calculation result agreed within a 2 % error rate.

Figure 6 shows the experimental results of the relation between the porous Rayleigh number Ra_s and the Nusselt number Nu of the upward convection and conduction loss from the collector plate for conditions No. 1 – No. 4 measured with a 80°C horizontal collector plate in a room without solar radiation. The Nusselt number for condition No. 1 was near 1.0, which shows that there was no natural convection in the porous medium. However the Nusselt number for conditions No. 2 – No. 4 were greater than 1.0, indicating that natural convection had occurred. For condition No. 2, the porous Rayleigh number was near $Ra_{s\cdot critical}$, but only weak natural convection occurred. This is because the string pitch used in the experimental apparatus had some manufacturing errors. The calculation result of Eq. (4) is shown as a black line. Experimental results and the calculation result agreed within a 30 % error rate.

Figure 7 shows the experimental results of the relation between the Rayleigh number Ra and the Nusselt number Nu for conditions No. 1 – No. 5 measured with an 80°C horizontal collector plate in a room without solar radiation. The calculation result of Eq. (2) is indicated by the black line. The experimental result of condition No. 5 without the porous medium and the calculation result were in good agreement. The experimental results of conditions No. 1 – No. 4 were about 30% lower than the calculation result due to the effect of the porous medium.

Figures 8 and 9 show the vertical temperature distribution in the porous medium for conditions No. 1 and No. 5 measured with the 80°C inclined angle $\theta = 60°$ collector plate in a room without solar radiation. The temperature distribution was almost linear for condition No. 1, indicating that there was no natural convection in the porous medium. The temperature distribution for condition No. 5 also showed that there was natural convection.

Figures 10 and 11 show the temperature distribution in the collector plate for conditions No. 1 and No. 5 measured with the 100°C and inclined angle $\theta = 60°$ collector plate with solar radiation. The center temperature of the collector plate was high. The temperature difference between the top and bottom ends of the collector plate was small for condition No. 1 because there was no natural convection. However, the bottom end temperature was lower than the top end temperature for condition No. 5 due to the natural convection.

Figure 12 shows the effect of the inclined angle θ on the Nusselt number Nu for conditions No. 1 and No. 5 measured with the 80°C collector plate in a room without solar radiation. The effect of the inclined angle on the Nusselt number was small.

Figures 13 and 14 show the effect of the collector temperature on the collector efficiency for conditions No. 1 and No. 5 measured with the inclined angle θ=60° collector plate with solar radiation. We define the collector efficiency as the ratio of the collected heat q_5 by the inlet solar radiation q_s. The collector efficiency was high at a low collector temperature because of the low heat loss.

We found that the shading effect D of the porous medium was accurately calculated with Eq. (13) and that the Nusselt number Nu of the upward convection and the conduction loss from the collector plate was well calculated with Eq. (4) proposed by Gupta et al. (1973).

3. Analysis of collector efficiency

We calculated the effect of the various parameters on the collector efficiency of a solar thermal collector with a high-porosity porous medium. The calculation conditions were similar to the experimental conditions, although with a few differences. Figures 1 and 2 show the calculation model of the porous medium in a flat-plate-type solar thermal collector. The conditions of the porous medium are that it is made of transparent nylon strings with a diameter of d = 0.05 mm and a horizontal pitch c = 2 mm, vertical pitch p = 2 mm, number of string net layers n = 7, and transparency of string ψ = 0.88. The inlet solar radiation was q_s = 800 W/m^2, the temperature of the collector plate was T_p = 100°C, the temperature of the glass plate was T_g =25°C, the surrounding air temperature was T_a = 25°C, and the downward thermal insulator was a urethane wool with a thermal conductivity of λ_u = 0.024 W/mK and a thickness of h_u = 0.1 m.

The collected heat per unit area of the collector plate q_5 was calculated by the following equation.

$$q_5 = q_1 - q_2 - q_3 - q_4 \tag{14}$$

The absorbed solar radiation q_1 was calculated with the following equation.

$$q_1 = q_s\ \tau_g\ \varepsilon_1\ (1 - D) \tag{15}$$

where q_s is the inlet solar radiation (q_s = 800 W/m^2), τ_g is the transmissivity of the glass plate (τ_g = 0.93), ε_1 is the absorptivity of the selective absorption film on the collector plate for solar radiation (ε_1 = 0.95), and D is the shading effect calculated by Eq. (13). The upward natural convection heat loss q_2 was calculated with the following equation.

$$q_2 = \alpha(T_p - T_g) \tag{16}$$

where α is the heat transfer coefficient of natural convection calculated from the Nusselt number using Eq. (4). The radiation loss q_3 was calculated with Eq. (7). The backward conduction loss through the wool q_4 was calculated with Eq. (8). When natural convection occurred in a horizontal space without porous medium of h = 0.05 m (experimental condition No. 5), the Nusselt number was Nu = 5 and the upward convection heat loss was q_{20} = 210 W/m^2 for our calculation condition. Therefore, the reduction rate of the upward convection and conduction heat loss without natural convection by placing the porous medium above the collector plate was defined as $\{(q_{20} - q_2) / q_s\}$. The net increase of collector efficiency was then defined as $\{(q_{20} - q_2) / q_s - D\}$.

Figure 15 shows the effect of the number of string net layers n on the ratio of the porous Rayleigh number (Ra_s / $Ra_{s\cdot critical}$) (black broken line), the shading effect D (blue line, negative value of $-D$ is shown), the reduction of the upward convection and conduction heat loss (brown line), and the net increase of the collector efficiency (green line). When the number of the string net layers n = 8 with the string diameter d = 0.05 mm, the net increase of collector efficiency was 7 %, which was the highest.

Figures 16, 17, and 18 show the effects of the string diameter d, the horizontal string pitch c, and the distance between the lower and upper plates h on the ratio of the porous

Rayleigh number (Ra_s / $Ra_{s\text{-}critical}$), the shading effect D, the reduction of upward convection and conduction heat loss, and the net increase of the collector efficiency. When the distance between the collector plate and the glass plate h was larger than $\{(n + 1) \times p\}$, a space was inserted between the glass plate and the top layer of the string net. When the space between the glass plate and the top layer of the string net is greater than the pitch of string net layers p, the collector efficiency decreases. The highest net increase of the collector efficiency was also 7% for all cases. We found that the collector efficiency of the no natural convection by porous medium was 7% higher than the conventional collector. In contrast the increase rates of collector efficiency of the evacuated solar thermal collectors from the conventional collector was 22%, which were obtained for the distance between the lower and upper plates h =50 mm. Even though the increase rate by no natural convection by placing a high-porosity porous medium in the solar thermal collector was low, it is a good way to increase collector efficiency because it is not necessary to maintain the vacuum condition for as long as a solar collector. Under the condition of no natural convection by porous medium, the upward convection and conduction heat loss was 20%, the upward radiation heat loss was 6%, the downward conduction heat loss was 2%, the reflection and absorption of glass was 12%, and the collector efficiency was 60%.

4. Summary

We studied the reduction of natural convection heat loss from a solar thermal collector by placing a high-porosity porous medium above the collector plate. We obtained the following results.

1. Upward convection and conduction heat loss of a collector plate can be reduced by placing the porous medium above the collector plate. Under our standard condition, the net increase of the collector efficiency from the conventional collector was 7%, and the collector efficiency was 60% when the temperature of the collector plate was 100°C.

2. Experimental results of the Nusselt number of natural convection in a porous medium with high porosity agreed with Eq. (4), previously proposed by Gupta et al. The effect of inclined angle on the Nusselt number was small.

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Table 1 Experimental conditions of porous medium.

Condition No.	1	2	3	4	5
Diameter d (mm)	0.05	0.05	0.05	0.05	0
Horizontal pitch c (mm)	2	2	2	2	0
Vertical pitch p (mm)	2	2	2	2, 10	0
Number of string net layers n	6	8	8	8	0
Distance h (mm)	14	18	34	58	50
Ra_s / $Ra_{s\cdot critical}$	0.6	0.8	1.5	2.6	–

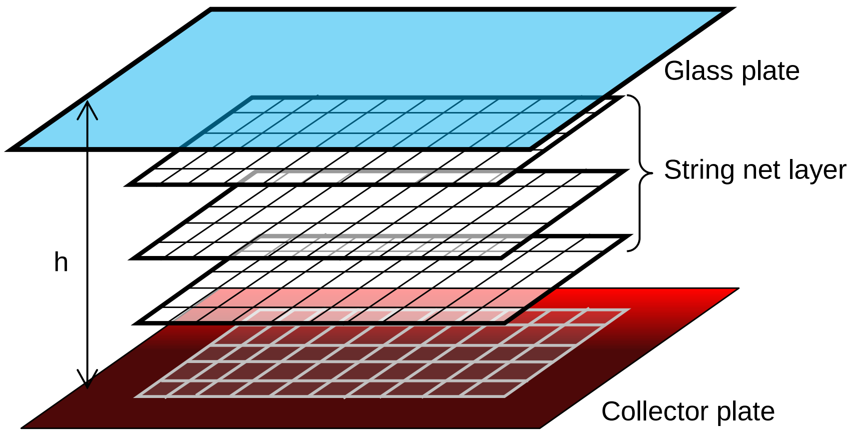

Fig. 1. Model of porous medium in flat-plate-type solar thermal collector.

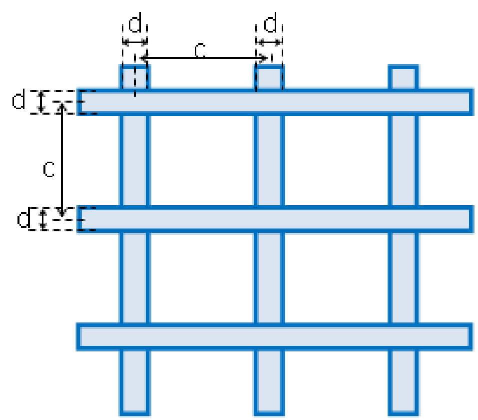

Fig. 2. Schematic view of string net.

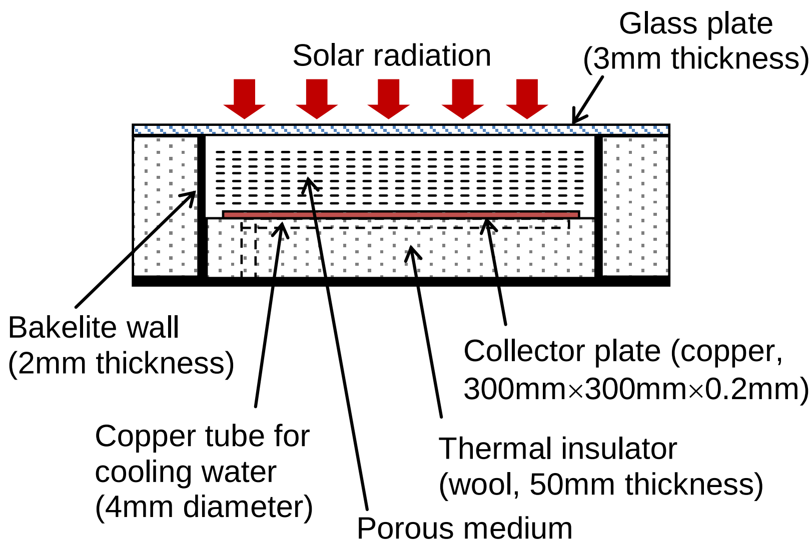

Fig. 3. Experimental apparatus.

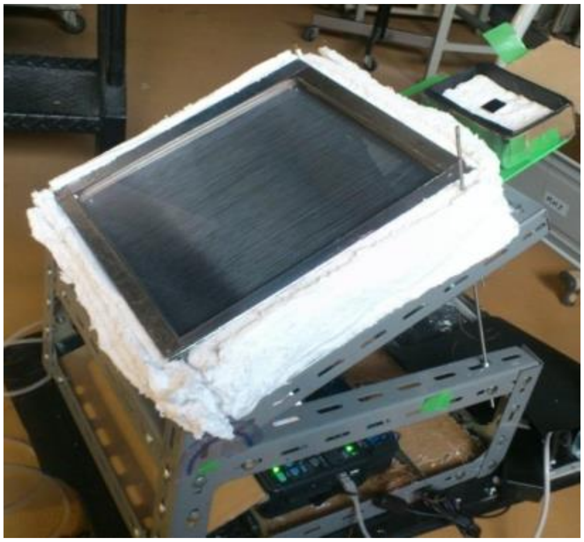

Fig. 4. Outside view of experimental apparatus.

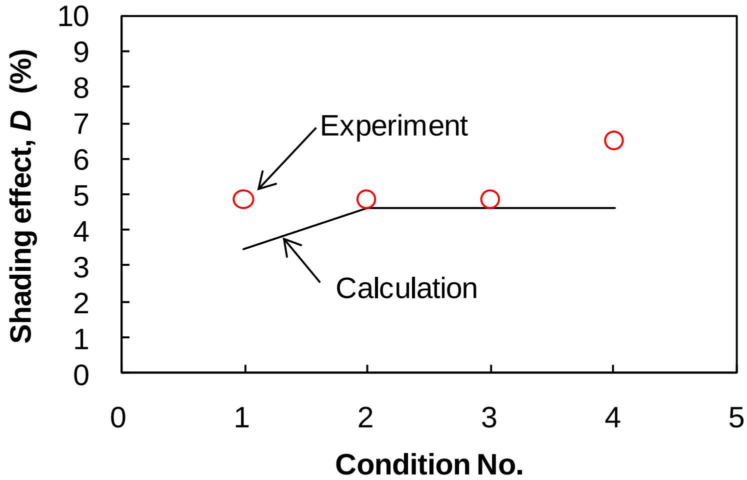

Fig. 5. Shading effect of porous medium.

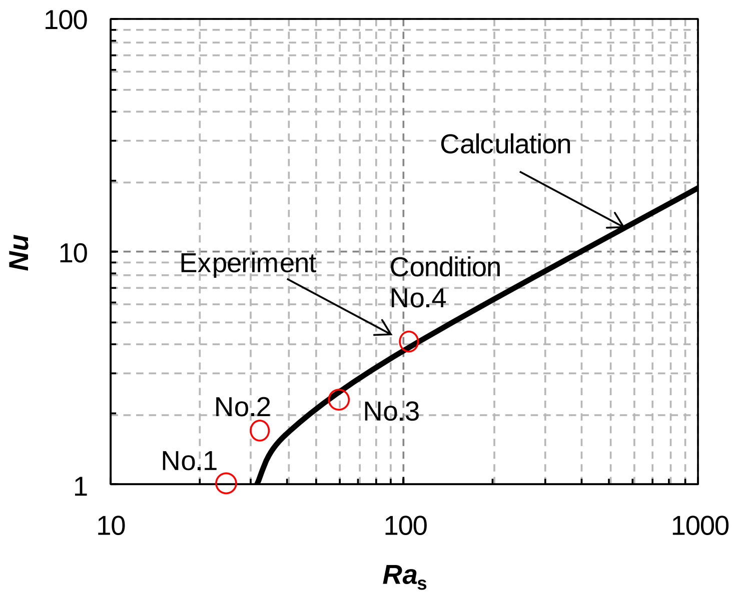

Fig. 6. Porous Rayleigh number and Nusselt number.

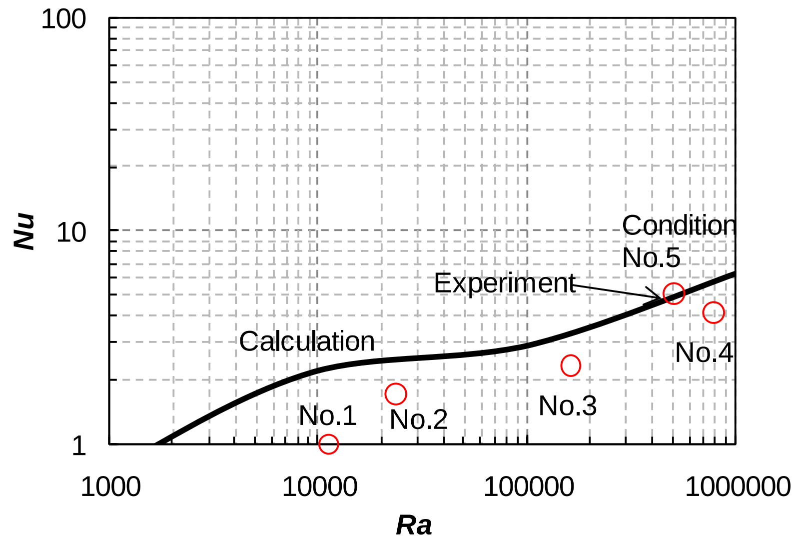

Fig. 7. Rayleigh number and Nusselt number.

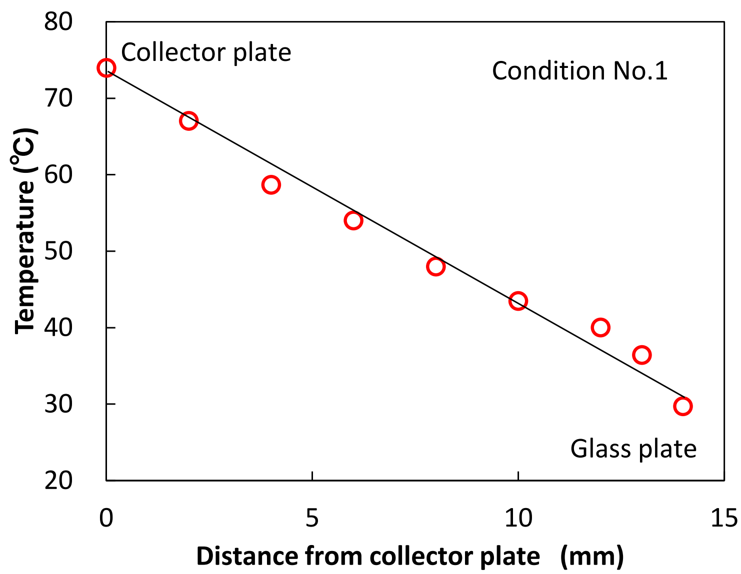

Fig. 8. Temperature distribution in porous medium for condition No. 1.

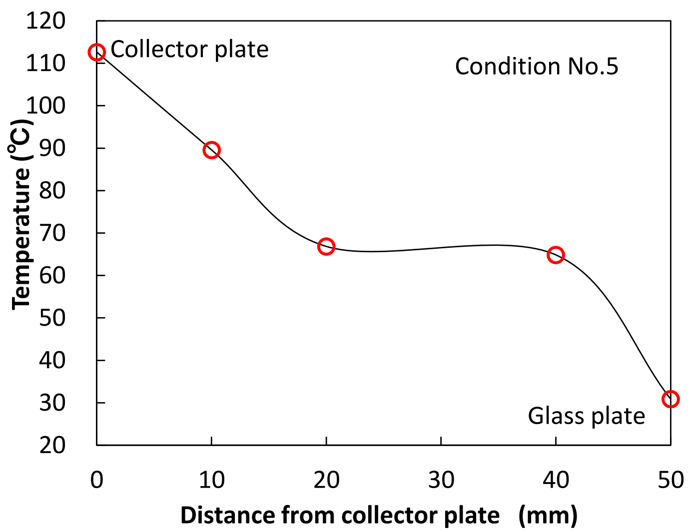

Fig. 9. Temperature distribution in porous medium for condition No. 5.

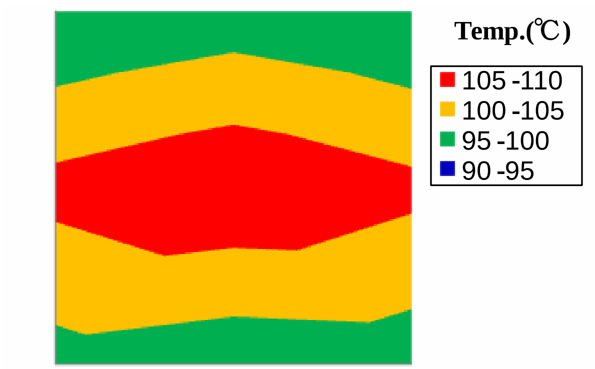

Fig. 10. Temperature distribution in collector plate for condition No. 1.

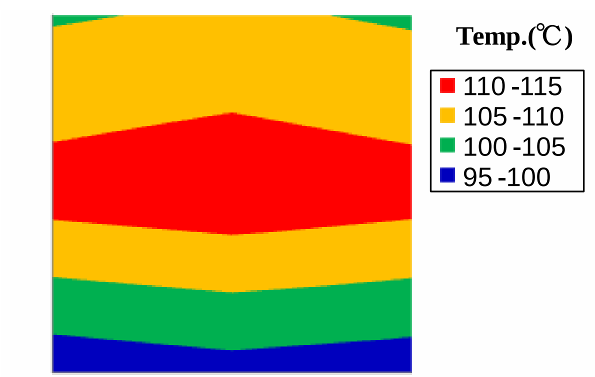

Fig. 11. Temperature distribution for condition No. 5.

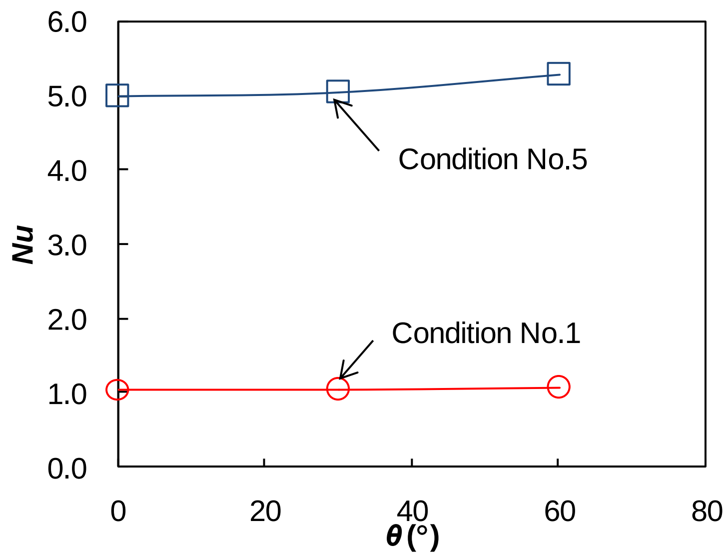

Fig. 12. Effect of inclined angle on Nusselt number for conditions No. 1 and No. 5.

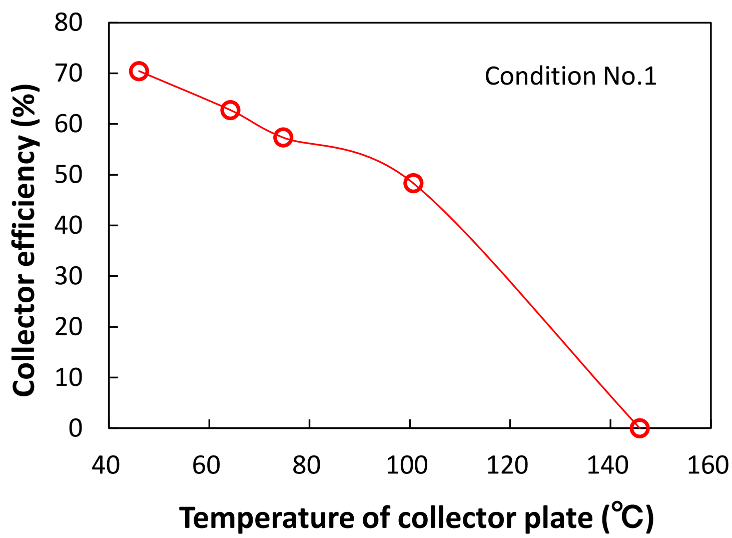

Fig. 13. Effect of collector temperature on collector efficiency for condition No. 1.

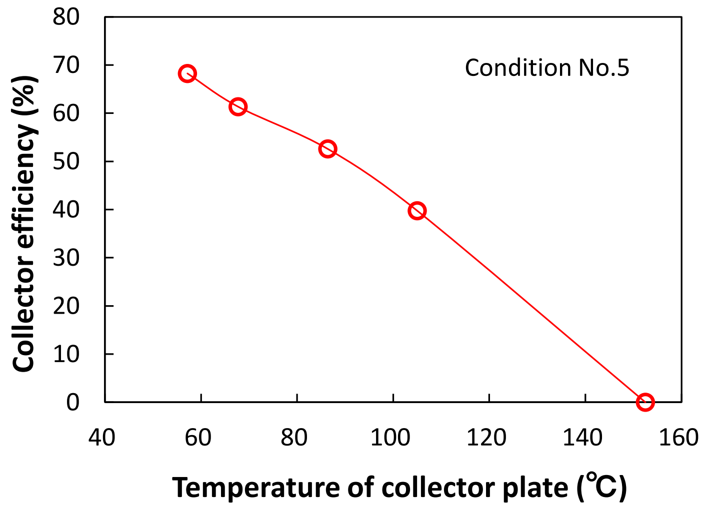

Fig. 14. Effect of collector temperature on collector efficiency for condition No. 5.

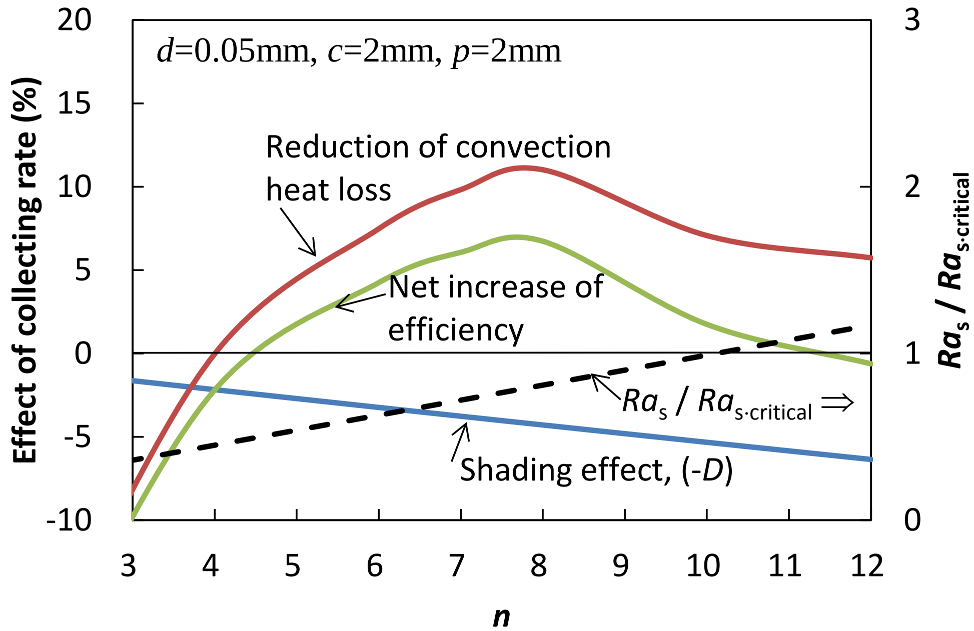

Fig. 15. Effect of number of string net layers.

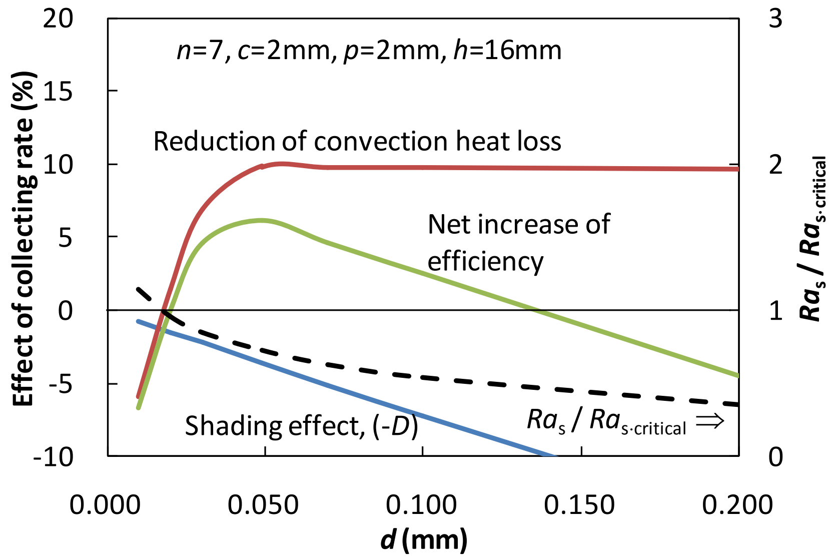

Fig. 16. Effect of string diameter.

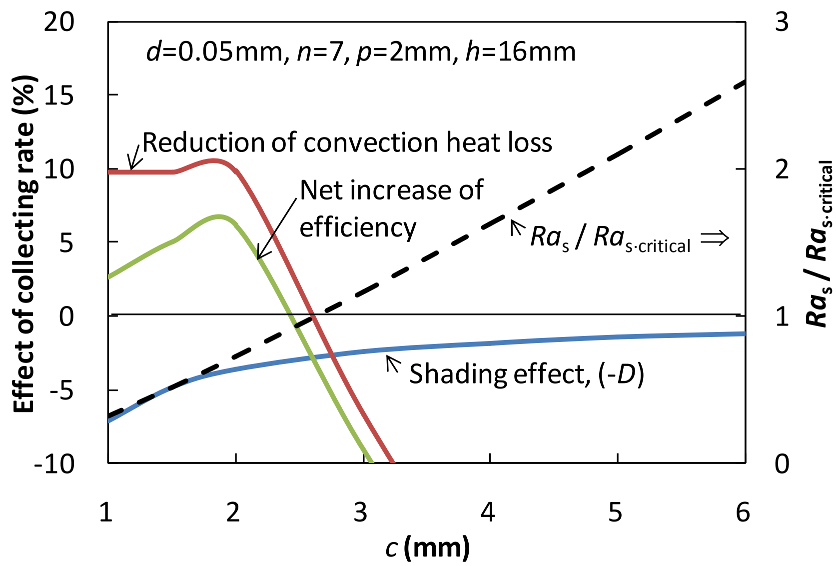

Fig. 17. Effect of horizontal string pitch.

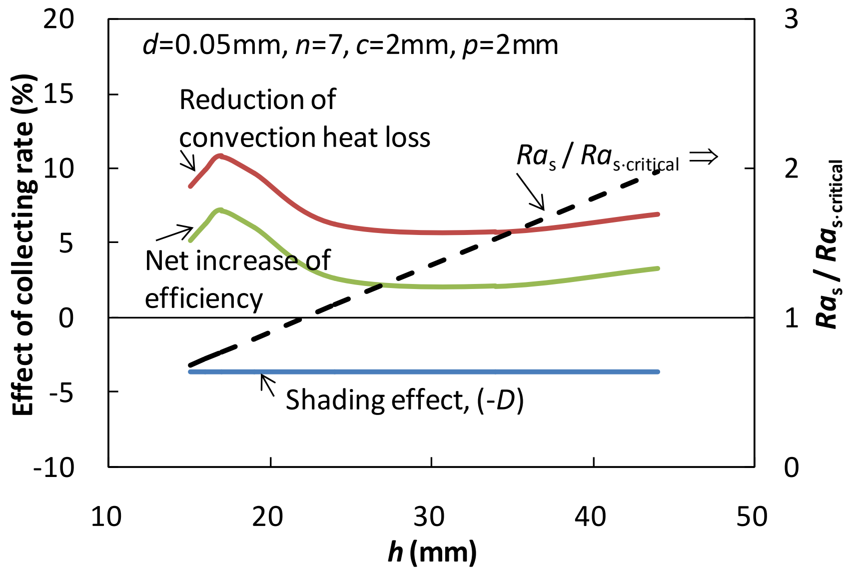

Fig. 18. Effect of distance between collector plate and glass plate.