Performance of Honeycomb Solar Collectors* (Effects of Thickness, Aspect Ratio and Height of Honeycomb Structure)

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Experiments have been made to clarify the effects of the thickness, aspect ratio and height of honeycomb structures on the performance of honeycomb solar collectors, and a new model, in which the honeycomb heat capacity and the absorption of the solar irradiation by the honeycomb wall are taken into account, has been proposed to predict the performance. Calculated values by this model agree better with the experimental results than those by a previous model, and the suitable honeycomb thickness, aspect ratio and height are determined by using this model. Furthermore, the performance of the honeycomb collector is compared with those of other types of collectors and the effectiveness of the honeycomb collector is indicated.

Key Words : Thermal Engineering Equipment, Solar Energy, Honeycomb Collector, Performance, Honeycomb Configuration

1. Introduction

The efficiency of solar collectors decreases steeply with increasing heat loss because of the small energy density of the solar irradiation. Among many types of solar collectors, a honeycomb collector is considered to be very effective since it reduces heat losses by both convection and radiation. Although several studies⁽¹⁾⁻⁽⁵⁾ have been reported on the performance of the honeycomb collector, the effects of the wall thickness, aspect ratio and height of the honeycomb structure are not systematically understood. Furthermore, since the performance strongly depends on the solar incident angle, the usefulness of the honeycomb collectors can not be correctly estimated by the NBS method in which the performance is evaluated only near the time of southing of the sun⁽⁵⁾.

In the present study, experiments are carried out under such an actual condition that the solar incident angle varies widely with time, to estimate the performance of the honeycomb collectors for various wall thicknesses and aspect ratios of the honeycomb structure. The results are com-

pared with those of a conventional flat plate collector. Moreover, by modification of the previous model^{(1),(2)}, a new calculation model is proposed in which the heat capacity of the honeycomb structure and the absorption of solar irradiation by the honeycomb wall are taken into account. With this model, the effects of the wall thickness, aspect ratio and height of the honeycomb structures on the collector performance are systematically clarified, and the performance of the honeycomb collector is compared with those of other types of collectors.

2. Experimental apparatus and procedures

Solar collectors and a flow circulation system are schematically shown in Fig.1. Two collectors having the same collector plate area $A_c=1.35 \text{ m}^2$ are employed in this work. One is a honeycomb

Fig.1 Experimental apparatus

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collector and the other a conventional flat plate collector, which are prepared to directly compare their performances. The collector surfaces are inclined at 30 degrees to the horizontal, and water with a flow rate $\dot{m}$ controlled by a valve goes into each collector and then returns to a storage tank. Temperatures at points shown by symbols a ~ h in Fig.1 and the ambient air temperature T_a are measured with copper-constantan thermocouples. The solar irradiation is measured by an Epply pyranometer mounted at the same inclination as the collector plate, and the wind speed, by a Biram vane anemometer.

Figure 2 shows the configuration and dimensions of the honeycomb collector. A collector plate consists of a 0.3 mm-thick copper plate painted black, and 11 collector tubes, the outer and inner diameters of which are $d_o=12.7$ mm and $d_i=11.1$ mm, are partially soldered to the collector plate. The distance W between collector tubes is 105 mm and a 2.7 mm-thick glass plate is used as a cover glass. The honeycomb structure is placed in the space $L_a=50$ mm between the collector plate and the cover glass. The sides and bottom of the collector are insulated by 25 mm- and 50 mm-thick glass wool, respectively.

The top view of honeycomb arrangements and the shape of honeycomb elements are shown in Fig.3. Figures 3(a) and (b) indicate a pyrex-glass cylinder honeycomb (abbreviated to G-honeycomb) and a hexagonal polycarbonate honeycomb (abbreviated to P-honeycomb), respectively. Symbols D_i , D_o , δ and L_a represent the inner diameter, outer diameter (equivalent diameter for P-honeycomb), thickness and height of the honeycomb elements, respectively. The aspect ratio As is defined as L_a/D_i for both honeycomb elements.

Table 1 shows the specifications of the honeycomb structure. Symbol f_h in Table 1 denotes the ratio of the honeycomb cross-sectional area to the collector plate area and m_h is the mass of the honeycomb structure. The wall thickness δ of G-honeycomb is 2.1, 1.2 and 1.0 mm, and that of P-honeycomb 0.52 and 0.11 mm. Ex-

periments are performed for the aspect ratio $As=1.1$, 3.7 and 6.2 in the case of G-honeycomb and for $As=5.0$ in the case of P-honeycomb. The specific heat C_h of the polycarbonate is larger, but its thermal conductivity λ_h is much smaller, than those of the pyrex glass. The values of absorption coefficient $K^{(6)}$ are estimated from the measurements of spectral transmittance of materials and the spectral irradiation of the sun. The value of K of polycarbonate is much larger than that of the pyrex glass, and that of the cover glass is 35.2 m^{-1} . The heat capacity $m_h C_h$ of the honeycomb structure with $\delta=0.11$ mm is nearly equal to the sum of those of the collector plate and the collector tubes and is $2.9 \times 10^3 \text{ J/K}$. Since this value is not very large, the honeycomb heat capacity does not significantly affect the collector performance in this case as explained later. Experiments are performed from 8 a.m. to 6 p.m. on clear days to estimate the performance of the honeycomb and the flat plate collectors under the actual working conditions. Hence, the procedure is different from the NBS method in which measurements are made only near the time of southing of the sun.

3. Experimental results

3.1 Effects of the honeycomb thickness on the collector performance

The effects of the honeycomb thickness on the collector performance are shown in Fig.4 for almost the same aspect ratio As in the case of $\dot{m}=0.0124 \text{ Kg}/(\text{m}^2 \cdot \text{s})$. The abscissa is the ratio $X=(T_{fm}-T_a)/I_s$ of the temperature difference between the average water temperature T_{fm} and the ambient air temperature T_a to the solar irradiation I_s , and the ordinate is the col-

Fig.2 Configuration and dimensions of honeycomb collector

Fig.3 Arrangements and elements of honeycomb structures

Table 1 Specifications of honeycomb structures

Values	Materials	Pyrex glass			Polycarbonate	
δ Thickness	mm	2.1	1.2	1.0	0.52	0.11
As Aspect ratio		1.1	3.7	6.2		5.0
L_a Height	mm	50.0			50.0	
D_i Inside diameter	mm	45.2	13.6	8.1	10.00	10.00
D_o Outside diameter	mm	49.4	16.0	10.1	11.04	10.22
f_h Cross-sectional area ratio		0.131	0.246	0.318	0.125	0.029
m_h Specific mass	Kg/m^2	14.17	26.64	34.50	7.49	1.71
C_h Specific heat	$\text{J}/(\text{Kg} \cdot \text{K})$	0.754×10^3			1.256×10^3	
$m_h C_h$ Heat capacity	J/K	1.44×10^4	2.70×10^4	3.50×10^4	1.26×10^4	2.89×10^4
λ_h Thermal conductivity	$\text{W}/(\text{m} \cdot \text{K})$	0.756			0.193	
K Absorption coefficient	$1/\text{m}$	14.0			84.0

Fig.4 Effects of wall thickness on collector performance ($\dot{m}=0.0124 \text{ kg}/(\text{m}^2 \cdot \text{s})$)

lector efficiency $\eta \equiv q_u/I_s$ defined as the ratio of the collected useful heat flux q_u to I_s . The collector efficiency of the flat plate is also shown for comparison. As seen from this figure, the efficiencies of the honeycomb collectors are smaller than that of the flat plate collector at points Q indicating the starting points of experiments and they increase with X up to maximum points b. At the point b, η of the honeycomb collector for $\delta=0.11$ mm is much larger than that of the flat plate collector. As X increases beyond the point b, the difference between the efficiencies of the honeycomb and flat plate collectors becomes larger and the decreasing rate of η to X becomes smaller for a larger δ . The reasons will be explained later. The description above refers to the case of $\dot{m} = 0.0124$ Kg/(m²·s) and the same results were obtained for $\dot{m} = 0.0372$ and 0.0618 Kg/(m²·s).

3.2 Daily efficiencies of honeycomb and flat plate collectors

The collector efficiency curves shown in Fig.4 are not sufficient to indicate the effectiveness of the honeycomb collector since the difference between the efficiency of the honeycomb collector and that of the flat plate collector varies with X , i.e. with time t . Accordingly, the average efficiency $\eta_{ds} = \frac{\int_{8:00}^{18:00} q_u dt}{\int_{8:00}^{18:00} I_s dt}$ called the daily efficiency⁽⁶⁾ is calculated for both collectors, where tm denotes the time when q_u becomes zero. The results are presented in Table 2, where $(\eta_{dh})_{exp}$ represents the daily efficiency of the honeycomb collector and $(\eta_{dh}/\eta_{df})_{exp}$ the ratio of the daily efficiency of the honeycomb collector to that of the flat plate collector. Explanations of $(\eta_{dh})_{cal}$ and $(\eta_{dh}/\eta_{df})_{cal}$ will be given later. In this table, $(\eta_{dh}/\eta_{df})_{exp}$ is almost equal to, or slightly smaller than, unity in the case of G-honeycomb collector with a large δ , i.e., the effectiveness of the honeycomb collector is not recognized. However, for P-honeycomb collector with a small δ , $(\eta_{dh})_{exp}$ is large in comparison with

G-honeycomb collector and in particular, $(\eta_{dh}/\eta_{df})_{exp}$ reaches the value of 1.31 for $\delta=0.11$ mm. Consequently, η_{dh} is larger than η_{df} by 31 %, and the effectiveness of the honeycomb collector is appreciable. In the cases of almost the same δ , i.e. $\delta=1.2$ mm and 1.0 mm, $(\eta_{dh})_{exp}$ for $A_s=3.7$ is larger than that for $A_s=6.2$. The reason is that as A_s increases for the fixed value of $L_a=50$ mm, m_h/A_c also increases, so that the honeycomb wall absorption of the solar irradiation, the effects of the heat conduction loss through the honeycomb wall and the honeycomb heat capacity become considerably larger although the heat losses by the convection and radiation decrease with increasing A_s . The values of $(\eta_{dh})_{exp}$ increase with $\dot{m}$ for all δ and A_s . This is due to the fact that the mean water temperature in the collector tube decreases with increasing $\dot{m}$ and the heat losses from the collector plate become small.

4. Calculation model of collector performance

As described above, the performance of the honeycomb collector depends strongly on δ and m_h/A_c . However, since the previous calculation model⁽¹⁾⁽²⁾ neglects the effects of the absorption of the solar irradiation and the honeycomb heat capacity, it cannot predict the performance correctly for large δ and the effects of δ on the collector performance can not be revealed sufficiently. Therefore, taking account of the effects neglected by the previous model, we propose a new calculation model to systematically clarify the effects of the honeycomb wall thickness, aspect ratio and height on the collector performance. Figure 5 shows this new calculation model. In this figure, symbol T denotes temperature and subscripts have the following meanings; a: ambient air, g: cover glass, h: honeycomb wall, p: collector plate and f: water in collector tube. Symbols R_1 ~ R_5 denote thermal resistances between those temperatures, which are expressed by the following Eqs.(1)~(4).

Table 2 Daily efficiencies of honeycomb and flat plate collectors

δ mm	A_s	$\dot{m}$ Kg/(m ² ·s)	$(\eta_{dh})_{exp}$	$(\eta_{dh}/\eta_{df})_{exp}$	$(\eta_{dh})_{cal}$	$(\eta_{dh}/\eta_{df})_{cal}$
2.1	1.1	0.0124	33.1	0.991	37.6	0.933
		0.0372	42.1	0.915	44.9	0.943
		0.0618	42.5	0.973	43.5	0.933
1.2	3.7	0.0124	30.7	1.01	37.2	0.961
		0.0372	41.6	1.01	42.9	1.00
		0.0618	47.7	1.04	45.2	0.974
1.0	6.2	0.0124	29.9	0.943	36.7	0.912
		0.0372	40.6	0.900	43.7	0.928
		0.0618	40.7	0.843	43.7	0.895

(a) Glass honeycomb

δ mm	A_s	$\dot{m}$ Kg/(m ² ·s)	$(\eta_{dh})_{exp}$	$(\eta_{dh}/\eta_{df})_{exp}$	$(\eta_{dh})_{cal}$	$(\eta_{dh}/\eta_{df})_{cal}$
0.52	5.0	0.0124	39.5	1.15	45.9	1.25
		0.0372	44.4	1.08	49.9	1.18
		0.0618	53.5	1.12	52.9	1.12
0.11	5.0	0.0124	47.4	1.22	54.1	1.51
		0.0372	58.9	1.29	58.6	1.35
		0.0618	61.2	1.31	59.3	1.33

(b) Polycarbonate honeycomb

Fig.5 Calculation model -

$$R_1 = R_2 \equiv L_a / 2\lambda_h f_h \dots\dots\dots (1)$$

$$R_3 \equiv 1 / [h_{pg}(1-f_h) + h_r] \dots\dots\dots (2)$$

$$R_4 \equiv 1 / (h_w + h_{rs}) \dots\dots\dots (3)$$

$$R_5 \equiv L_b / \lambda_b \dots\dots\dots (4)$$

where λ_h : the thermal conductivity of the honeycomb, h_{pg} : the convective heat transfer coefficient between the collector plate and the cover glass [the values of h_{pg} for $As=6.2$, 3.7 and 5.0 in the present work are given by the experimental equation for $As \geq 4$, in Ref.(7), and for $As=1.1$ we approximately use the experimental data for $As=2.0$ presented in the same reference], $h_r \equiv \epsilon_e(T_p + T_g)(T_p^2 + T_g^2)$: the radiation heat loss coefficient⁽⁶⁾ from the collector plate to the cover glass, h_w : the convective heat transfer coefficient⁽⁶⁾ from the cover glass to the ambient air, h_{rs} : the radiation heat loss coefficient⁽⁶⁾ from the cover glass to the sky (the emittance ϵ_e of the cover glass equals 0.708), and λ_b : the thermal conductivity of the glass wool and equals $0.0395 \text{ W/(m}\cdot\text{K)}$. The effective emittance ϵ_e is calculated using the method in Ref.(8) in which it is assumed that the honeycomb wall has a gray surface, and the collector plate and the cover glass are black bodies. Also, $I_s \tau_g \tau_h \alpha_p$ (τ_g and τ_h : the transmittance of the cover glass and honeycomb, respectively, α_p : the absorptance of the collector plate and equals 0.97) represents a fraction of the solar irradiation transmitted through the cover glass and the honeycomb wall and then absorbed by the collector plate. Heat fluxes I_g and I_h are obtained by subtracting heat fluxes due to the heat capacities of the cover glass and the honeycomb structure from those due to the absorption of solar irradiation by them, and are expressed by the following equations.

$$I_g = I_s \alpha_g - (m_g C_g / A_c) (\Delta T_g / \Delta t) \dots\dots\dots (5)$$

$$I_h = I_s \tau_g \alpha_h - (m_h C_h / A_c) (\Delta T_h / \Delta t) \dots\dots\dots (6)$$

Subscripts g and h represent the cover glass and the honeycomb, respectively and symbol α denotes the absorptance. The terms $\Delta T / \Delta t$ in Eqs.(5) and (6) express the temperature variations with time. The honeycomb wall temperature T_h also depends on I_h and is given by Eq.(7) referring to Fig.5.

$$T_h = [I_h L_a / (2\lambda_h f_h) + T_p + T_g] / 2 \dots\dots\dots (7)$$

Therefore, Eqs.(6) and (7) must be solved simultaneously to obtain the value of I_h . The heat flux I_p flowing into the collector plate is evaluated

$$I_p = I_s (\tau_g \tau_h \alpha_p + \xi_h \tau_g \alpha_h + \xi_g \alpha_g) - \xi_h \frac{m_h C_h}{A_c} \frac{\Delta T_h}{\Delta t} - \xi_g \frac{m_g C_g}{A_c} \frac{\Delta T_g}{\Delta t} \dots\dots\dots (8)$$

where

$$\xi_h \equiv \frac{(R_1 + R_2)R_4 + R_3(R_2 + R_4)}{(R_1 + R_2)(R_3 + R_4) + R_3 R_4} \dots\dots\dots (9)$$

$$\xi_g \equiv \frac{(R_1 + R_2)R_4 + R_3 R_4}{(R_1 + R_2)(R_3 + R_4) + R_3 R_4} \dots\dots\dots (10)$$

The collected useful heat flux q_u and the collector efficiency η are then calculated from Eqs.(11) and (12), respectively

$$q_u = F_R [I_p - U_L (T_{fi} - T_a)] \dots\dots\dots (11)$$

$$\eta = q_u / I_s \dots\dots\dots (12)$$

In Eq.(11), symbols F_R and T_{fi} represent the collector heat removal factor⁽⁶⁾ and the inlet temperature of water, respectively and U_L is the overall loss coefficient expressed by the next equation.

$$U_L \equiv \frac{R_1 + R_2 + R_3}{(R_1 + R_2)(R_3 + R_4) + R_3 R_4} + \frac{1}{R_5} \dots\dots\dots (13)$$

The mean temperature T_{fm} and outlet temperature T_{fo} of water can be obtained from the following equations.

$$T_{fm} = T_{fi} + q_u (1 - F_R / F') / (U_L F_R) \dots\dots\dots (14)$$

$$T_{fo} = q_u A_c / (\dot{m} C_f) + T_{fi} \dots\dots\dots (15)$$

where F' is the collector efficiency factor⁽⁶⁾ and C_f the specific heat of water. The value of the bond conductance needed to evaluate F' is $4.5 \text{ W/(m}\cdot\text{K)}$ for the collector used in the present experiment and the convective heat transfer coefficient in the collector tube is calculated by using Hausen's equation⁽⁹⁾.

Considering the upward heat flow from the collector plate to the ambient air, we can derive the following equation.

$$\frac{R_1 + R_2 + R_3}{(R_1 + R_2)(R_3 + R_4) + R_3 R_4} (T_p - T_a) + I_s (1 - \xi_h) + I_g (1 - \xi_g) = \frac{1}{R_4} (T_g - T_a) \dots\dots\dots (16)$$

In Eqs.(16), (2) and (3), h_{pg} , h_r and h_{rs} are functions of T_p and T_g . Since these temperatures are not uniform over the collector plate, we employ the mean temperatures T_{pm} and T_{gm} . The values of these mean temperatures are first assumed and

Fig.6 Flow chart of calculation

checked by Eq.(16) and the next equation.

$$q_u = I_p - U_L(T_{pm} - T_a) \quad (17)$$

The transmittance τ_g of the cover glass is obtained from Eq.(18) on the assumption of specular and multiple reflections⁽⁶⁾ in the glass. The honeycomb transmittance τ_h is evaluated from Eq.(19) based on the fact that the sum of the rays transmitting through the honeycomb walls and those reflected from the honeycomb walls reaches the collector plate.

$$\tau_g = \frac{\alpha_g(1-r_g)^2}{1-r_g^2\alpha_g^2} \quad (18)$$

$$\tau_h = \frac{\alpha_h(1-r_h)^2}{1-r_h\alpha_h} + r_h \quad (19)$$

Both absorptances α_g and α_h are calculated from

$$\alpha = (1-a)(1-r)/(1-ar) \quad (20)$$

where $a = e^{-Kl}$. The symbol l denotes the actual path of the solar rays through the cover glass and the honeycomb wall, and this path is determined by the geometry of the honeycomb structure and the solar incident angle θ_i . The value of θ_i is calculated from the data of the altitude and the time of southing of the sun. The symbol r represents the reflectivity⁽¹⁰⁾ of materials, which depends on the refraction index n ($n=1.53$, 1.47 and 1.59 for the cover glass, G-honeycomb and P-honeycomb, respectively).

A flow chart for the calculation by the present model is shown in Fig.6. As mentioned before, since h_{pg} , h_r and h_{rs} are functions of T_{gm} and T_{pm} , an iterative calculation is required to evaluate the heat transfer coefficients. In the present calculation, the assumed values of T_{gm} and T_{pm} are regarded as correct if the absolute values of the differences between the assumed values and the calculated values from Eqs.(16) and (17) become less than 0.05 K, and η and T_{fo} are then obtained from Eqs.(12) and (15), respectively.

5. Calculated results and discussions

5.1 Comparison between calculated and experimental collector performances

Comparison between the calculated and experimental values of the collector efficiency is made for $\dot{m}=0.0124$ Kg/(m²·s) in Fig.7. The abscissa and ordinate are the same as in Fig.4. The calculated values by the present model are represented by solid and broken lines for $\delta=0.11$ mm and 1.0 mm, respectively, and the experimental values are indicated by circular and square symbols. For reference, the calculated values by the previous model⁽¹⁾⁽²⁾ are also shown by dash-dotted and dash-two-dotted lines in this figure. As shown in Fig.7, in the case of $\delta=0.11$ mm, the difference between the calculated values by the present model and those by the pre-

vious model is very small, and the calculated values agree well with the experimental ones except in the region of small X . Therefore, it is seen that the transient effect due to the honeycomb heat capacity is not significant for such a thin honeycomb wall as $\delta=0.11$ mm. On the other hand, in the case of large wall thickness $\delta=1.0$ mm, the calculated values by the present model are in close agreement with the experimental ones, and the difference between the values by the previous model and the experimental results is very large except near the maximum point of η where the transient effect becomes small. From the facts mentioned above, it is concluded that in the case of a relatively large wall thickness, the transient effect is so large that the honeycomb heat capacity and the absorption of the solar irradiation by the honeycomb wall have to be taken into consideration. The values of $(\eta_{dh})_{cal}$ and $(\eta_{dh}/\eta_{df})_{cal}$ in Table 2 represent respectively the efficiency of the honeycomb collector and the ratio of the efficiency of the honeycomb collector to that of the flat plate collector calculated by the present model. From Table 2, the calculated values by the present model are found to agree well with the experimental ones over all experimental ranges, and therefore, the present model is considered a reasonable one.

The reasons why η of the honeycomb collector is much smaller than that of the flat plate collector at the point Q in Fig.4 are as follows: The first one is that, because of the large incident angle θ_i at that point, τ_h becomes small due to an increase of the actual path of the solar rays through the honeycomb. The second is that, since $\Delta T_h/\Delta t$ in Eq.(8) is positive, the value of I_p decreases. At the point b, η of the honeycomb collector with $\delta=0.11$ mm becomes much larger than that of the flat plate collector. This is because the effects of the suppression of the convective and radiative heat losses are predominant over those of the heat loss by the conduction through the honeycomb wall and the decrease in τ_h . Furthermore, the reason why, as X becomes large beyond the point b, the reduction rate of η to X becomes smaller for a larger δ is as follows: Since $\Delta T_h/\Delta t$ is negative in almost all parts of this region and the amount of the heat storage by

Fig.7 Comparison between calculated and experimental collector efficiencies ($\dot{m}=0.0124$ kg/(m²·s))

the honeycomb becomes large, the reductions of T_h and T_g with time become small and the heat losses from the collector plate decrease.

5.2 Effects of the honeycomb thickness, aspect ratio and height on the daily efficiency

In order to show the effects of the honeycomb thickness δ , aspect ratio A_s and height L_a on the daily efficiency η_d , the values of η_d are calculated for various values of δ , A_s and L_a by using the present model. In the calculation, the inlet water temperature T_{fi} is kept constant to make transient effects small, and the input data of I_s and T_a are given using a sine curve by which the experimental values of I_s and T_a in the case of $\delta=1.0$ mm in Fig.4 (on 14th, November, 1980; the total amount of I_s is 2.16×10^7 J/m² and the mean value of $T_a=11.2^\circ\text{C}$) are approximated. Figure 8 shows the effects of δ on η_d for $A_s=5.0$ and $L_a=50$ mm. The solid and broken lines are for P- and G-honeycomb collectors, respectively and the values for the flat plate collector are also indicated for each T_{fi} by arrows on the right ordinate. As seen from Fig.8, the values of η_d of both honeycomb collectors decrease gradually with increasing δ up to $\delta=0.1$ mm and then decrease rapidly. Consequently, the smaller value of δ is more desirable from the viewpoint of

Fig.8 Relation between daily efficiency and honeycomb thickness ($A_s=5.0$, $\dot{m}=0.0124$ kg/(m²·s), $L_a=50$ mm)

Fig.9 Relation between daily efficiency and aspect ratio ($\delta=0.1$ mm, $\dot{m}=0.0124$ kg/(m²·s), $L_a=50$ mm)

the efficiency. If we take account of the strength of the honeycomb structure, the value of $\delta \approx 0.1$ mm seems to be suitable.

As shown in Table 1, the absorption coefficient of the polycarbonate is larger, while its thermal conductivity is smaller than that of the pyrex glass. Hence, for the same values of δ and T_{fi} , the energy loss due to the absorption of the solar irradiation by P-honeycomb is larger, while the heat loss due to the conduction through P-honeycomb is smaller than that with G-honeycomb. The reason why for $T_{fi}=20^\circ\text{C}$ in Fig.8, η_d of P-honeycomb becomes smaller than that of G-honeycomb with increasing δ is, that although the conduction heat loss is not significant for such a small T_{fi} , the absorption loss increases with δ . On the contrary, in the case of $T_{fi} \geq 40^\circ\text{C}$, the conduction heat loss by G-honeycomb becomes greater than the absorption loss by P-honeycomb, so that η_d of P-honeycomb becomes larger than that of G-honeycomb. The description above refers to the case of $A_s=5.0$, $\dot{m}=0.0124$ Kg/(m²·s) and $L_a=50$ mm, and the same results were obtained other cases.

Figure 9 shows the relation between η_d and the aspect ratio A_s for $\delta=0.1$ mm, $\dot{m}=0.0124$ Kg/(m²·s) and $L_a=50$ mm. For all T_{fi} , the values of η_d of both honeycomb collectors increase steeply with A_s up to $A_s=5.0$ and they are then held nearly constant. Since the increase in A_s causes an increase in the cost of production due to the increase in the number of honeycomb elements, the value of $A_s=5$ seems to be reasonable. In the case of $T_{fi}=20^\circ\text{C}$, η_d of P-honeycomb is smaller than that of G-honeycomb. This is because the effects of the absorption loss are greater than those of the conduction loss.

The effects of the honeycomb height L_a on η_d are shown in Fig.10 for $\delta=0.1$ mm, $A_s=5.0$ and $\dot{m}=0.0124$ Kg/(m²·s). The values of η_d reach maxima near $L_a=50$ mm for all T_{fi} . Therefore, this is considered the suitable height. As L_a becomes smaller than 50 mm, η_d decreases for all T_{fi} , and this is due to the following reason. As the number of honeycomb elements increases with decreasing L_a for a fixed A_s , the absorption and conduction losses through the honeycomb wall become large. The decrease in η_d in the region of $L_a > 50$ mm is due to the fact that the convection loss becomes large, as the Rayleigh number increases

Fig.10 Effects of honeycomb height on δ ($\delta=0.1$ mm, $A_s=5.0$, $\dot{m}=0.0124$ kg/(m²·s))

with L_a ⁽⁷⁾. Furthermore, for a small L_a , η_a of P-honeycomb is larger than that of G-honeycomb. This can be considered to be due to the same thing as in the case of Fig.9.

5.3 Comparison with other type collectors

In order to compare the performance of the honeycomb collector with $\delta = 0.1$ mm, $A_s = 5.0$ and $L_a = 50$ mm with those of other types of collector, the daily efficiency η_a of various collectors was calculated. The results are shown in Fig.11 by taking T_{fi} as the abscissa. The solid lines represent the honeycomb collectors and the broken lines the other types of collectors. The curves a ~ f denote the types of collectors; a: selective surface (the emittance $\epsilon_p = 0.16$ and the absorptance $\alpha_p = 0.96$ ⁽¹¹⁾) + vacuum, b: G-honeycomb, c: P-honeycomb, d: selective surface, e: vacuum, and f: flat plate. The shape of the vacuum collector is usually different from that of Fig.2, but in order to directly examine the effects of the convection and conduction losses, the calculations are carried out by only putting h_{pg} in Eq.(2) equal to zero without changing the shape of the collector. In the case of the other types of collectors, η_a can be readily obtained from the present model excluding the part of the honeycomb. From Fig.(11), η_a of the honeycomb collectors is found to be smaller than that of the selective surface + vacuum type, but larger than those of the other types of collectors. In particular, the honeycomb collectors show good performance for large T_{fi} .

6. Conclusions

Experiments were made to clarify the effects of the honeycomb thickness, aspect ratio and height on the performances of honeycomb collectors, and a new calculation model was proposed by taking account of the honeycomb heat capacity and the absorption of the solar irradiation by the honeycomb wall. The calculated results were compared with experimental values,

and the effects of the honeycomb configuration on the performance of honeycomb collectors are systematically examined using this model. Furthermore, its performance was compared with those of the other types of collectors. The results obtained are summarized as follows.

(1) If the honeycomb thickness δ becomes larger than 1.0 mm, the effectiveness of the honeycomb collector is not recognized. However, the ratio of the daily efficiency η_a of the honeycomb collector to that of the flat plate collector increases with decreasing δ and reaches the value of 1.31 for $\delta = 0.11$ mm and $A_s = 5.0$.

(2) In the case of small δ , the difference between the calculated values by the present model and those by the previous model, is scarcely recognized, and the calculated values agree well with the experimental ones. On the other hand, in the case of large δ , the values by the present model are in close agreement with the experimental values, and the difference between the values by the previous model and the experimental results is quite large. Therefore, in the case of a relatively large δ , the honeycomb heat capacity and the absorption of the solar irradiation have to be taken into consideration.

(3) From the results obtained using the present model, it is seen that η_a is large, and it remains nearly constant in the region of $\delta \leq 0.1$ mm and it decreases with increasing δ in the region of $\delta > 0.1$ mm. The ranges of the honeycomb heights and aspect ratios which hold the daily efficiency large are indicated.

(4) The daily efficiency of the honeycomb collector with a suitable configuration is smaller than that of the selective surface + vacuum type collector, but larger than those of the vacuum, selective surface and flat plate types. In particular, the honeycomb collectors show good performance for high inlet water temperature.

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Fig.11 Comparison between honeycomb collector and other types of collector
($\dot{m} = 0.0124$ kg/(m²·s), $L_a = 50$ mm)

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