The Optimum Spacing of Strapping Wires in a Solar Thermal Flat-Plate Collector

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ABSTRACT

This paper describes how to determine the economic optimum spacing of strapping wires in a solar thermal flat-plate collector. The relationship between the thermal efficiency of the solar collector and the spacing of strapping wires is firstly developed by conducting outdoor efficiency tests following the ASHRAE standard 93-77. The economic optimum spacing under certain assumptions is then determined by considering the marginal cost and marginal revenue. It may also be obtained by considering the minimum cost of useful energy gained from the solar collector. The optimum spacing is found to be 0.07 meters.

INTRODUCTION

In a solar thermal flat-plate collector, bond conductance between the solar absorbing plate and the water carrying tube (see Fig. 1) whose thermal bridge is guaranteed by strapping wires depends on contact surfaces and spacing of strapping wires. The effect of bond conductance on the thermal efficiency of flat-plate collectors was shown by Whillier (1964), Whillier and Saluja (1965) and Noparatanakailas and Soponronnarit (1986). At high values of bond conductance, the efficiency is also high and tends to be constant. When the bond conductance is small, the efficiency is low and varies significantly. The details are shown in Fig. 2.

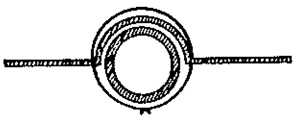


Fig. 1 Strapping wire between absorbing plate and water carrying tube.

Determination of bond conductance between a solar absorbing plate and a water carrying tube in a solar thermal flat-plate collector may be obtained by indoor tests [Khan (1957), Whillier (1964), Whillier and Saluja (1965), McGregor (1984), and Noparatanakailas and Soponronnarit (1986)] or outdoor tests [Khan (1957), Whillier and Saluja (1965), and Agarwal and Pilli (1982)]. Some experimental results of bond conductance are summarized in Table 1.

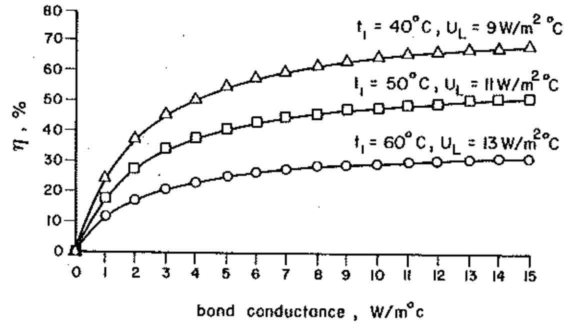


Fig. 2 Effect of bond conductance on thermal efficiency of a solar thermal flat-plate collector.

Table 1
Some experimental results of bond conductance between a solar absorbing plate and a water carrying tube in a solar thermal flat-plate collector.

Type of bond	Pair of metal	Bond conductance W/m K	Reference	Remark
Strapping wires at 50 mm spacing	Cu-Fe	27.7	Whillier (1964)	
Soldered bond (dull black surface)	Fe-Fe	3.5	Whillier and Saluja (1965)	cracking of bond
Soldered bond (selective surface)	Fe-Fe	2.6	Whillier and Saluja (1965)	cracking of bond
Soldered bond	Fe-Fe	37.2	Khan (1957)	
duPong adhesive bond	Fe-Fe	6.6	Khan (1957)	
Strapping wires at 152 mm spacing	Fe-Fe	5.0	Khan (1957)	
Strapping wires at 150 mm spacing	Cu-Al	7.4	Noparatanakailas and Soponronnarit (1986)	
Strapping wires at 75 mm spacing	Cu-Al	9.3	Noparatanakailas and Soponronnarit (1986)	

For strapping wires, the bond conductance varies from 5.0 to 27.7 W/m K. Most of the results previously determined show that it is around 5.0-9.3 W/m K. The result reported by Whillier (1964) is, however, 27.7 W/m K which is very much higher than the others.

For soldered bond, the bond conductance varies from 2.6 W/m K to 37.2 W/m K. In some experiments it was found that the bond cracked and resulted in very low values of bond conductance.

Comparing among the three types of bond, the bond conductance of soldered bond is highest if the bond is not cracked. Those of strapping wires and duPong adhesive bond are about the same values.

Knowing the bond conductance at different spacings of strapping wires, the thermal efficiency at different spacings may then be calculated by employing the theory of flat-plate collector

Table 2
Effect of material and labour costs on the economic optimum spacing of strapping wires.

Type of cost	Variation %	Amount (Baht)	Amount (US$)	Optimum spacing (mm)
Material cost	0.0	2500	100	
Labour cost	0.0	100	4	70
Material cost	+20.0	3000	120	
Labour cost	0.0	100	4	60
Material cost	−20.0	2000	80	
Labour cost	0.0	100	4	80
Material cost	0.0	2500	100	
Labour cost	+20.0	120	4.8	80
Material cost	0.0	2500	100	
Labour cost	−20.0	80	3.2	60

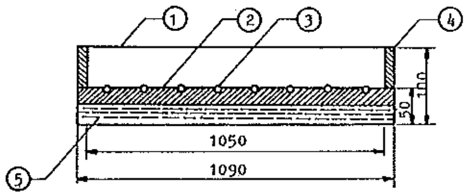
presented by Duffie and Beckman (1980). The economic optimum spacing may be determined for a given working condition and surrounding. This procedure tends to be preferred because the experiment may be done indoors without simulated sunshine. The only inconvenience is the need to use a temperature measuring device having an accuracy much greater than ± 0.1 °C. Otherwise one can have no confidence in obtaining a good bond conductance (Noparatanakailas and Soponronnarit, 1986). The other method for determining optimum spacing is the use of comparative outdoor tests of thermal efficiency. The tests may follow ASHRAE standard 93-77 (Anon, 1977). Knowing the efficiency at different spacings, the economic optimum spacing may be determined for a given working condition and surrounding. The concept for the economic consideration may be the intersection point the graphs of marginal cost and marginal revenue or may be the lowest cost of energy obtained from the solar collector.

The objective of this research work is to determine the economic optimum spacing of strapping wires in a solar thermal flat-plate collector.

PROCEDURE

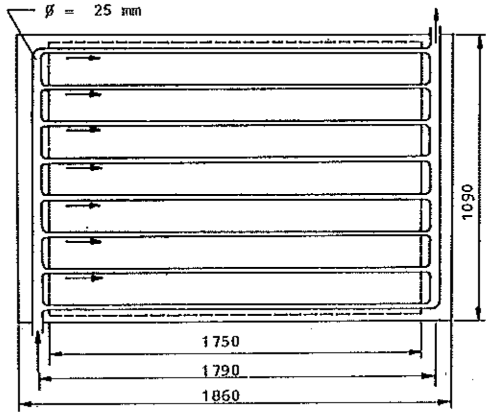
Details of experimental solar collector

Figure 3 shows the experimental solar thermal flat-plate collector. The outside dimensions are 1.09 m × 1.86 m. The thickness is 0.10 m. The solar absorbing plate is made of 0.62 mm thick aluminium sheet. It has been grooved manually in a circular pattern. The depth of the groove is about one-half the diameter of the water carrying tube which is 12.7 mm. There are eight grooves per one absorber. The absorber is sprayed with dull black paint. The absorptance and emittance are 0.97 and 0.92, respectively. There is a 3 mm thick window glass covering at the top of the solar collector. At the bottom, the solar collector is insulated with 25 mm thick glass wool and 25 mm thick styrofoam. The spacings of the strapping wires for the experiments are 65, 130, 195, and 390 mm, respectively.



3 a. Section

1 glass cover 3 mm
2 solar absorbing plate 0.62 mm
3 water carrying tube Ø 12.5 mm
4 glass wool 25 mm
5 styrofoam 25 mm



3 b. Top view

Fig. 3 Details of the experimental solar collector (unit in mm)

Test procedure

The outdoor tests of thermal efficiency of solar collectors follow the ASHRAE Standard 93-77 (Anon, 1977). The efficiency is calculated by the following equation.

$$\eta = GC_p\,(t_2 - t_1)/G_T \qquad (1)$$

where η = thermal efficiency, decimal

G = mass flow rate of water per solar collector area, kg/s-m^2

C_p = specific heat at constant pressure, J/kg K

t_1 = inlet water temperature, °C

t_2 = outlet water temperature, °C

G_T = solar radiation flux on the plane of solar collector, W/m^2

At near steady state, the temperatures of inlet and outlet water and ambient temperature are measured by thermocouple type K associated with a multilogging meter having a repeatability of ± 0.1 °C. Global solar radiation is measured by a Kipp & Zonen pyranometer and the measured values are integrated by a Kipp & Zonen solar integrator at 30 minute-intervals. The solar radiation flux on the plane of the solar collector is then calculated from the integrated measured values. Average wind speed at 30 minute-intervals is obtained using a meteorological measuring device (Meteorology Research Model 1037). Mass flow rate of water per solar collector area of 0.02 kg/s-m^2 or mass flow rate of 0.038 kg/s are used during the tests.

RESULTS AND DISCUSSIONS

Technical results

The results of the outdoor efficiency tests are presented in Fig. 4. It is obvious that the thermal efficiency is linearly related to the temperature difference divided by solar radiation flux incident on the plane of the solar collector. Also, it depends on the spacing of strapping wires. It increases when the spacing decreases. Equations (2) – (5) represent the efficiency curves for several spacings of strapping wires. They are as follows:

$$\eta_{65\,mm} = 76.86 - 0.79\,X_T, \qquad R = 0.80,\ \delta = 4.16 \tag{2}$$

$$\eta_{130\,mm} = 73.53 - 0.81\,X_T, \qquad R = 0.84,\ \delta = 3.92 \tag{3}$$

$$\eta_{195\,mm} = 71.41 - 0.88\,X_T, \qquad R = 0.81,\ \delta = 5.32 \tag{4}$$

$$\eta_{390\,mm} = 60.26 - 0.67\,X_T, \qquad R = 0.80,\ \delta = 3.77 \tag{5}$$

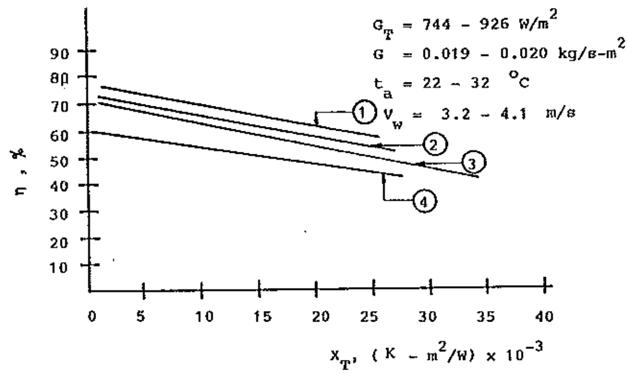


Fig. 4 Thermal efficiency curves of a solar thermal flat-plate collector having different spacings of strapping wires.
1 spacing of 65 mm
2 spacing of 130 mm
3 spacing of 195 mm
4 spacing of 390 mm

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where η = thermal efficiency, %

$X_T = (t_1 - t_a)/G_T$, (°C-m²/W) × 10^{-3}

t_1 = inlet water temperature, °C

t_a = ambient temperature, °C

G_T = Solar radiation flux on the plane of solar collector, W/m²

R = correlation coefficient

δ = standard error of the regression estimate

Equations (2) – (5) are for the spacings of strapping wires of 65, 130, 195, and 390 mm, respectively.

Economic considerations

If the values of solar radiation flux and ambient temperature are assumed to be 800 W/m² and 30°C, respectively, the relationship between the thermal efficiency and the spacing of strapping wires for each inlet water temperature may be established by employing equations (2)–(5). The relationship is shown in Fig. 5 and also presented in equations (6)–(8). They are as follows.

$$\eta_{t1 = 40°C} = 69.63 - 0.46\,X \qquad (6)$$

$$\eta_{t1 = 50°C} = 58.78 - 0.41\,X \qquad (7)$$

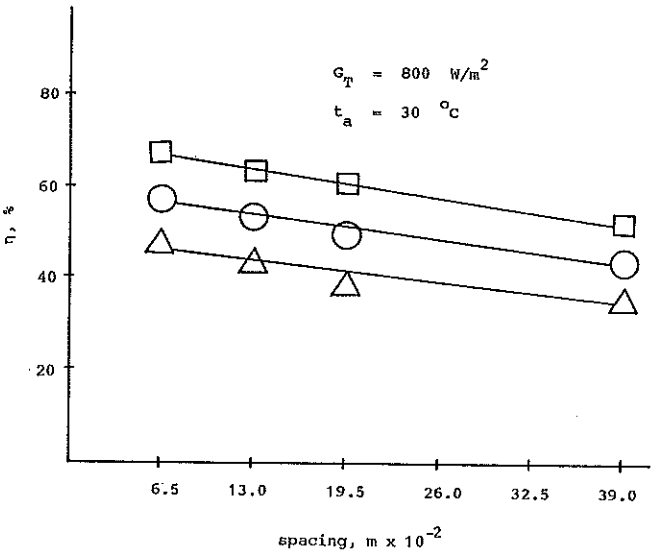

Fig. 5 Relationship between thermal efficiency and spacing of strapping wires at different inlet water temperatures.
□ inlet temperature of 40°C
○ inlet temperature of 50°C
△ inlet temperature of 60°C.

$$\eta_{t1\ =\ 60°C} = 47.93 - 0.36\,X \tag{8}$$

where η = thermal efficiency, %

X = spacing of strapping wires, m $\times$ 10^{-2}

Equations (6) – (8) are valid for the range of spacing from 0.06 to 0.39 m.

From Fig. 5 or equations (6) – (8), it is found that the thermal efficiency increases when the spacing of strapping wires decreases. The relationship is approximately linear for the testing range of spacing.

For a fixed amount of useful energy obtained from a solar collector, the manufacturer may use a smaller collector area if the thermal efficiency is improved, for example by reducing the spacing of the strapping wires. In contrast, because efficiency decreases when the spacing of strapping wires increases the manufacturer has to use a large collector area. In the former case, the manufacturer has to pay more due to reduced spacing but he can save on the cost of the solar collector due to a smaller collector area. In other words, he has marginal cost and marginal revenue simultaneously. The economic optimum spacing may be determined from the intersection point of the graphs of marginal cost and marginal revenue. Or it may be determined from the lowest cost of useful energy gained from a solar collector.

a. Conditions for consideration

1. Useful heat gained from the solar collector is Q_u.
2. The thermal efficiency depends on inlet water temperature and spacing of strapping wires as previously discussed.
3. The calculation starts with the 2 m^2 solar collector at the spacing of 0.4 m. There are 8 water carrying tubes which are 1.82 m long each.
4. Material cost of a 2 m^2 solar collector is 2500 Baht (US$100).
5. To construct a solar collector of 2 m^2, 18 man-hours are required.
6. One man-hour costs 16.67 Baht (US$0.6668).
7. Material cost of strapping wires is 0.08136 Baht (US$3.2544 $\times$ 10^{-3})/strap.
8. For one strap, 0.03461 man-hour is required.
9. Other costs are equal to 20% of the material and labour costs.

b. Details of analysis

Cost

cost_1 = (material cost of solar collector + labour cost) $\times$ 1.2.

cost_2 = (cost of strapping wire + labour cost) $\times$ 1.2.

total cost = $\text{cost}_1 + \text{cost}_2$

According to the assumptions stated above, total cost may be determined as follows:

$$C = 3360 + 6.3183\,n \tag{9}$$

where C = total cost, Baht

n = number of strap per each water carrying tube, $n = 1 + 180/X$ (10)

Let X_1 and X_2 be spacings of the 1st and 2nd solar collectors respectively, it may be shown that the marginal cost is as follows:

$$\Delta C = 6.3183\ [(1 + 180/X_2) - (1 + 180/X_1)] \quad (11)$$

where ΔC = marginal cost, Baht

Revenue

The revenue is obtained from the solar collector area which is saved due to higher thermal efficiency if the quantity of useful heat obtained from the solar collector is fixed. The rate of useful heat gain is determined as follows:

$$Q_u = \eta A G_T \quad (12)$$

where Q_u = rate of useful heat gain, W

A = solar collector area, m^2

The solar collector area which may be saved due to reduced spacing may be determined as follows.

From equation (12), the rate of useful heat gain may be determined for the 1st and 2nd solar collectors having the spacing of X_1 and X_2, respectively. They are as follows:

$$Q_u = \eta_1 A_1 G_T \quad (13)$$

$$Q_u = \eta_2 A_2 G_T \quad (14)$$

Equating Q_u in equations (13) and (14), one obtains

$$A_2 = (\eta_1/\eta_2) A_1 \quad (15)$$

The solar collector area which may be saved is computed as follows:

$$\Delta A = A_1 - A_2$$

$$\text{or } \Delta A = (1 - \eta_1/\eta_2) A_1 \quad (16)$$

where ΔA = solar collector area which is saved, m^2.

The marginal revenue can be determined as follows:

$$\Delta R = (C_1/A_1) \Delta A \quad (17)$$

where ΔR = marginal revenue, Baht

C_1/A_1 = total cost per unit area of the 1st solar collector, Baht/m^2

Initially, the spacing of strapping wires is 0.4 m. It is then reduced 0.01 m each step of calculation. The final spacing considered herein is 0.05 m. The calculated marginal cost and marginal revenue are presented in Fig. 6. The intersection point of these two curves yields the economic optimum spacing of strapping wires which is approximately 0.07 m and is somewhat independent of inlet water temperature from 40-60°C. The optimum spacing may also be obtained by considering the minimum cost of useful energy gained from the solar collector. It is found that the values obtained from both methods are approximately the same.

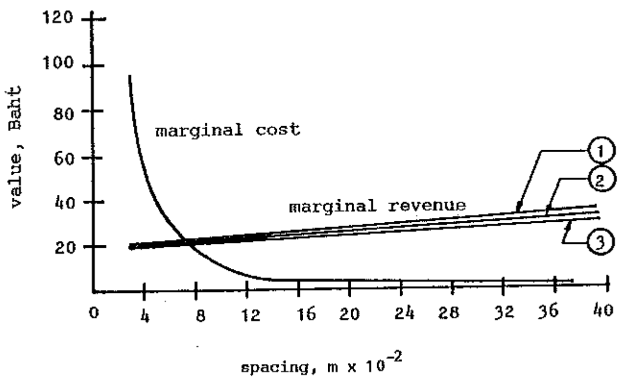

Fig. 6 Marginal cost and marginal revenue due to reducing the spacing of strapping wires.
1 inlet temperature of 40°C
2 inlet temperature of 50°C
3 inlet temperature of 60°C

The effect of material cost and labour cost on the economic optimum spacing of strapping wires was also studied. The results are summarized in Table 2. When the material cost increases or the labour cost decreases 20%, the manufacturer may reduce the economic optimum spacing to 0.06 m.

CONCLUSIONS

1. The thermal efficiency of a solar thermal flat-plate collector depends on the spacing of strapping wires. The efficiency increases when the spacing decreases.

2. The economic optimum spacing of strapping wires under the assumptions stated is approximately 0.07 m.

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