A Numerical Analysis on Heat Transfer Between the Air and the Liquid in a Hybrid Solar Collector

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Abstract. A hybrid solar collector, in this study, means the flat plate solar collector that has a fin-and-tube heat exchanger combining with a heat pump system. This collector can get the thermal energy from the ambient air for heating the circulated water in the collector when solar radiation is not enough. Thus, this collector can supply thermal energy to evaporator of the heat pump using heated water. For a foundation design of this collector, the numerical analysis was conducted for confirming the heat gain of water by the ambient air according to the length and the installation angle of fins in the fin-and-tube heat exchanger of solar collector. As a result, much of heat gain of water was obtained on the higher fin length with 30° of installation angle, but the pressure drop of air side increased adversely with heat transfer rate. Thus an area goodness factor considering both heat transfer enhancement and pressure drop of air side was also investigated. As a result, 50 mm of the fin length with 0° of installation angle has a good heat transfer enhancement than that of the other installation conditions compare with increment of pressure drop. However, mostly, higher heat transfer rate was obtained when the area goodness factor was low. So, it is needed to be considered whether the condition, maximum value of area goodness factor satisfying the heat transfer rate, can be expected or not.

Keywords: Solar thermal energy · Flat plate solar collector · Fin-and-tube heat exchanger · Solar assisted heat pump

Nomenclature

$\dot{Q}$:	Heat transfer rate [W]
$\dot{m}$:	Mass flow rate [kg/s]
T :	Temperature [°C]
U :	Overall heat transfer coefficient [W/m^2K]
C_p :	Specific heat of heating medium [kJ/kgK]
F:	Correction factor [–]

V.H. Duy et al. (eds.), *AETA 2016: Recent Advances in Electrical Engineering and Related Sciences*, Lecture Notes in Electrical Engineering 415, DOI 10.1007/978-3-319-50904-4_17

$\Delta T_{lm,CF}$: Logarithmic mean temperature difference on counter flow [°C]
A_o : Air-side total surface area $[m^2]$
A_i : Tube inner surface area $[m^2]$
A_m : Tube mean surface area $[m^2]$
A_t : Tube outer surface area $[m^2]$
A_f : Fin surface area $[m^2]$
D_h : Hydraulic diameter [m]
h : Heat transfer coefficient $[W/m^2K]$
Δx: Tube thickness [m]
k : Thermal conductivity [W/mK]
d_t : Tube diameter [m]
V : Velocity [m/s]
ΔP: Pressure drop [Pa]
F_L : Fin length [mm]
α : Installation angle of fin [°]
Re : Reynolds number [–]
Pr : Prandtl number [–]
j : Colburn j factor [–]
f_p : Petukhov friction factor [–]
f : Friction factor [–]

Greek symbols

η: Surface efficiency [–]
η_f : Fin efficiency [–]
P : Density $[kg/m^3]$

Subscripts

w : Of water
air : Of air
avg : Of average
i : Of inlet
o: Of outlet

1 Introduction

As a part of effort to increase the use of solar thermal energy, many researches about a solar assisted heat pump using solar collector have been conducted [1, 2]. Solar assisted heat pump system uses solar thermal energy as heat source for evaporator of heat pump. So, C.O.P. of heat pump can be increased with increment of evaporating temperature. And the collector efficiency also can be increased because of the lower operating temperature than the traditional collecting system. But these systems are hard to use the solar collector when the solar radiation is not enough such as a cloudy, rainy day and at night.

So, a hybrid solar collector being able to heat circulated water of the collector using ambient air has been developed [3, 4]. This collector is a flat plate solar collector that has fin-and-tube heat exchanger under the absorbing plate, so it can get a thermal energy from ambient air for heating circulated water like an outdoor unit of heat pump. This heated water can be used as heat source of the evaporator in heat pump when the solar radiation is not enough.

Thus, in this study, heat transfer between air and water was investigated according to length and installation angle of plate fin of fin-tube exchanger in the hybrid solar collector and the numerical analysis also performed for a foundation design. And this study aims to confirm heat transfer and pressure drop characteristic with respect to fin length and installation angle to find the best fin condition after considered heat transfer and pressure drop for real product.

2 Numerical Model and Methods

2.1 Hybrid Solar Collector

Figure 1 shows a schematics of hybrid solar collector for analysis. This collector was composed of glass cover, absorbing plate, fin-and-tube heat exchanger and case. A fin-and-tube heat exchanger was installed under the absorbing plate.

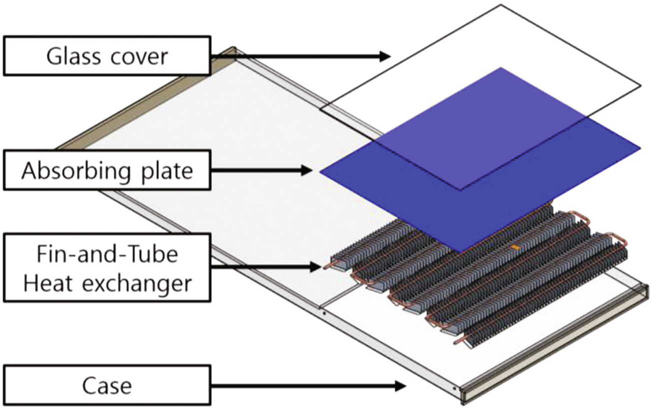

Fig. 1. Exploded view of hybrid solar collector

This collector can use both solar thermal energy and ambient air selectively depending on the weather. The materials of glass cover, absorbing plate, copper pipe and plate fin were defined as glass, copper and aluminum respectively.

Figure 2 shows a schematic diagram of heat transfer method between air and water in the collector. Air came from the ambient air and it flows through the air channel of the collector and the cold water flows through the tube of fin-and-tube heat exchanger after coming from evaporator outlet of heat pump. Thus, the cold water can get thermal

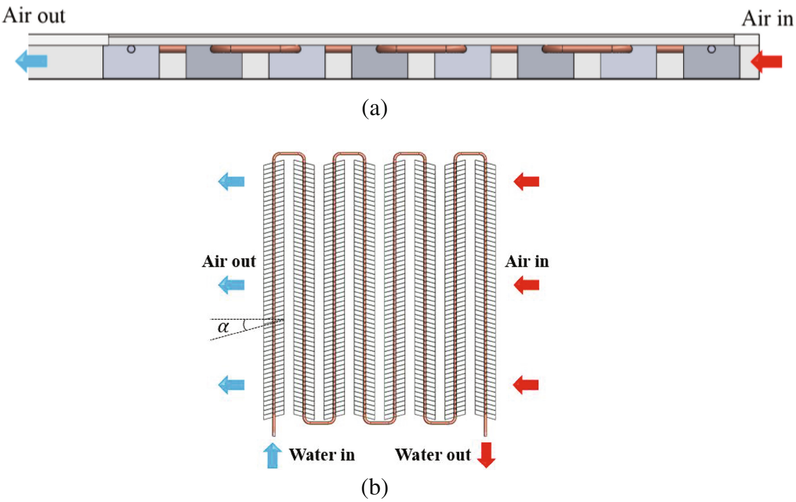

Fig. 2. Schematic diagram of fin-and-tube heat exchanger in hybrid solar collector; (a) Side view (b) Plan view

energy from ambient air when solar radiation is not enough and heat transfer between the air and the water occurred by cross counter flow as shown in Fig. 2.

Simulation was conducted on various air flow rates with various fin length and installation angles. Simulation conditions including geometric conditions of the collector were tabled in Table 1.

2.2 Data Reduction

Heat transfer rate was obtained by calculated simulation results and Eqs. (1), (2) and (3).

Table 1. Simulation conditions

Parameter		Value
Collector size	Length (mm)	755
	Width (mm)	976
	Height (mm)	54.2
Height of air duct (mm)		40
A number of tube row		8
Plate fin	Length (mm)	5, 7
	Installation angle (°)	0, 15, 30, 45
Reynolds number of air side		4,000, 8,000, 12,000, 16,000
Reynolds number of water side		9,444 (5 l/min)
Temperature	Inlet air (°C)	21
	Inlet water (°C)	10

$$\dot{Q}_w = \dot{m}_w C_{p,w}\left(T_{w,o} - T_{w,i}\right) \tag{1}$$

$$\dot{Q}_{air} = \dot{m}_{air} C_{p,air}\left(T_{air,o} - T_{air,i}\right) \tag{2}$$

$$\dot{Q}_{avg} = \frac{\dot{Q}_w + \dot{Q}_{air}}{2} \tag{3}$$

Also, overall heat transfer coefficient, U, is obtained by simulation results and Eq. (4)

$$\mathrm{U} = \frac{\dot{Q}_{avg}}{A_o F \Delta T_{lm,CF}} \tag{4}$$

So, the overall heat transfer coefficient can be rewritten as

$$\frac{1}{U} = \frac{1}{h_o} + R_f + R_c + \frac{\Delta x}{A_m k_t / A_o} + \frac{A_o}{A_i h_i} \tag{5}$$

Where

$$h_i = \frac{(f_p/8)(Re - 1000)Pr}{1 + 12.7(f_p/8)^{\frac{1}{2}}(Pr^{\frac{2}{3}} - 1)}\left(\frac{k_t}{d_t}\right) \tag{6}$$

$$f_p = (0.79 \ln Re - 1.64)^{-2} \tag{7}$$

Since the numerical analysis was conducted in this study, thermal contact resistance, R_c, and fouling factor, R_f, can be ignored. Then, air side heat transfer coefficient can be expressed by

$$h_o = 1\Big/\left(\frac{1}{U} - \frac{\Delta x}{A_m k_t / A_o} - \frac{A_o}{A_i h_i}\right) \tag{8}$$

$$h_o = \eta h = \frac{(A_t + \eta_f A_f)}{A_o} h \tag{9}$$

But, fin efficiency is difficult to be obtained of this collector's structure. So, air side heat transfer coefficient including the affect of fin efficiency referred to the research of Yun and Lee [5].

Colburn j factor and friction factor f are, respectively, expressed by

$$j = \mathrm{St}Pr^{2/3} = \frac{h_o}{\rho C_{p,air} V_{avg}} Pr^{2/3} \tag{10}$$

$$f = \frac{D_h}{L}\frac{2\Delta P}{\rho V_{avg}^2} \tag{11}$$

Thus, area goodness factor considering heat transfer enhancement and pressure drop can be given by

$$\text{Area goodness factor} = \frac{j}{f} \tag{12}$$

3 Results and Discussion

Heat transfer rate according to fin length and installation angle was shown in Fig. 3.

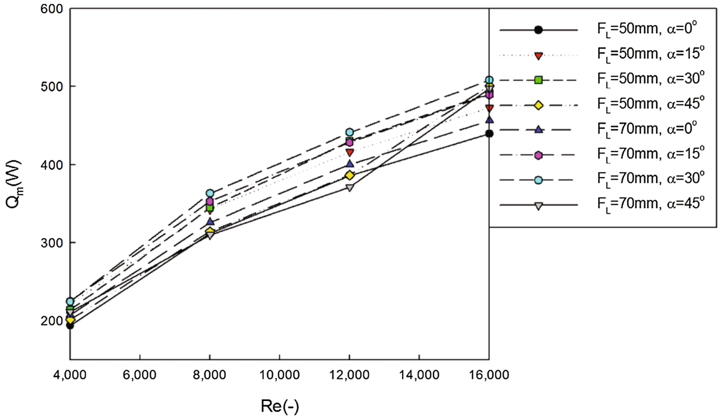

Fig. 3. Heat transfer rate between air and water according to fin length and installation angle

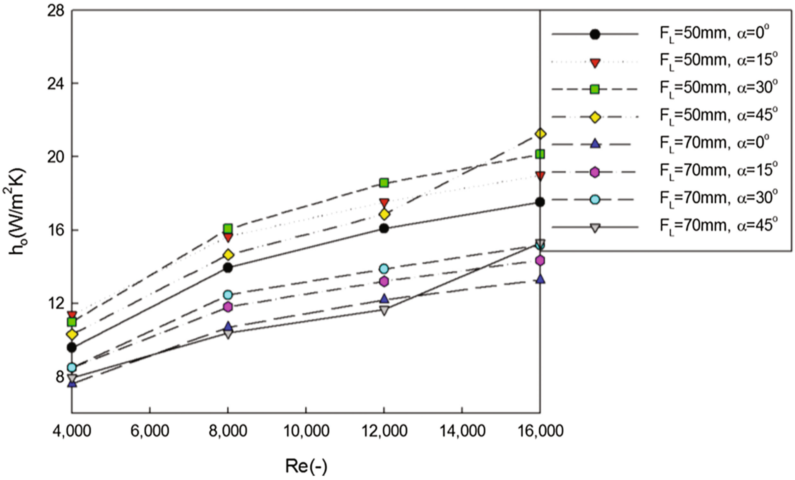

Fig. 4. Heat transfer coefficient of air side according to fin length and installation angle

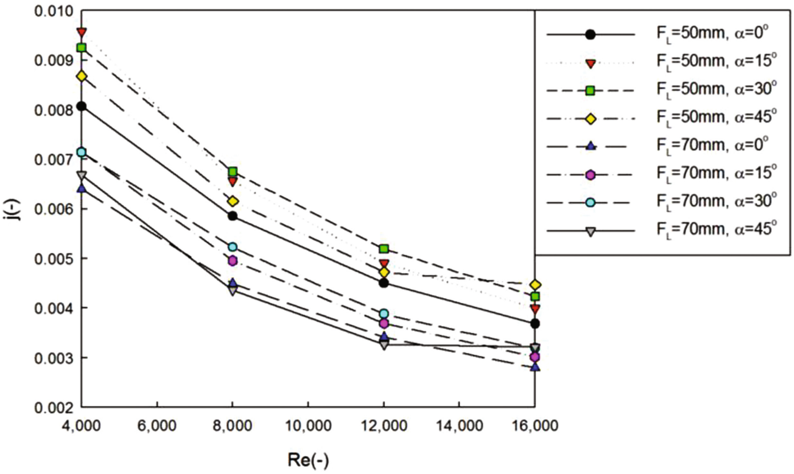

Fig. 5. Colburn j-factor of air side according to fin length and installation angle

Heat transfer rate was shown as range of 194 W to 500 W and it was increased with the increment of fin length and installation angle because of the increment of heat transfer area and improvement of mixture of air flow. But the lower heat transfer rate was shown on 45° of installation angle than 30°. The reason of decrement of heat transfer rate at 45 ° was considered as too excessively velocity through the fin (Figs. 4 and 5).

The pressure drop is related to blowing power. It is also needed to be considered according to fin length and installation angle as well as heat transfer rate. Figures 6 and 7 are illustrating pressure drop and friction factor calculated by simulation results. These values have higher value on the higher length and installation angle of fin looking similar

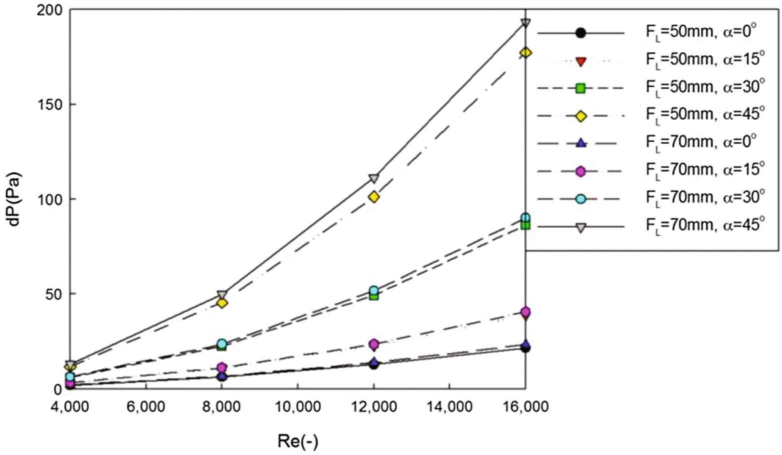

Fig. 6. Pressure drop of air side according to fin length and installation angle

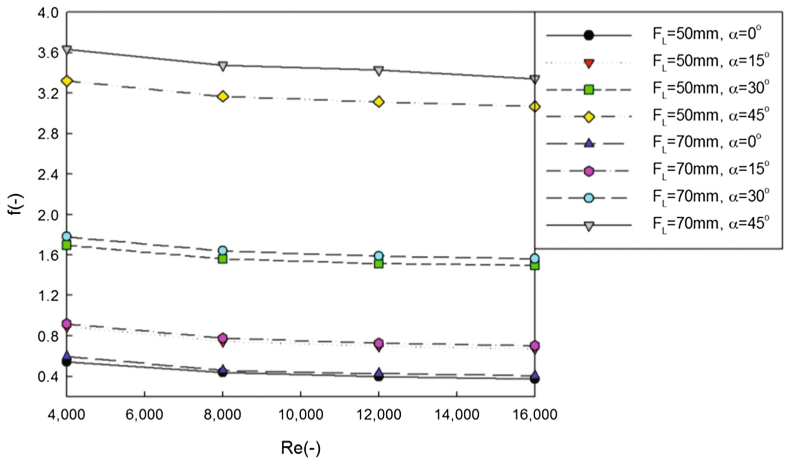

Fig. 7. Friction factor of air side according to fin length and installation angle

with heat transfer rate. So, it was confirmed that enhancement of heat transfer rate according to fin length and installation angle leads to higher pressure drop of air side.

Thus, the area goodness factor comparing with both heat transfer increase and pressure drop simultaneously was shown in Fig. 8. As a result, the area goodness factor was decreased with increment of fin length and installation angle. Maximum value of this was shown at 50 mm of fin length and 0° of fin installation angle. Heat transfer rate, however, was increased with increment of fin length and installation angle. Thus, if there are some minimum or maximum heat transfer rate that we want to achieve, it is needed to be considered whether the installation condition shows maximum value of area goodness factor satisfying minimum or maximum heat transfer rate or not.

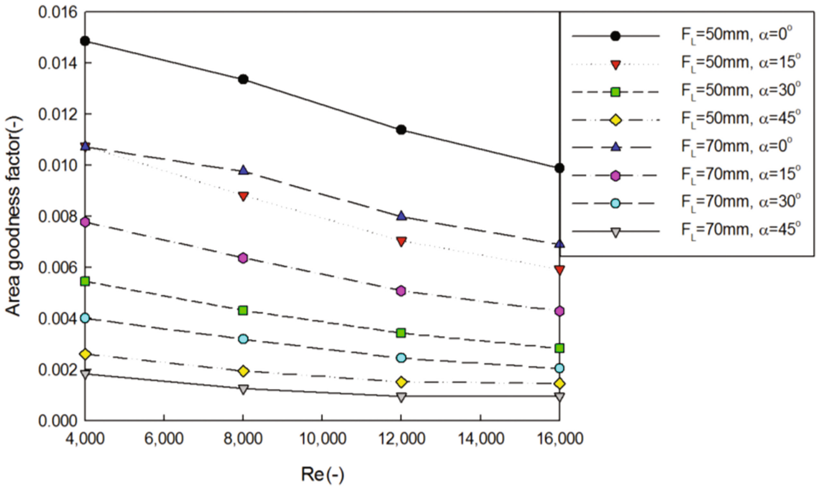

Fig. 8. Area goodness factor of air side according to fin length and installation angle

4 Conclusion

In this study, heat transfer between air and water in the fin-and-tube heat exchanger of the hybrid solar collector was investigated according to fin length and installation angle. As a result, higher heat transfer coefficient was obtained on higher length with 30^{o} of installation angle, but pressure drop also increased as the same as increment of heat transfer rate. So, the area goodness factor considering both heat transfer enhancement and pressure drop was confirmed and the maximum value was shown on 50 mm of fin length with 0^{o} of installation angle.

Thus, it is confirmed that installation condition has the highest heat transfer improvement compare with increment of pressure drop among installation conditions of the plate fin investigated in this study. Higher heat transfer rate was mostly obtained when the area goodness factor was low. So, it is considered that the actual experiment should be conducted with the fin length and installation angle showing maximum area goodness factor after confirming whether this installation condition can satisfy minimum or maximum heat transfer rate or not.

Acknowledgments. This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20153030081190)

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