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A STUDY ON RELATIONSHIP BETWEEN THE ENERGY BALANCING AND THE REAL EXPERIMENT IN A HYBRID SOLAR HEATING SYSTEM

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Abstract

Research of the hybrid solar collector that can heat air and liquid simultaneously has been conducted for enhancement of the usage of solar energy. Thermal efficiency of this solar collector was investigated ranging from various operating conditions. This efficiency of the collector, however, was hard to generalize because of many factors that effect on the efficiency more than the traditional solar collector. Thus, in this study, the efficiency of hybrid collector was expressed by the energy balance and the efficiency of the collector was also investigated according to operating and external conditions. As a result, efficiency of the air side was increased with the increment of the inlet liquid temperature when the other conditions were constant different with traditional solar air heater. In case of liquid heating performance, efficiency was decreased with increment of inlet liquid temperature and decrement of solar radiation same as the traditional solar collector for hot water. Total thermal efficiency expressed as the ratio of the useful energy gain of heating mediums(air and liquid) to the incident of solar radiation was decreased with increment of inlet heating temperature and decrement of solar radiation similar with the traditional solar collector. Those tendencies are similar with the results of previous study, thus it can be regarded that the efficiency expressed from the energy balance as in appropriate. Furthermore, from these results it is expected to generalize the evaluation method of the hybrid solar collector and contributing for practical use if additional experiment with more various conditions are conducted.

Keywords: *Solar thermal system, Hybrid solar collector, Air-conditioning, Hot-water supply, Energy saving*

1. Introduction

In the use of solar energy, flat plate solar collector usually has been used for making hot water or heated air. In case of solar water heater, many research was conducted for enhancing the thermal efficiency(S. Sadhishkumar and T. Balusamy, 2014) and these heated water can be used for hot-water supply system in building, heat source for regenerating of liquid desiccant in liquid desiccant dehumidifier system(K. Gommed and G. Grossman, 2007; Mahmut et al, 2015) and so on. In case of solar air heater, it can be used in many field like drying application(M.A. Karim and M.N.A. Hawlader, 2004), air conditioning system(Ali Al-Alili et al., 2004; Zhi Yu et al., 2014) and so on.

But, different with this, study about hybrid solar collector heater that can make both hot water and heated air have been conducted(K.H. Choi et al., 2014; H.W. Choi et al., 2014; H.W. Choi et al., 2015). This collector can be applied for air conditioning system as well as hot water supply system. So, the usage of hybrid solar collector per unit area is being a more than traditional flat plate solar collector. But, efficiency of hybrid solar collector was hard to generalize because of the many factors that effect on the efficiency.

Thus, in this study, the efficiency of hybrid collector was expressed by the energy balance. And the efficiency of the collector was also investigated according to operating and external conditions by using the heat removal factor and the heat loss coefficient calculated from measured values when the air and liquid were heated simultaneously in flat plate solar collector. Furthermore, this paper put the purpose on the confirming of performance of hybrid solar collector when it was heating both air and.

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2. Experimental apparatus and method

Hybrid solar collector was made by installing air channel beneath the absorb plate of flat plate solar collector for hot water, so it can make hot water and heated air. Actual feature of hybrid solar collector is shown in Fig. 1. Fins were installed in air chnnel for enhancing the heat transfer rate from absorber to flow air. It has a $2m^2$ absorbing area and installed 33° angle from horizontal and azimuth 171° in Busan, South Korea. Fig. 2 shows the schematics of hybrid solar collector system.

Fig. 1: Actual feature of hybrid solar collector for experiment

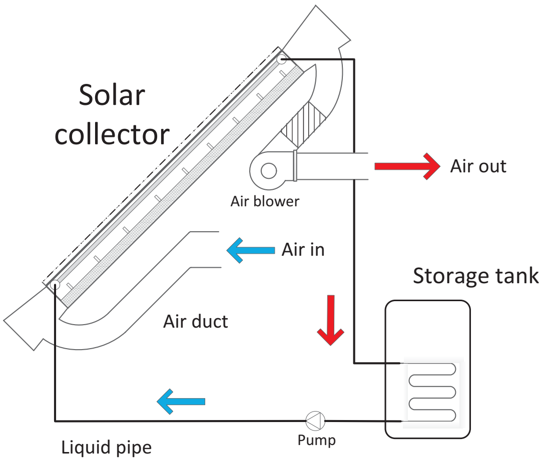


Fig. 2: Schematics of hybrid solar air-water heater system

Experiment was conducted at clear day. Air mass flow rate was changed from 0.02 kg/s to 0.10 kg/s on constant liquid mass flow rate 4 l/min and both air and liquid was heated simultaneously. Outdoor air was used directly as inlet air and T-type thermocouple was installed at lower side, center, upper side, left side and right side of absorbing plate for measuring mean temperature of absorber plate. Temperatures of inlet and outlet air were also measured by T-type thermocouple and liquid temperatures at inlet and outlet were measured by PT-100.

3. Data analysis

In this study, thermal efficiency of collector was defined using energy balance when the air and liquid were heated simultaneously. Useful thermal energy is defined as the heat gain of heating mediums and it also can be expressed by energy input and output as

$$\dot{Q}_u = \dot{Q}_{air} + \dot{Q}_L = \dot{Q}_i - \dot{Q}_o \quad \text{(eq. 1)}$$

At this time, Q_i and Q_o can be written as equation (2), (3)

$$\dot{Q}_i = G\tau\alpha A_c \quad \text{(eq.2)}$$

$$\dot{Q}_o = U_{L,t} A_c (T_c - T_a) \quad \text{(eq.3)}$$

So, equation (1) can be rewritten as equation (4).

$$\dot{Q}_{air} + \dot{Q}_L = \dot{Q}_i - \dot{Q}_o = G\tau\alpha A_c - U_{L,t} A_c (T_c - T_a) \quad \text{(eq.4)}$$

Overall heat loss coefficient of collector can be written as equation (5) from equation (4).

$$U_{L,t} = \frac{G\tau\alpha A_c - (\dot{Q}_{air} + \dot{Q}_L)}{A_c (T_c - T_a)} = \frac{G\tau\alpha - (q_{air} + q_L)}{T_c - T_a} \quad \text{(eq.5)}$$

Heat gain of liquid can be written as equation (6) from "Hottel-Whillier-Bliss equation"(Duffie and Beckman, 1991).

$$\dot{Q}_L = \dot{m}_L C_{p,L} (T_{o,L} - T_{i,L}) = F_{R,L} A_c [G\tau\alpha - U_{L,L} (T_{i,L} - T_a)] \quad \text{(eq.6)}$$

At equation (6), $U_{L,L}$ is defined as heat loss coefficient of liquid side and the heat gain of air is condidered as heat loss of liquid side. This value can be assumed as constant value on the constant air and liquid mass flow rate and temperature difference between inlet air and outdoor air. it can be written as equation (8) from equation (7) if outoor air used as inlet air.

$$\dot{Q}_L = G\tau\alpha A_c - U_{L,L} A_c (T_c - T_a) \quad \text{(eq.7)}$$

$$U_{L,L} = \frac{G\tau\alpha A_c - \dot{Q}_L}{A_c (T_c - T_a)} = \frac{G\tau\alpha - q_L}{T_c - T_a} = f(\dot{m}_{air}) \quad \text{(eq.8)}$$

$U_{L,L}$ is changed by inlet air temperature, air and liquid mass flow rate. But in this experiment, $U_{L,L}$ is considered as a function of air mass flow rate as shown in equation (8) because only outdoor air used for inlet air directly and experiment was conducted on constant liquid mass flow rate. Heat gain of air side can be written as equation (9)

$$\dot{Q}_{air} = \dot{m}_{air} C_{p,air} (T_{o,air} - T_{i,air}) = \dot{Q}_i - \dot{Q}_o - \dot{Q}_L \quad \text{(eq.9)}$$

Heat gain of air side can be rewritten as equation (10) by substituting the equation (2), (3), and (6) to equation (9).

$$\dot{Q}_{air} = \dot{Q}_i - \dot{Q}_L - \dot{Q}_o = G\tau\alpha A_c - F_{R,L} A_c [G\tau\alpha - U_{L,L} (T_{i,L} - T_a)] - U_{L,t} A_c (T_c - T_a) \quad \text{(eq.10)}$$

The maximum heat gain of air side can be obtained when the whole collector surface is at the inlet air temperature. Then, heat removal factor of air side that represent the ratio of heat gain to maximum heat gain can be written as equation (11).

$$F_{R,air} = \frac{\dot{m}_{air} C_{p,air} (T_{o,air} - T_{i,air})}{G\tau\alpha A_c - F_{R,L} A_c [G\tau\alpha - U_{L,L}(T_{i,L} - T_a)] - U_{L,t} A_c (T_{i,air} - T_a)} \quad \text{(eq.11)}$$

So, heat gain of air side can be rewritten as equation (12).

$$\dot{Q}_{air} = F_{R,air} A_c \{G\tau\alpha - F_{R,L}[G\tau\alpha - U_{L,L}(T_{i,L} - T_a)] - U_{L,t}(T_{i,air} - T_a)\} \quad \text{(eq.12)}$$

The thermal efficiency of a collector is defined as ratio of the useful thermal energy to the total incident solar radiation. So, thermal efficiency of liquid side is expressed as equation (13) from equation (6).

$$\eta_L = \frac{\dot{Q}_L}{GA_c} = \frac{F_{R,L} A_c [G\tau\alpha - U_{L,L}(T_{i,L} - T_a)]}{GA_c} = F_{R,L}\tau\alpha - F_{R,L} U_{L,L} \frac{(T_{i,L} - T_a)}{G} \quad \text{(eq.13)}$$

Thermal efficiency of air side can be written as equation (14) from equation (12).

$$\eta_{air} = \frac{\dot{Q}_{air}}{GA_c} = \frac{F_{R,air} A_c \{G\tau\alpha - F_{R,L}[G\tau\alpha - U_{L,L}(T_{i,L} - T_a)] - U_{L,t}(T_{i,air} - T_a)\}}{GA_c} \quad \text{(eq.14)}$$

It can be rewritten as equation (15).

$$\eta_{air} = F_{R,air} \left\{ \tau\alpha(1 - F_{R,L}) + \frac{[F_{R,L} U_{L,L}(T_{i,L} - T_a) - U_{L,t}(T_{i,air} - T_a)]}{G} \right\} \quad \text{(eq.15)}$$

In the equation (15), relation of inlet heating medium temperature, ambient temperature, solar radiation and thermal efficiency of air side is derived. In this equation, η_{air} will be increased if inlet liquid temperature is increased or solar radiation is decreased If the inlet liquid temepr ature is larger than ambient temperature. And if inelt air and ambient temperature is same, η_{air} will be change with $(T_{i,L} - T_a)/G$ to linear on the constant air and liquid mass flow rate. Total thermal efficiency of collector can be written as the sum of the thermal efficiency of air and liquid side. It can be expressed as follows:

$$\eta_t = \frac{\dot{Q}_L + \dot{Q}_{air}}{GA_c} = \eta_L + \eta_{air} = A - B\left(\frac{T_{i,L} - T_a}{G}\right) - C\left(\frac{T_{i,air} - T_a}{G}\right) \quad \text{(eq.16)}$$

Where,

$A = (F_{R,air} + F_{R,L} - F_{R,air} F_{R,L})\tau\alpha$

$B = F_{R,L}(1 - F_{R,air}) U_{L,L}$

$C = F_{R,air} U_{L,t}$

Therefore, total thermal efficiency of collector is written as heat removal factor and heat loss coefficient of two heating medium with operating conditions. Then if the heat removal factor and heat loss coefficient of each heating mediums can be obtained from experiment, total thermal efficiency or thermal efficiency of each heating medium is expected to predict. And also, A, B and C can be assumed as constant value on the constant temperature difference between inlet air and outdoor air, air and liquid mass flow rate.

4. Results and discussion

In this experiment, temperatures of two heating mediums and collector was measured with change of air mass flow rate on the constant liquid mass flow rate at noon that was shown similar solar radiation. Fig. 3 shows the measured temperatures of air, liquid and absorbing plate with air mass flow rate.

Outlet air temperature was decreased with increment of air mass flow rate and also temperature difference between inlet and outlet liquid was decreased with increment of air mass flow rate. It was considered as a result of the increment of heat transfer from liquid pipe to flow air with incremnet of air mass flow rate.

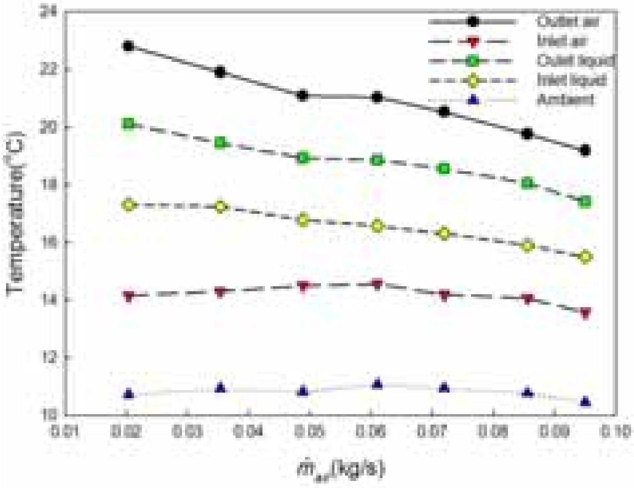


Fig. 3: Temperature profile when the air and liquid were heated simultaneously

Heat gain of each heating medium with solar intensity was shown in Fig. 4. Heat gain of liquid was higher than air on the low air mass flow rate. But it was decreased and the heat gain of air was increased with increment of air mass flow rate due to the increment of heat transfer from liquid pipe to flow air. Total heat gain in hybrid solar collector was increased with increment of air mass flow rate and it means extra heat gain was occured in addition to heat transfer from liquid to air with increment of air mass flow rate. it considered as a result of the heat transfer enhancement from absorbing plate to flow air with increment of air mass flow rate as well as from liquid pipe.

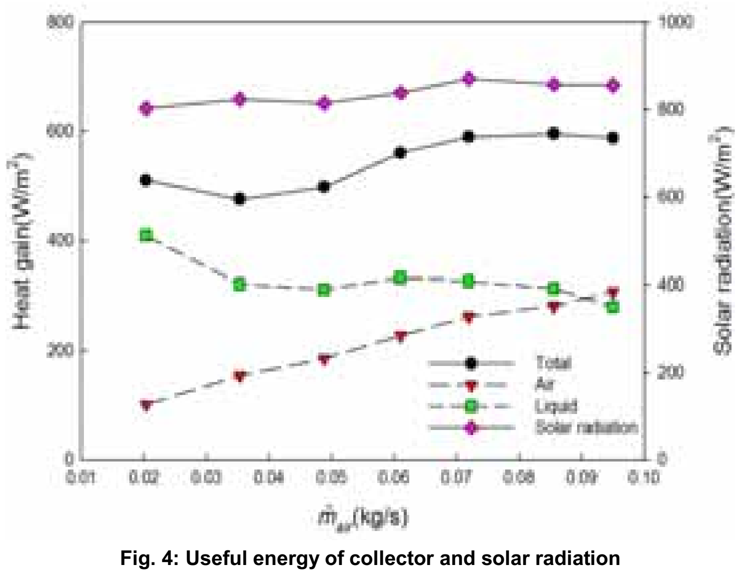


Fig. 4: Useful energy of collector and solar radiation

Heat loss coefficient of collector calculated from equation (5), (8) using measured value was shown in Fig. 5. Heat loss coefficient of liquid side was increased with increment of air mass flow rate. This result signifies that the heat transfer from liquid pipe to flow air was enhanced with increment of air mass flow rate. Whereas, total heat loss coefficient of collector was slightly decreased with increment of air mass flow rate because of the increment of heat transfer from liquid pipe and absorbing plate to flow air as previously stated.

Fig. 6 shows heat removal factors of air and liquid side. Heat removal factor of air side was increased with increment of air mass flow rate. As previously shown, this tendency is considered as a result of heat transfer increment from absorbing plate and liquid pipe to flow air with increment of air mass flow rate and by this, heat removal factor of liquid side was decreased with increment of air mass flow rate.

At this time, heat removal factor and heat loss coefficient can be expressed as a function of air mass flow rate from the experiment result as shown in Fig. 5, 6. In other words, heat removal factor and heat loss coefficient of collector at specific air mass flow rate can be predicted when the outdoor air was used as inlet air on constan liquid mass flow rate. Therefore, total thermal efficiency of hybrid solar collector can be expressed as a function of air mass flow rate, inlet temperature of liquid, ambient temperature and solar radiation.

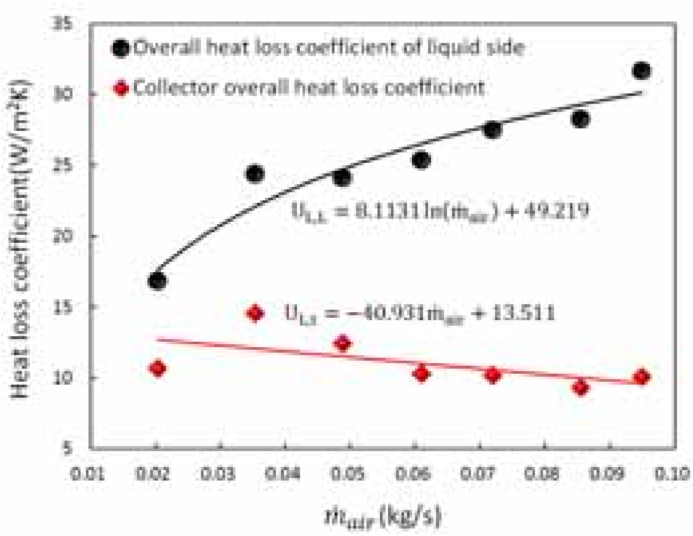


Fig. 5: Overall heat loss coefficient of collector and liquid side

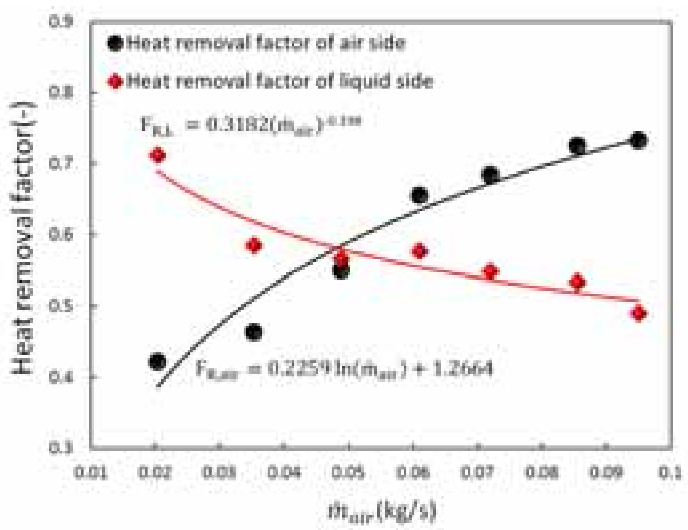
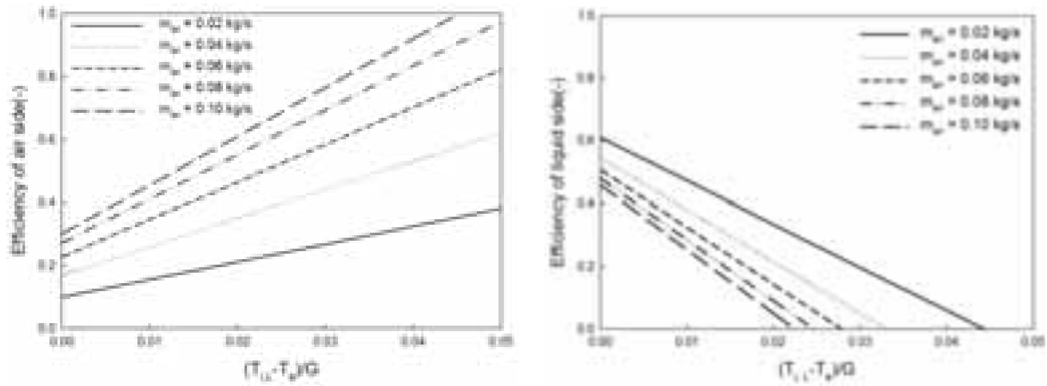


Fig. 6: Heat removal factor of air and liquid side

Namely, thermal efficiency can be predicted with respect to each operation and external condition using heat removal factor and heat loss coefficient obtained from experiment. Fig. 7 shows the thermal efficiency of air and liquid side with $(T_{i,L} - T_a)/G$. using equation (13), (15). The efficiency of air was changed to linear because the temperature difference between inlet air and ambient was as small as ignored. These tendency was included in equation (15). The higher slope angle of air efficiency curve means that the higher efficiency increase of air side when the inlet liquid temperature was increased when the other conditions are same and it was increased with increment of air mass flow rate.

In case of the thermal efficiency of liquid, it was shown the maximum thermal efficiency about 0.6 while the air was also heated and it was decreased with increment of inlet air temperature, air mass flow rate and decrement of solar radiation. It is similar with tranditional flat plate solar collector for hot water but, decline of efficiency was higher than traditional flat-plate solar collector for hot water because heat gain of flow air was also considered as a heat loss of liquid.



(a) (b)

Fig. 7: Prediction of the thermal efficiency of hybrid solar collector; (a) air side (b) liquid side

Fig. 8 shows total thermal efficiency of hybrid solar collector including heat gain of air and liquid. Total thermal efficiency was increased with increment of air mass flow rate, solar radiation and decrement of temperature different between inlet liquid and ambient. Maximum total thermal efficiency of collector expressed as A in equation (16) was shown from 0.710 to 0.759 with air mass flow rate. And also, heat loss coefficient of liquid side expressed as B in equation (16) shown from 4.974 to 8.151 and it is decreased with increment of air mass flow rate.

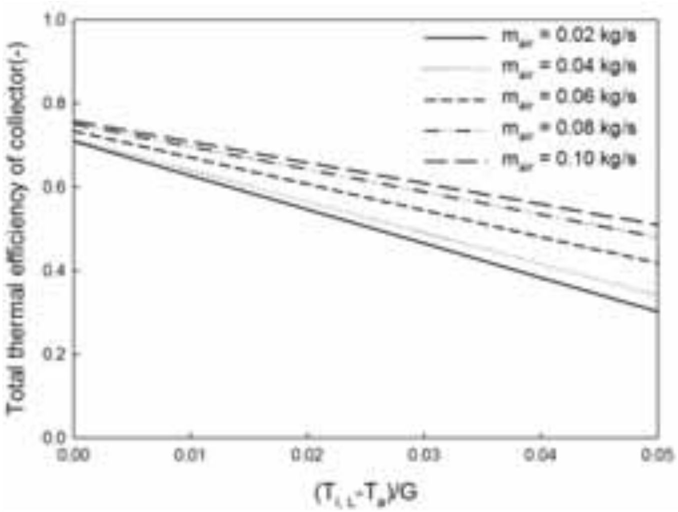


Fig. 8: Prediction of total thermal efficiency of collector

5. Conclusions

This study conducted a performance evaluation when the air and liquid were heated simultaneously in flat plate solar collector and the efficiency of hybrid solar collector influced by many factors was confirmed using the equation expressed by energy balance.

As a result, efficiency of the air side was increased with the increment of the inlet liquid temperature when the other conditions were constant and the efficiency of liquid side was decreased with increment of inlet liquid temperature and decrement of solar radiation. Total thermal efficiency of collector was decreased with increment of inlet air and liquid temperature and decrement of solar radiation similar with the traditional solar collector. From these results, the tendency of efficiency change confirmed using expressed equationit considered as an appropriate and it is expected to generalize the evaluation method of the flat plat solar collector that heating air and liquid simultaneously if additional experiment with more various conditions are conducted.

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