Exergy Analysis of Solar Collector

Lee, Suk Gun*, Lee, Hyun Woo*

* *Department of Agricultural Engineering, Kyung Pook National University*

Abstract ☐ Important factors in evaluating solar collcetor efficiency are solar radiation, temperature and flow rate of the working fluid. The effects of these factors on the energy and the exergy gained by water, the working fluid, from the collector were analyzed. The results indicated that the collector efficiency and the energy and the exergy gained by the water from the collcetor increased with the increase of solar radiation. According to the exergy analysis, as the water temperature at the inlet of the collector increased, the exergy gained by the water increased while the energy gained by the water decreased. The water temperature at the outlet of the collector could be calculated with a mean error of 2.8%, and the energy and the exergy could be calculated theoretically with mean errors of 16.8% and 19.1%, respcetively.

Keywords ☐ Energy, Exergy, Collector efficiency, Heat transfer, Solar collector, Solar radiation, Reference condition, Water flow rate, Water temperature, Working fluid

I. INTRODUCTION

Solar energy is considered as an important alternative energy source in the future because of its various usage with minimum environmental pollution compared to other energy sources.

A solar collector is a kind of heat exchanger which converts solar radiant energy to thermal energy, and transfers it to the working fluid. The performance of the collector is affected by materials, construction, and meteorological and operating conditions.

There have been a number of studies about collector performance by the energy method. Recently, the exergy method, which uses the concept of the available energy by the second law of thermodynamics, is recommended as more effective method than the energy method in the analysis of heat system. The exergy method has been developed to avoid much of the complexities and confusions that exist in the classical approach to the second law of thermodynamics. The use of exergy method in the system analysis appeared in several books and technical reports in the early 1960s, thereafter it has been used frequently in the analysis of a heat system.

In this study, the exergy method for a solar collector is described and is compared with the conventional energy method. The energy and the exergy were calculated for the various operating conditions such as the solar radiation, the water temperature, and the water flow rate.

II. MATERIALS AND METHODS

1. Experimental collector and collector efficiency

The energy and the exergy analysis for the vacuum tube flat collector, which has 1.75m^2 of collection area per unit, were conducted. Fig. 1 shows a schematic layout of heat transfer in a collector, and the available heat transfer was calculated as follow ;

$$Q_c = Q_a - Q_l \tag{1}$$
$$Q_a = (\tau \alpha) I \tag{2}$$
$$Q_l = \{K_{up} + K_{rr} + K_{sd}(A_s/A_c)\} \quad (T_{co11} - T_a) \tag{3}$$

where,

Q_c : Rate of useful heat transfer to the working fluid, Kcal/m^{2}h

Q_a : Rate of heat absorbed to the collector, Kcal/m^{2}h

Q_l : Heat loss from the collector, Kcal/m^{2}h

τ : Transmittance of the collector cover

α : Absorptance of the collector-absorber

I : Solar radiation on the collector surface, Kcal/m^{2}h

K_{up} : Surface heat transfer coefficient for the top of collector, Kcal/m²h℃

K_{rr} : Surface heat transfer coefficient for the bottom of collector, Kcal/m²h℃

K_{sd} : Surface heat transfer coefficient for the sides of collector, Kcal/m²h℃

A_s : Side area of the collector, m²

A_c : Available area of the collector, m²

T_a : Ambient air temperature. ℃

T_{coll} : Mean temperature of the working fluid, which is the average of the T_{coll1} and T_{coll2}, the temperatures of the working fluid at the inlet and the outlet of the collector, ℃

However, the heat loss from the sides can be ignored, because the sides of a collector are insulated and have a comparatively small area. So Eq.(1) becomes :

$$Q_c=(\tau\ \alpha)I-K_t(T_{coll}-T_a) \quad (4)$$

where, K_t is the sum of K_{up} and K_{rr}.

The collector efficency (η_c) is calculated by Eq.(5) :

$$\eta_c=Q_c/I \quad (5)$$

Substituting Eq.(4) into Eq.(5) :

$$\eta_c=(\tau\ \alpha)-K_t(T_{coll}-T_a)/I \quad (6)$$

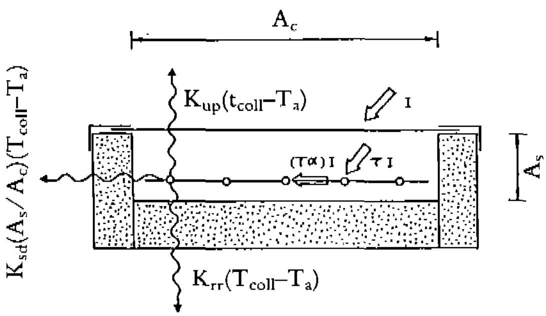


Fig. 1. Heat transfer in a solar collector

2. Energy and exergy analysis

a. Exergy

Exergy (Die Exergie) is defined as the work that is available in a gas, liquid or solid as a result its nonequilibrium condition relative to some reference condition. Exergy represents an effective energy which is the work performed by a material until it equilibrates with the surrounding enviroment. It can be used in evaluating the energy quality of materials under any condition. The temperature and the pressure under the equilibrium condition are called a reference temperature and a reference pressure, respectively, and the equilibrium condition is called a reference condition. Especially, the energy quality is more important than the energy quantity when the heat source of the system has a low temperature as solar collector.

b. Reference condition

The basic principle of the exergy method is that calculation of the exergy is related to a common reference condition. This reference condition is generally the surrounding environment of the system since the final disposition of the initially available energy will be made by external cooling systems or ejection of energy-bearing matter into the enviroment. The use of the surrounding enviroment as a zero-energy reference offers many advantages for engineering design and analysis of energy-related systems.

A solar collector is a small system using a heat source of low temperature and its performance is affected by ambient air temperature. So, the ambient air temperature was used as the reference condition of temperature. And, 1 atm was used as the reference condition of pressure because water, the working fluid, has a small compressibility, and the exergy variation by the pressure change was not considered.

c. Energy and exergy gained by working fluid

The energy and the exergy gained by the working fluid from the collector were calculated by Eq.(7) and Eq.(8).

$$EN=(h_2-h_1)F \quad (7)$$

$$EX=\{(h_2-h_1)-T_0(s_2-s_1)\}\ F \quad (8)$$

where,

EN : Flow rate of energy gained by the working fluid, Kcal/h

EX : Flow rate of exergy gained by the working fluid, Kcal/h

h : Enthalpy of the working fluid, Kcal/kg

s : Entropy of the working fluid, Kcal/kg°K

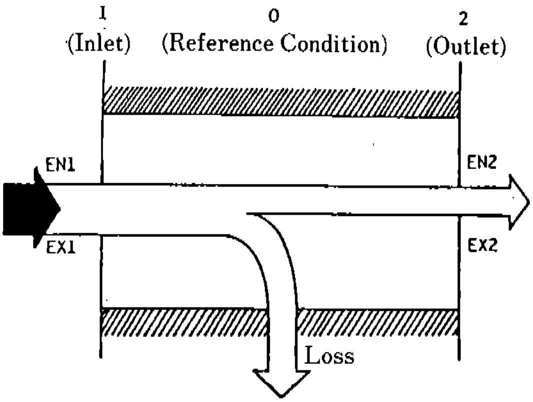
T_0 : Absolute temperature of the ambient air, °K

F : Mass flow rate of the working fluid, kg/h

Fig.2 illustrates the energy and the exergy balance of a unit. The subscripts 1, 2, and 0 in Fig.2 represent the conditions of the inlet and the outlet of the collector, and the reference condition, respectively. In this study, the energy and the exergy loss from the absorber of the collector was ignored.

d. Energy and exergy computation

Fig.3 show the flow chart of the energy and



Temperature	: T_1	T_0	T_2
Pressure	: p_1	p_0	p_2
Enthalpy	: h_1	h_0	h_2
Entropy	: s_1	s_2	s_3
Energy	: EN1	-	EN2
Exergy	: EX1	-	EX2

Fig. 2. Energy and exergy balance of a unit

the exergy computation program for the solar collector.

The components of the program are : 1) input of the formulae of enthalpy and entropy of water for the variations of temperature and pressure, 2) calculation of enthalpy and entropy for a given conditions, 3) calculation of solar radiation and the exergy efficiency of the collector, and 4) outputs of the results of the computation.

III. RESULTS AND DISCUSSION

1. Collector efficiency and water flow rate

The collector efficiency is determined by transmittance, absorptance, heat transfer coefficient, water temperatures at the inlet and the outlet of the collector, and solar radiation as given in Eq. (6).

Fig.4 shows the effects of the water flow rate in the collector on the water temperature at the

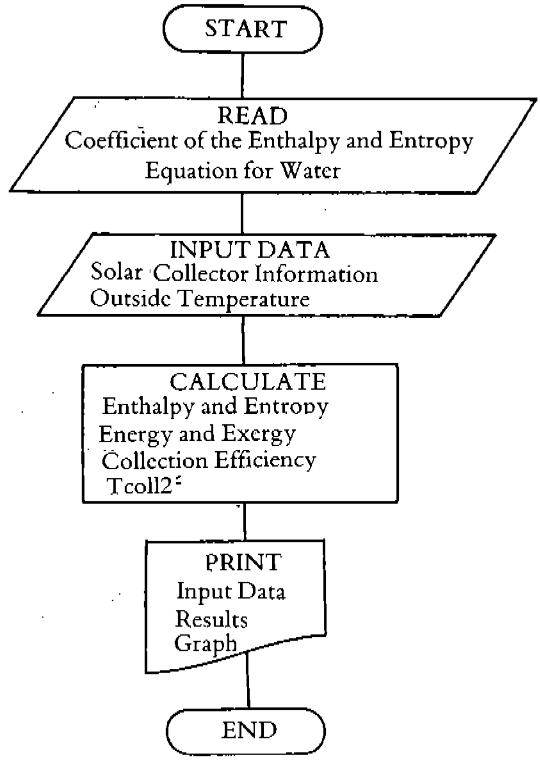


Fig. 3. Flow chart of the energy and the exergy analysis program

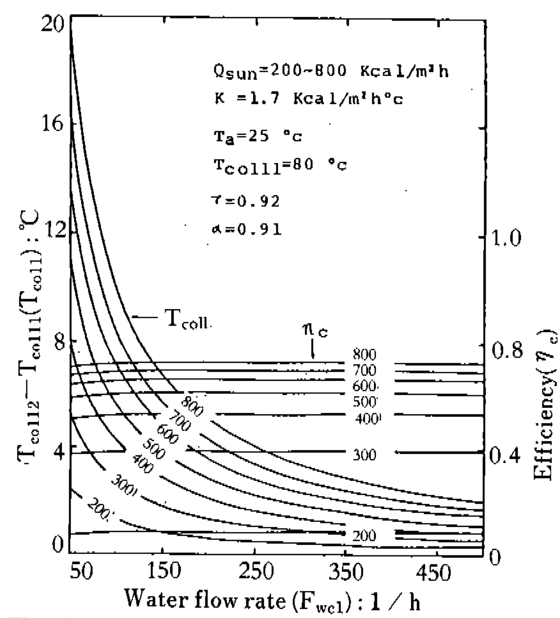


Fig. 4. Effect of the water flow rate on the differences of the water temperature and the collector efficiency

outlet of the collector and the collector efficiency. The effect of the variation of water flow rate on the collector efficiency can be ignored under a constant solar radiation. When the water flow rate was constant, the collector efficiency increased with the increase of solar radiation. Fig. 4 also shows that the temperature difference between the inlet and the outlet of the collector decreased as the water flow rate increased.

2. Exergy and water flow rate

The effects of the variation of the water flow rate and the solar radiation on the energy and the exergy gained by the water are shown in Fig. 5.

Under the constant water flow rate, both the energy and the exergy gained by the water increased with the increase of the solar radiation. However, as the water flow rate increased under the constant solar radiation, the energy increased a little while the exergy decreased a little.

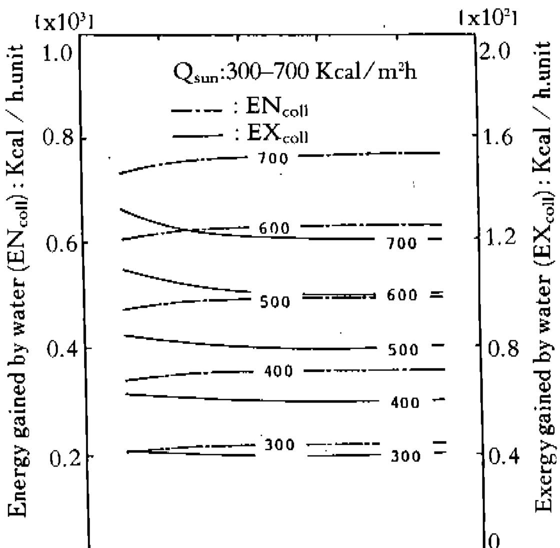


Fig. 5. Energy and exergy vs. water flow rate

3. Exergy and water temperature

a. Exergy and water temperature for various solar radiation

The significant fact was obtained from the analysis of the effect of the water temperature at the inlet of collector on the energy and the exergy gained by the water. As shown in Fig. 6, when the solar radiation was constant, the exergy increased with the increase of water temperature. But the energy rather decreased with the increase of water temperature. However, when the water temperature at the inlet of collector was constant, both the energy and the exergy increased with the increase of solar radiation.

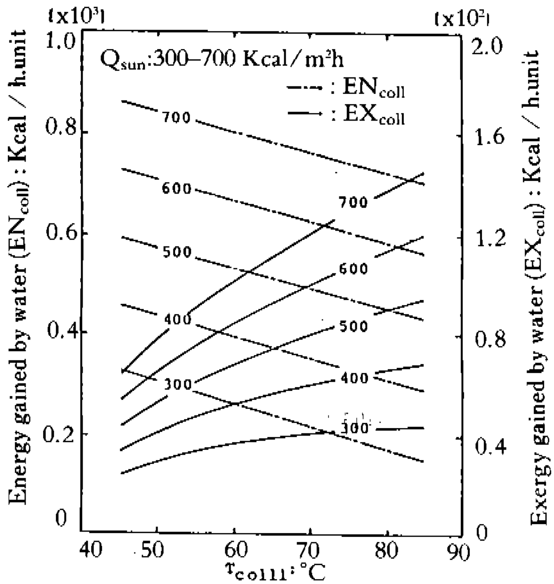


Fig. 6. Energy and exergy vs. water temperature at the inlet of the collector for the various solar radiation

b. Exergy and water temperature for various water flow rate

The relationship between the water temperature at the inlet of the collector, and the energy and the exergy for the various water flow rate is shown in Fig. 7.

Under the constant water flow rate, as the water temperature increased, the exergy increased while the energy decreased. However, when the water flow rate increased under the constant water temperature at the inlet of collector, the energy increased a little while the exergy decreased a little. These results shown in Fig. 7 are similar to those in Fig. 6.

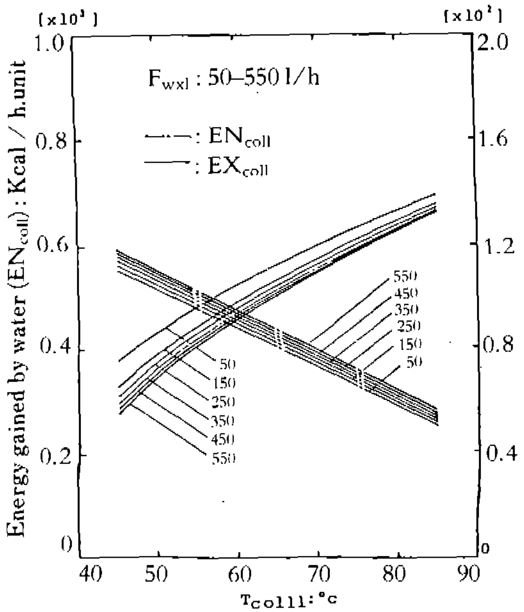


Fig. 7. Energy and exergy vs. water temperature at the inlet of the collector for the various various water flow rate

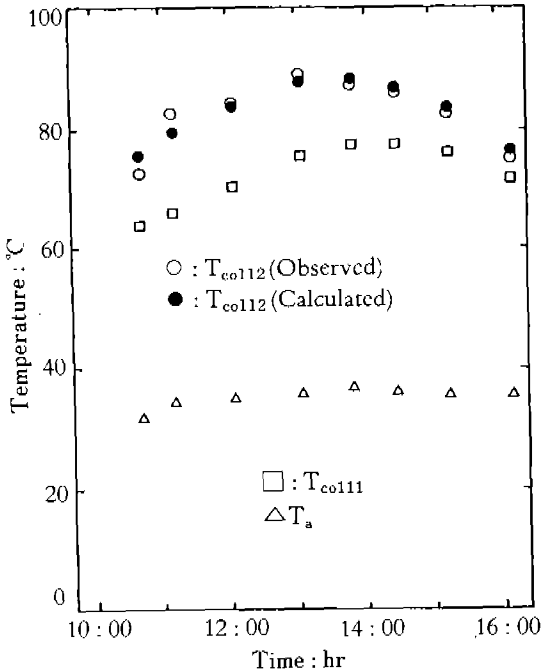


Fig. 8. Water temperature calculated at the outlet of collector compared to the observed data

4. Comparison of the computed and the observed values

a. Water temperature at the outlet of collector

Fig.8 shows the comparison of the calculated output and the observed data for the water temperature at the outlet of the collector.

The water temperature at the outlet of the collector could be calculated with a mean error of 2.8% under the experimental condition. During the early stage of the experiment, the difference between the calculated and the observed values of the water temperature at the outlet of the collector was comparatively higher than others. This is presumably because the water temperature of the collector was not influenced completely by the air temperature.

b. Energy and exergy

As shown in Fig. 9, both the energy and the exergy gained by the water from the collector could be calculated theoretically with mean errors of 16.8% and 19.1%, respectively. During the early stage of the experiment, the differences between the calculated and the observed values of the energy and the exergy gained by the water were comparatively high. This is attributed to the face that the energy and the exergy gained by the water was not fully influenced by the solar radiation.

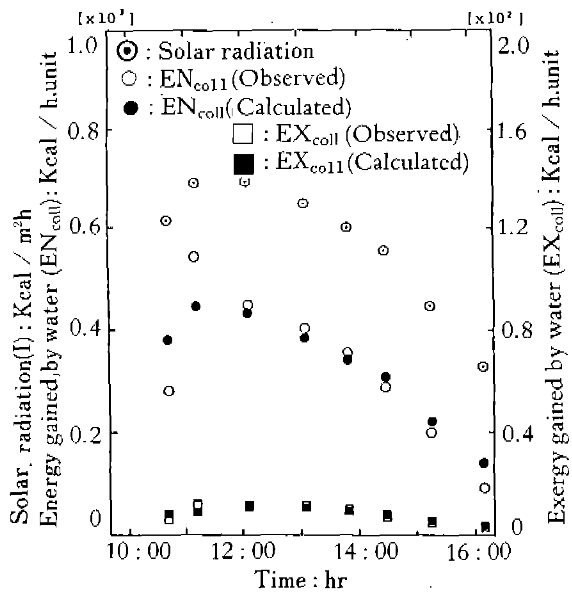


Fig. 9. Comparison of calculated and observed energy and exergy values

V. CONCLUSIONS

The results of the energy and the exergy analysis for solar collector are as follows :

1. The effect of the variation of the water flow rate on the collector efficiency could be ignored under constant solar radiation. When the water flow rate was constant, the collector efficiency increased with the increase of solar radiation. And, the water temperature difference between the inlet and the outlet of the collector decreased as the water flow rate increased.
2. Under the constant water flow rate, both the energy and the exergy gained by the water incresed with the increase of the solar radiation. However, as the water flow rate increased under the constant solar radiation, the energy increased a little while the exergy decreased a little.
3. When the solar radiation was constant, the exergy increased with the increase of water temperature. But the energy rather decreased with the increase of water temperature. However, when the water temperature at the inlet of collector was constant, both the energy and the exergy increased with the increase of solar radiation.
4. Under the constant water flow rate, as the water temperature increased, the exergy increased while the energy decreased. However, when the water flow rate increased under the constant water temperature at the inlet of collector, the energy increased a little while the exergy decreased a little.
5. The water temperature at the outlet of the collector could be calculated with a mean error of 2.8%, and the energy and the exergy gained by the water from collector could be calculated theoretically with mean errors of 16.8% and 19.1%, respectively.

NOMENCLATURE

A_c : Available collector area, m^2

A_s : Side area of collector, m^2

EN : Energy, $Kcal/m^2h$

EN_{coll} : Energy gained by the water from the collector, $Kcal/m^2h$

EX : Exergy, $Kcal/m^2h$

EX_{coll} : Exergy gained by the water from the collector, $Kcal/m^2h$

F : Mass flow rate of working fluid, ℓ /h

h : Enthalpy of working fluid, Kcal/kg

I : Solar radiation on a collector surface, $Kcal/m^2h$

K_{rr} : Surface heat transfer coefficient of the bottom, $Kcal/m^2h$℃

K_{sd} : Surface heat transfer coefficient of the side, $Kcal/m^2h$℃

K_{up} : Surface heat transfer coefficient of the top, $Kcal/m^2h$℃

Q_c : Rate of useful heat transfer to a working fluid, $Kcal/m^2h$

Q_a : Rate of heat absorbed to the collector, $Kcal/m^2h$

Q_l : Heat loss from the collector, $Kcal/m^2h$

s : Entropy of working fluid, Kcal/kg°K

T_a : Ambient air temperature, ℃

T_{coll} : Mean temperature of the working fluid, ℃

T_o : Absolute temperature of reference condition, °K

τ : Transmittance

α : Absorptance of the collector absorber

η c : Collector efficiency

ACKNOWLEDGEMENTS

This study was performed by the financial support from the Korea Science and Engineering Foundation and Kyung Pook National Unirersity.

REFERENCES

1. Ahern, J.E., (1980), The exergy method of energy systems analysis, John Wiley & Sons. Inc., pp. 30-37, 48-80
2. Tabor, H. (1978), Testing of solar collectors, Solar energy, 20 : 293-303
3. Kreith, F. and J.F. Kreider, (1978), Principles of solar engineering, McGraw-Hill book Co., pp. 203-306
4. Marschall, E. and D. Adams, (1978), The effiency of solar flat plate collectors, Solar energy, 20 : 413-414
5. Klein, S.A., (1978), Calculation of flat-plate collector utilizability, Solar energy, 21 : 393-402
6. Smith, T.F., P.A. Jensen, and D.L. Spencer, (1980), Thermal performance of the distributed flow, subatomspheric pressure, flat plate solar collector, Solar energy, 25 : 429-436