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확산형 반사구조물 부착시 태양열 평판 집열기의 성능향상에 관한 연구

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Enhancement in the Performance of Flat-plate Solar Collector with Diffuse Reflecter

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요약

기존의 태양열 평판집열기에 확산형 평판반사구조물을 부착시켰을 때의 성능 향상에 관한 연구로서 온수용 집열판에 관한 실험과 전산기 모사를 통해 분석 검토하였다. 수평면과 52.3°로 기울어져 있는 물 순환식 평판 집열기의 하부에 일정면적의 알루미늄 판을 부착시켜 여러 일기 조건하에서 얻은 실험결과와 이론치를 비교하여 수학적 모델의 타당성을 검토했다. 청명한 날에는 실험결과와 모사결과가 비교적 잘 일치하였으며, 난방 수요가 큰 가을 및 겨울의 기상조건에서 반사구조물과 평판집열기 사이의 최적 각도는 110—120°로 밝혀졌다. 또한 전산기모사를 통하여 각 월별의 반사구조물의 최적각도를 구하였으며, 연중 반사구조물의 각도를 115°로 고정시켰을 때 집열기 단위 면적당 15% 이상의 열량이 반사 구조물에 의해서 증가됨을 알 수 있었다.

ABSTRACT

The use of diffuse flat reflector to enhance the performance of flat-plate solar collector has been analyzed by both experiment on a water heating collector and its digital simula-

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tion. Fair agreement is obtained between experimental and simulated results for clear days. In this study the reflector covered with self-adhesive aluminum sheet (non-Cr-coated) has been placed below a collector optimally oriented at 52.3°. An optimum reflector and collector orientation angle is found to be between 110° and 120° for fall and winter solar conditions. For typical fall and winter operating conditions, the addition of an optimally oriented diffuse reflector can result in an improvement in energy collection per unit area by more than 15 percent over that expected with an optimally tilted flat-plate collector. Finally, digital simulation has been used to estimate the monthly performance of a water heating collector with an optimal angle of the reflector.

Ⅰ. Introduction

Flat-plate collectors have been used for both liquid and air heating systems that require thermal energy at comparatively low temperatures as the simplest and one of the most effective means of collecting solar energy. Usually they are tilted at an optimum angle which will provide maximum annual energy collection.[1)] At this fixed angle the amount of direct light gathered is low in winter when heating demand is high. Planar reflectors have been suggested as a means of increasing the heat collection of flat-plate solar collectors to meet the winter demand. The addition of reflectors increases the effective area of collection and collector output by increasing the amount of radiation that falls on the collector properly. Remarkably, collector output can be increased by a great factor than the same increase in effective collection area would of itself account for.

There have been several examples of the use of reflectors with flat-plate collectors to increase the amount of solar energy collected for their solar devices. Tabor[2)] has recommended various arrangements of reflectors and calculated output increasing factor. McDaniels and Lowndes[3)] have studied a specular reflector-collector system with the reflector located below the collector both experimentally and theoretically. They have calculated an enhancement factor based on incident radiation and system geometry. Other investigators have analyzed the performance obtainable with flat reflectors placed either below or above flat-plate collectors.[4~6)] Recently, Larson[6)] analyzed enhancement in the performance expected with a flat mirror placed below a flat-plate collector for determination of optimal geometries and optimal orientation strategies, and generalized the analyses reported in the literature.

The objective of this study is to analyze the performance of a reflector-collector system with a diffuse reflector placed below a flat-plate collector by means of mathematical model which provides an optimal placement of reflector and collector. Experiments are conducted on a water heating collector to show adequacy of the model for a reflector-collector system and to compare the performance of a collector system with that of a same collector without a reflector.

Ⅱ. Theoretical Analysis

Ⅱ-1. Total Solar Radiation on Tilted Surface

Flat-plate solar collectors absorb both beam and diffuse component of solar radiation. In order to use horizontal total radiation data, it is necessary to derive a value for effective ratio of solar energy on the tilted surface to that on the horizontal surface, R, for total solar radiation.

Generally the radiation on a tilted surface has been derived by considering that solar radiation reflected from the ground to be negligible,

$$I_t = I_b R_b + I_d \frac{1 + \cos s}{2} \tag{1}$$

where R_b is the beam correction factor which can be given as

$$R_b = \frac{\cos(\phi - s)\ \cos\delta \cos\omega + \sin}{\cos\phi \cos\delta \cos\omega + \sin\phi}$$
$$\frac{(\phi - s)\sin\delta}{\sin\delta} \tag{2}$$

With the monthly data for the total solar radiation, one can thus immediately determine the optimum collector tilt which can maximize the amount of collected energy used efficiently throughout the year for any latitude and any weather condition.

Ⅱ-2. The Basic Energy Balance Equation for Flat-Plate Collector

The energy balance on the whole collecter can be written as

$$Q_A = A_C\{[IR(\tau\alpha)]_b + [IR(\tau\alpha)]_d\}$$
$$= Q_U + Q_L + Q_S \tag{3}$$

A measure of collector performance is the collection efficiency, defined as the ratio of the useful gain over any time period to the incident solar energy over the same time period.

$$\eta = \int \frac{Q_u}{A_c}\, dt \Big/ \int IR\,dt \tag{4}$$

The detail analysis of a solar collector is a very complicated problem. However, a number of simplifying assumptions[7] can be made to obtain useful results without obscuring the basic physical situations.

The outlet fluid temperature can be derived theoretically from an energy balance on the fluid through one pipe as follows[7]:

$$T_{fo} = T_a + \frac{q_A}{U_L} + \left[(T_{fi} - T_a) - \frac{q_A}{U_L}\right]$$
$$\epsilon - [U_L W F' L / m c_p] \tag{5}$$

where the overall loss coefficient, U_L, is found by adding together the top and bottom coefficients:

$$U_L = U_t + U_b \tag{6}$$

The back loss coefficient, U_b, is approxmately

$$U_b = \frac{k_{ins}}{L_{ins}} \tag{7}$$

and for a single-cover collector, the top loss coefficient, U_t, has been developed empirically by Klein[8]

$$U_t(45^\circ) = \left[\frac{1}{\left(\frac{344}{T_p}\right)\left(\frac{T_p - T_a}{1 + f}\right)0.31} + \frac{1}{h_w}\right]^{-1}$$
$$+ \frac{\sigma(T_p + T_a)(T_p{}^2 + T_a{}^2)}{[\epsilon_p + 0.0425(1 - \epsilon_p]^{-1} + \left[\frac{1 + f}{\epsilon_g}\right] - 1} \tag{8}$$

where

$$h_w = 5.7 + 3.8\,V$$
$$f = 1.058(1 - 0.04\,h_w + 0.0005\,h_w{}^2)$$

As Eq. (8) is prepared using a tilt of 45°, it needs to correct for tilt by a method given below[8]

$$U_t(s)/U_t(45) = 1 - (s - 45)$$
$$(0.00259 - 0.00144\,\epsilon_p) \tag{9}$$

Furthermore, the solution for the collector plate temperature, T_p, at each time is given as

$$T_p = T_a + \frac{q_A}{U_L} - \left[\frac{q_A}{U_L} - (T_{PI} - T_a)\right]$$
$$\epsilon - [AcU_Lt/(MC)e] \qquad (10)$$

For the geometry of a collector used in this study, collector efficiency factor, F' and be given as

$$F' = \frac{1/U_L}{W\left\{\frac{1}{U_L[D + (W-D)F]} + \frac{1}{C_{\text{bond}}} + \frac{1}{\pi Dh}\right\}} \qquad (11)$$

Usually, it is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the inlet fluid temperature. Mathematically the collector heat removal factor, F_R, is then

$$F_R = \frac{GC_p(T_{fo} - T_{fi})}{[q_A - U_L(T_{fi} - T_a)]} \qquad (12)$$

Thus theoretical outlet fluid temperature from Equation (5) can be compared with experimental value to show adequacy of the mathematical model.

The total useful energy gain of the collector, Q_u, can be written as

$$Q_u = A_cF_R[q_A - U_L(T_{fi} - T_a)] \qquad (13)$$

Values of U_L and F_R can be calculated using Equations (6), (7), (8), (9) and (12). The useful energy gain of the collector at any time can be also given as

$$Q_u = mc_p(T_{fo} - T_{fi}) \qquad (14)$$

Consequently theoretical energy gain of the collector can be calculated by use of Equation (13) and be compared with the experimental value obtained from Equation (14) with inlet and outlet fluid temperatures being measued at any time.

Ⅱ-3. Reflector-Collector System

For the collector with a diffuse refelector, it is assumed that the presence of the reflector does not alter the diffuse radiation falling on the collector from the sky. So the rate of energy absorption per unit area is given as

$$q_A = [IR(\tau\alpha)]_{bc} + [IR(\tau\alpha)]_{dc} + (\tau\alpha)_{rc}\,\rho_r(IR)_{br}\frac{A_{rc}}{A_c} \qquad (15)$$

where the exchange area A_{rc} equals A_rF_{rc} and represents an effective area for radiative interchange between the surfaces. The transmittance-absorptance product $(\tau\alpha)$ is a modified form which allows for the interreflection between the absorbing plate and the cover system.[7] $(\tau\alpha)$ is dependent on the angle of incidence, but the effect of the angle of incidence was neglected in this study for simplicity.

For radiant heat transfer between surface 1 and surface 2 of total areas A_1 and A_2, respectively as shown in *Figure 1*, the view factor F_{12} is defined as the fraction of the total radiation leaving surface 1 that impinges on surface directly. If surface 1 is diffuse, radiating uniformly in all directions, it can be shown that

$$F_{12} = \frac{1}{\pi A_1}\int_{A_1}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{r^2}\,dA_1\,dA_2 \qquad (16)$$

where r is the distance between two elements dA_1 and dA_2 on the respective surfaces, and θ_1 and θ_2 are the angles between the line joining dA_1 and dA_2 and their respective normals. Integration of Equation (16) can be expressed in complicated analytical solution terms with integral term.[9] Integral term in analytical solution of Equation (16) is calculated by use of Hamming's predictor-corrector method[10]

Consequently, a view factor is found to be an explicit function of the angle between collector and reflector, and reflector size. Thus the optimum reflector angle which maximizes the rate of energy absorption per unit area can be obtained for any operating conditions.

Ⅲ. Experiments

Two commercially available collectors (Samsung SFC-360 type, 0.92m x 1.84m) were used in a water heating system to compare the performance of a collector-reflector system with that of the same collector without a reflector under similar operating conditions. Experimental results were also compared with those obtained by digital simulation based on the model with the parameters and weather data of the experiments. The aluminum absorber plate is selectively coated with a material having absorptance $\alpha_p = 0.91$ and emittance $\varepsilon_p = 0.12$. The plate is covered with two glass plates being 3mm in thickness. Glass wool with conductance $k_{ins} = 0.0327$ kcal/m-hr-°C is used for back insulation. Design parameters of flat-plate collector and reflector are listed in *Table 1.*

Tble 1. Design Parameters of Flat-Plate Collector and Reflector

Solar collector
  collector slope $s = 52.3°$
  effective collector area $A_c = 1.62\text{m}^2$
  Gover glass
    number of cover $N = 1$
    transmittance $\tau = 0.876$
    emissivity $\varepsilon_g = 0.88$
    thickness = 3mm
    specific heat = 0.13 cal/g.°C
    density = 2.5g/cm^3
  Absorbing plate (slectively coated Aluminum sheet)
    absorptivity $\alpha_p = 0.91$
    emissivity $\varepsilon_p = 0.12$
    plate thickness $\delta_p = 2\text{mm}$
    tube distance $w = 11\text{cm}$
    tube diameter$D = 0.95\text{cm}$
    number of tubes = 7
    bond conductance $C_{bond} = 380\text{W/m.°C}$
    thermal conductivity $k_p = 210\text{W/m.°C}$
  Insulation material (glass wool)
    thermal conductivity $k_{ins} = 0.0327$kcal/m. hr. °C
    insulation thickness $L_{ins} = 50\text{mm}$
  Working fluid (water)
    viscosity = 0.0012kg/m.sec
    thermal conductivity $k = 0.588\text{W/m.°C}$
    specific heat = 1 cal/g.°C
Diffuse Reflector (non-Cr-coated aluminum sheet)
    size = 1m × 2m
    thickness = 300μm
    refletance $\rho_r = 0.5$

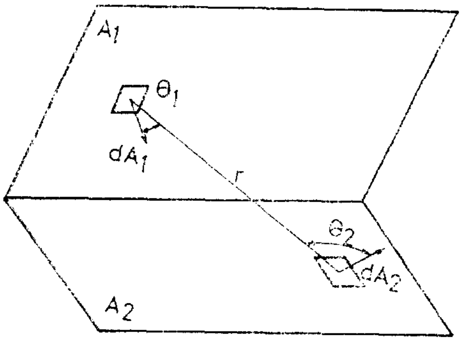

Fig. 1. Radatiion Exchange Beween Two Rectangular Planes.

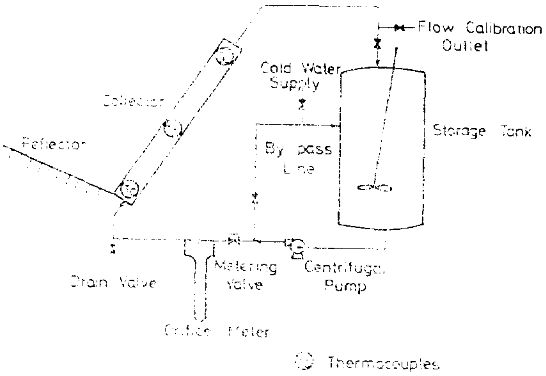

Fig. 2. Experimental Apparatus

A schematic diagram of experimental apparatus is shown in *Figure 2.* Each collector was mounted on a common plane (latitude = 37.5°N) with an east-west orientation which can have its angle changed as needed. However, the collector was tilted at 52.3° to the horizontal throughout the experiments. This tilt of the collector follwed the general rule that an optimum angle of the tilt in the northern hemisphere is latitude plus 15 degrees for heating.[7] Water flow from a storage tank to the collector was circulated by a centrifugal pump and adjusted by a metering valve and by-pass line. The flow was measured by orifice meters which could be calibrated simply at any time during operating by direct volumetric measurement. A mass flow of 1.5kg/min was used, which was found to be an optimum flow rate with respect to the collector efficiency and pumping cost.

One collector was provided with a reflector placed below the collector which could be set at various angles. The reflector 1m × 2m was covered with a self-adhesive aluminum sheet (non-Cr-coated) having a reflectance $\rho_r = 0.5$ to simulate a diffuse reflector. Its reflectance was measured simply by use of a potentiometer as described by Sheehan and Laszlo.[11]

The ambient temperature, collector plate temperature, inlet and outlet fluid temperatures were measured by use of iron-constantan (type J) thermocouples at time intervals of an hour. An Eppley pyranometer with its sensitivity of $9\mu v/W.m^{-2}$ measured the total radiation on a horizontal plane. These results were taken on a chart recorder. All the stream lines were insulated well enough to avoid heat losses by use of glass wool.

Experimental data were obtained with the reflector angle being varied from 90° and 120° by an increament of 5°.

Ⅳ. Results and Discussion

Experimental inlet and outlet fluid temperatures at any time in a water heating collector without a reflector are compared with theoretical values obtained form Equation (5) as shown in *Figure 3*. A typical comparison of experimental collector efficiency at every hour with theoretical values is shown in *Figure 4*. As can be seen from *Figures 3* and *4*, experimental results are found to be in fair agreement with theoretical values under good operating conditions except that there were large deviations around sunrise and suset. Possible explanations for these differences are quite lower collector plate temperatures, and energy balances on the storage tank and pipe line being neglec-

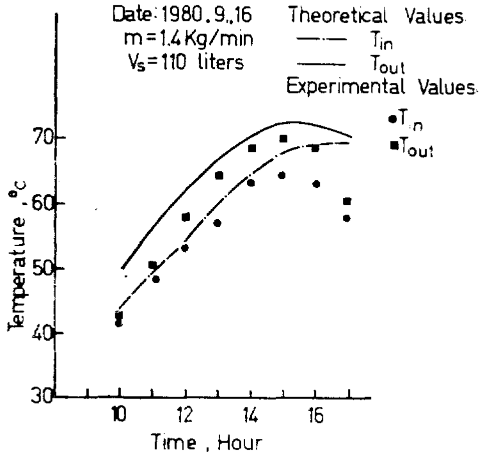

Fig. 3. Comparison of Experimental Fluid Temperatures with Theoretical Values

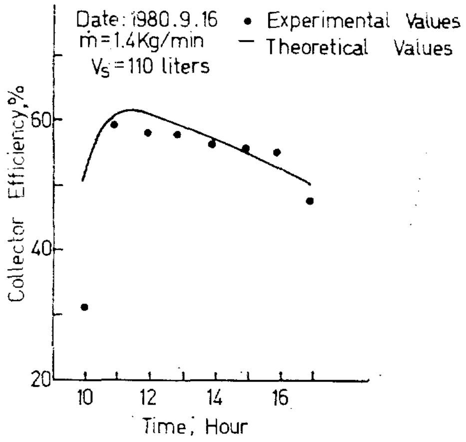

Fig. 4. Hourly Collector Efficiency

ted.

Figure 5 shows a typical overall efficiency of the collector-reflector system as a function of the reflector angle. Simulated results were obtained with solar insolation data for a typical clear day in autumn. In this case an optimum efficiency for the reflector-collector combination is obtained when the reflector is tilted at about 108°. From a practical point of view it is important to note that the efficiency curve plotted against reflector angle is seen to be reasonably flat near its maximum.

The model was used to estimate energy gain obtainable with the reflector for season when solar heating demand is high. Simulated results for several values of the reflector angle are shown in *Figure 6*. Based on monthly average values of solar insolation and these simulated results, an estimate of the optimum reflector angle was obtained for each month as shown in *Figure 7*. With change of solar altitude in each month, optimal winter collection can be provided by a reflector tilted between 110° and 120°. It can be also seen from *Figure 7* that the best way to maximize energy collection during the winter would be to use a 105° reflector and to move it to approximately 120° from the beginning of October till the end of February.

A theoretical performance of the collector-reflector system with the reflector tilted at 100° is compared with that obtained experimentally for typical clear day in autumn as shown in *Figure 8*. *Figure 8* shows a fair agreement between improvements in perfermance obtained both theoretically and experimentally with the diffuse reflector, and moreover illustrates the advantage of the reflector-collector system. The maximum increase of energy due to the diffuse reflector used in the experiment is about 80 percent of the collection without a reflector.

Based on monthly average values of solar insolation, an estimate of energy collection with the reflector-collector system is obta-

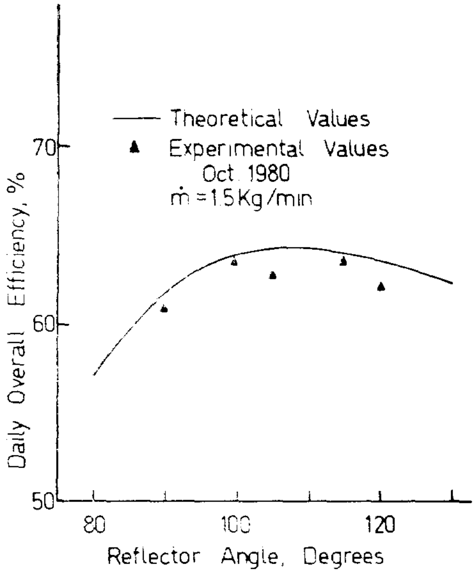

Fig. 5. Daily Overall Efficiency vs. Reflector Angle

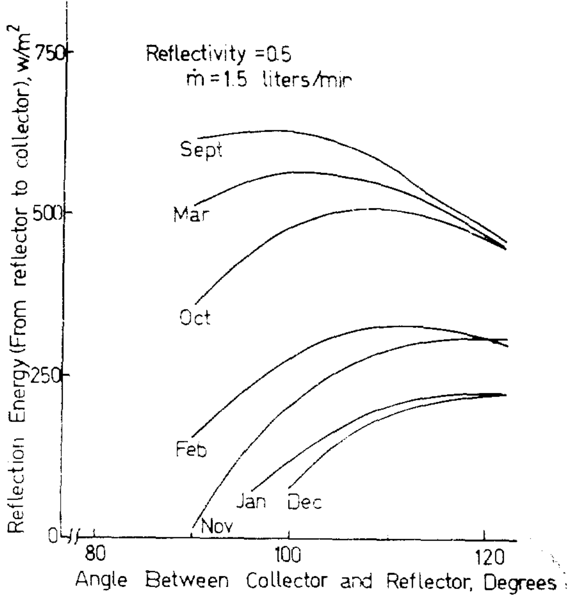

Fig. 6. Reflected Radiation from Reflector at Reflector Angles

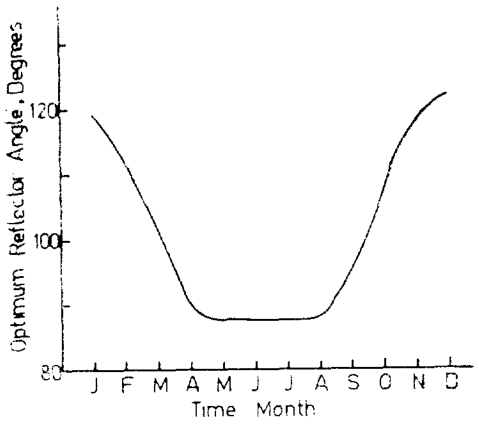

Fig. 7. Monthly Optimum Reflector Angle

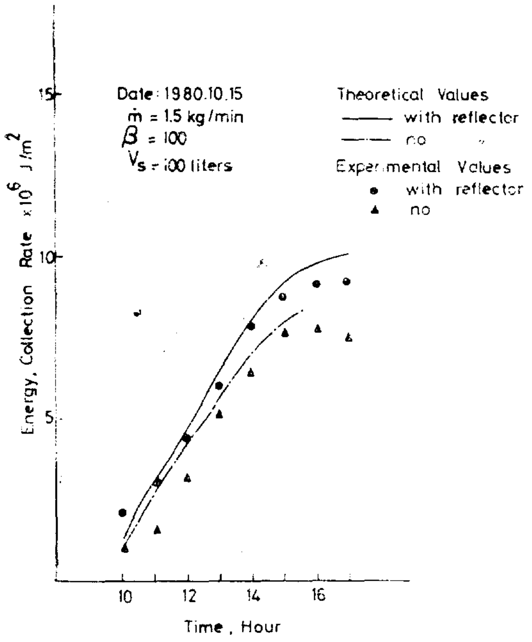

Fig. 8. Performance of Collector-Reflector for Clear Day

ined by digital simulation as shown in *Figure 9*. The estimate was made with the reflector tilted at 115° below the collector optimally oriented at 52.3°. It can be seen from *Figure 9* that the enhancement in energy collection for the reflector-collector combination is estimated to be more than 15% during the fall and winter over that obtained with an optimally oriented simple flat-plate collector. This enhancement can be directly related to the cost-down factor by use of a reflector of much lowers cost per unit area. Since a diffuse reflector is inherently cheaper to construct and maintain than a conventional collector, substantial cost reductions can be anticipated for a combined system. It is, however, reported[4] that at the midwinter peak angle specular reflector has contributed 40 percent more than the collector itself, and that specular reflectors are more effective than diffuse reflectors.

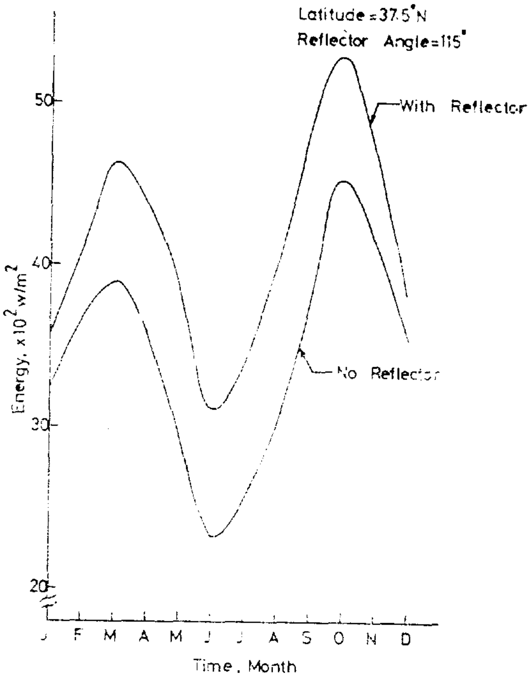

Fig. 9. Simulated Monthly Performance of of Collector-Reflector

V. Conclusion

This paper presents analyses of a collector-reflector system in order to reduce a total cost of solar heating systems by means of a mathematical model. Experiments have been

conducted to show adequacy of the model for a collector-reflector system. Comparison of experimental results shows fair agreement with simulated results. As results of simulation and experimental studies the optimum diffuse reflector angle is found to be between 110° and 120° during the fall and winter when heating demand is high. With a diffuse reflector tilted at 115° below a collector optimally oriented at 52.3°, the enhancement in energy collection is estimated to be more than 15% during the fall and winter.

Nomenclature

Roman Letters

A_c: Collector area, m^2

A_{rc}: Exchange area for radiative heat transfer between the reflector and the collector, m^2

C_p: Fluid specific heat, J/kg. K

C_e: Effective collector specific heat, J/kg. K

C_{bond}: Bond conductance, J/kg. K

D: Tube diameter, m

F: Standard fin efficiency

F': Collector efficiency factor

F_R: Collector heat removal factor

f: correlation factor

G: Mass flow rate per unit area, $Kg/s.m^2$

h: Heat transfer coefficient W/m^2k

h_w: Wind heat transfer coefficient, W/m^2 K

I: Solar energy incident on the plane of measurement, W/m^2

k_{ins}: Insulation thermal conductivity, W/m. K

L: Tube lengh, m

L_{ins}: Insulation thickness, m

M: Mass, kg

m: Mass flow rate, kg/s

Q_u: Rate of useful heat transfer to a working fluid in the solar exchanger, W

Q_L: Rate of energy losses from the collector to the surrounding by reradiation, convection and by conduction through supports for the absorber plate, and so on., W

Q_s: Rate of energy storage in the collector, W

q_A: Rate of energy absorbed per unit area, W/m^2

R: Ratio of total radiation on tilted surface to that on the plane of measurment

s: Slope of plane from the horizontal, degree

T: Temperature, K

t: Time, sec.

U_L: Overall loss coefficient, W/m^2 K

U_b: Back loss coefficient, W/m^2 K

U_t: Top loss coefficient, W/m^2 K

V: Wind speed, m/s

W: Distance between tubes, m

Greek Letters

α: Absorptance of plate

δ: Solar declination angle

ϵ: Emittance

η: Efficiency

θ: Angle (defined locally) of incidence

ρ: Reflectance

σ: Stefan-Boltzmann constant

τ: Transmittance of cover glass

ϕ: Latitude angle

ω: Solar hour angle, degree

Subscripts

a: ambient

b: beam

br: beam radiation

c: collector

d: diffuse

fi: fluid inlet

fo: fluid outlet

g: cover glass

p: plate
rc: reflector-collector

References

1. J. Kern and I. Harris, Solar Energy, 17 (1975), 67.
2. H. Tabor, Solar Energy, 10 (1966), 111.
3. D.K. McDaniels and D.H. Lowndes, Solar Enrgy, 17 (1975), 277.
4. S.C. Seitel, Solar Energy, 17 (1975), 291.
5. S.L. Grassie and N.R. Sheridan, Solar Enrgy, 19 (1977), 633.
6. D.C. Larson, Solar Energy, 24 (1980), 203.
7. J.A. Duffie and W.A. Beckman, "Solar Energy Thermal Process", 1st ed., John Wiley and Sons, New York, 1974, p. 120—177.
8. S.A. Klein, Solar Energy, 17 (1975), 79.
9. W. M. Rohsenow and J. S. Hartnett, "Handbook of Heat Transfer", 1st ed., McGraw-Hill, New York, 1973, p. 15—39 ~15—49.
10. B. Carnarhan, H.A. Luther and J.O. Wilkes, "Applied Numerical Methods", 1st ed., John Wiley and Sons, New York, 1969, p. 390—404.
11. J.P. Sheehan and T. S. Laszlo, Solar Energy, 10 (1966), 15.