太陽熱 集熱器 出口溫度 豫測方程式

Prediction Equation of Solar Collector Outlet Air Temperature

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농산물 건조를 위하여 평관형 태양열 집열기를 이용할 경우 가열된 출구공기는 각종 농산물건조적온보다 일반적으로 고온이므로 이의 조절을 위한 출구공기 온도의 예측이 중요시 된다. 본 연구에서는 차원해석법(dimensional analysis)을 이용하여 평관형 집열기의 출구에서 나오는 가열된 공기의 온도를 예측하는 방법이 제시되었으며, 이 방법을 이용하여 집열기의 출구공기온도 예측방정식들이 유량별로 유도되었다. 이 방정식들로부터 구한 출구온도들은 실측한 값들과 잘 일치하였으며($R^2-0.917\sim0.957$) 또한 집열기의 효율을 나타내는 이론식이 출구공기온도 예측방정식으로 부터 직접 유도되었다.

I. Introduction

Flat-plate solar collectors have been used extensively for space heating, cooling, supplying domestic hot water and processing of agricultural products. Since solar energy began attracting attention as one of the best substitute energy sources, many studies have been conducted to improve collector efficiency(1,3) and develop inexpensive collectors.(4,5)

It is often important to predict and control collector outlet air temperature. For example, to dry agricultural products with air heated by a flat-plate solar collector, the proper drying air temperature must be chosen to avoid damage of the products. To the best knowledge of the author,(6) there have been no attempts to develop an equation predicting collector outlet air temperature using dimensional analysis. The purpose of this paper is to show how to derive prediction equations of flat-plate solar collector outlet air temperature and efficiency.

II. Experimental Procedure

Dimensional analysis was used to develop the prediction equation for the outlet air temperature of the solar collector. The outlet air temperature may be described by a relationship involving several parameters as shown in the following equation:

$$To = f(L, d, b, v, \rho, \mu, Cp, k, Ti, I(t)) \qquad (1)$$

where,

T_o = outlet air temperature ($^\circ K$)
L = length of the collector (m)
d = depth of the collector (m)
b = width of the collector (m)
v = velocity of the heat transfer fluid (m/hr)
ρ = density of the heat transfer fluid (Kg/m^3)
μ = viscosity of the heat transfer fluid (Kg/m·s)
C_p = specific heat of the heat transfer fluid ($J/Kg\cdot{}^\circ K$)
k = thermal conductivity of the heat transfer fluid ($W/m\cdot{}^\circ K$)
T_i = inlet air temperature ($^\circ K$)
I(t) = solar energy incident upon the plane of the collector (W/m^2)

The Buckingham Pi theorem states that the parameters in Equation (1) may be combined into dimensionless Pi terms.(7) The theorem also states that

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the number of Pi terms required to express the relationship among the parameters is equal to the number of parameters involved minus the number of dimensions in which those quantities are measured. In Equation (1) there are 11 parameters involving 4 dimensions of measurement (mass, length, time and temperature).

In accordance with the Buckingham Pi theorem seven independent Pi terms may be developed as shown in Equation (2):

$$\frac{To}{Ti} = f\left(\frac{b}{L}, \frac{d}{L}, \frac{dv\rho}{\mu}, \frac{Cp\mu}{k}, \frac{CpTi}{v^2}, \frac{I(t)}{\rho v^3}\right) \quad (2)$$

In these Pi terms some parameters, i. e., ρ, μ, Cp and K are functions of temperature. But it is difficult to control these values in practical experiments and they vary little within a certain temperature range. For example, within the range from 38°C to 60°C, which is the common temperature obtained in a flat-plate solar collector for heating air, ρ varies 6.6%, μ varies 5%, Cp varies 0.4%, k varies 6.3% and Prandtl number, $Cp\mu/k$, varies 0.34%. Also, these properties of air are not important factors to influence outlet air temperature in comparison with solar insolation and air velocity. Therefore, it may be assumed that those parameters are constant within the temperature range between 38°C and 60°C. Since air velocity, v, was kept constant and inlet air temperature, Ti, is close to ambient air temperature which is almost constant during the time for a set of experiments (15 min.), Pi terms $dv\rho/\mu$, $Cp\mu/k$ and $CpTi/v^2$ may be eliminated. For a given solar collector, L, b and d are constants and can be eliminated from the Equation(2). Finally, the Equation (2) is simplified to a relationship involving two Pi terms:

$$\frac{To}{Ti} = f\left(\frac{I(t)}{\rho v^3}\right) \quad (3)$$

The solar energy collector used to define the relationship between these two Pi terms was a simple flat-plate solar collector to heat air. It was 4.88 m long, 0.61 m wide and 27.94 cm deep. To minimize heat losses from the collector to the ambient air, the base plate and the sides of the collector were insulated with 12.70 cm of fiberglass and 2.54 cm of urethane, respectively. The collector absorber plate, which was made of 5 v-crimp aluminum sheets painted with flat black paint, was covered with two layers of plastic film separated by a 1.27 cm air space. Located beneath the absorber plate was a 5.08 cm plenum through which air passed to collect heat. The effective solar collection area was 2.70 m^2. All joints were sealed with a silicone sealant. Flow was introduced and withdrawn through the space between the absorber plate and the air duct board. The solar collector was mounted on the top of a triangular steel frame.

Air flow rate was measured by means of the pressure drop across an orifice plate in the pipe line. A 7.62 cm diameter aluminum pipe was used and a 6.35 cm diameter orifice plate was inserted. The ratio of areas, A_2/A_1, was 0.664 where A_2 is the area of the orifice and A_1 is the cross section area of the pipe. The upstream pressure tap was positioned 12.07 cm forward from the orifice plate and the downstream pressure tap was located 2.36 cm from the orifice plate. The pressure drop was measured with a manometer connected to the upstream pressure tap and the downstream pressure tap of the air flow meter, respectively.

Inlet and outlet air temperature measurements were made using six copper-constantan thermocouples. An arrangement of parallel rows of thermocouples was located in both the inlet and outlet plenums. An arrangement of thermocouples to measure ambient temperature was located near the collector. These thermocouples were connected to a Speedomax multipoint strip chart recorder which continuously recorded air temperatures.

Insolation was measured by continuously recording the output of an Eppley black and white pyranometer with a Speedomax strip chart recorder. The chart speed of the recorder was 2.54 cm per 5 minutes. Solar insolation was recorded in millivolts. The pyranometer calibration recommended by the Eppley Laboratory, Inc., for the output to the recorder was 10.86 microvolts for one w/m^2 or 7.57 millivolts for one cal/cm^2· min.

Tests were conducted primarily on clear days. Data were taken over a 15-minute period of experimental time as recommended by ASHRAE Standard 93-77 and a set of data consisted of a minimum of 16 points.

Data were taken symmetrically with respect to solar noon to prevent biased results from transient effects. The test was started approximately one hour after the collector and all of the instruments were turned on to allow a warm-up period. For all tests the collector was tilted at 49 degrees with the horizontal with a zero azimuth angle.

III. Results and Discussion

The relationship between To/Ti and $I(t)/ʒv^3$ was investigated to determine the prediction equation (3).

Five different air velocities (2.688, 3.444, 4.017, 4.722 and 5.038 Km/hr) were used and the relationships were presented graphically. Figures 1 through 5 show that the ratio for the outlet air temperature to the inlet air temperature was linearly related to the Pi term, $I(t)/ʒv^3$. The ratio, To/Ti, increased as the variable $I(t)/ʒv^3$ increased. Also, it was found that the ratio, To/Ti, was dependent only on solar insolation for a given constant air flow rate. The outlet air temperature of the collector was fairly accurately described by the independent variable, $I(t)/ʒv^3$, as indicated by the R^2 values from 0.917 to 0.957, respectively.

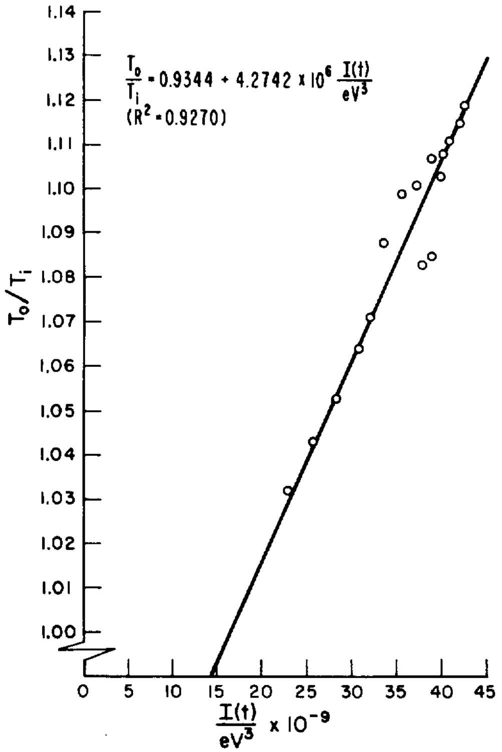

Fig. 1. Prediction equation for the ratio of the outlet to inlet air temperatures of the collector with air velocity of 2.668 km/hr

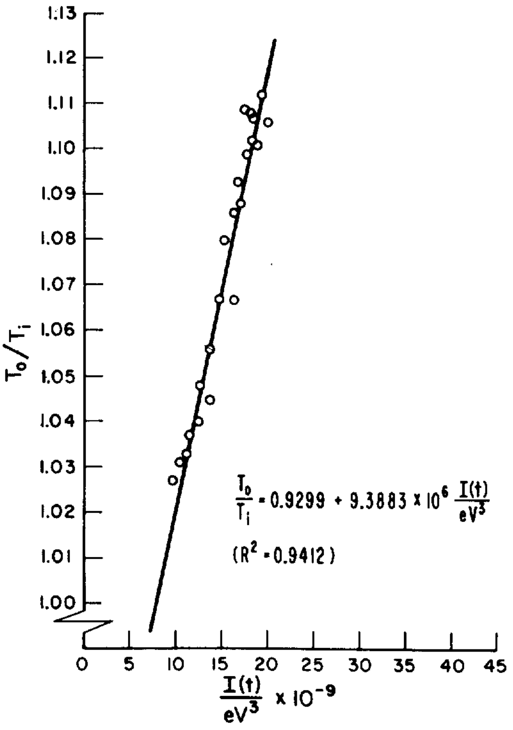

Fig. 2. Prediction equation for the ratio of the outlet to inlet air temperatures of the collector with air velocity of 3.444 km/hr

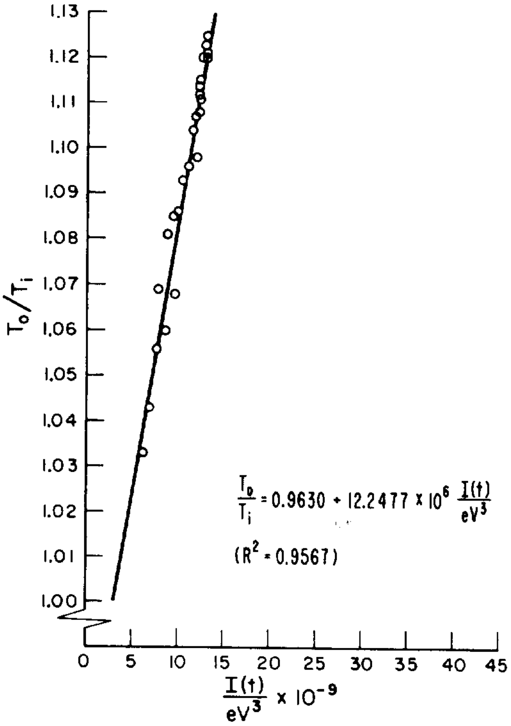

Fig. 3. Prediction equation for the ratio of the outlet to inlet air temperatures of the collector with air velocity of 4.017km/hr

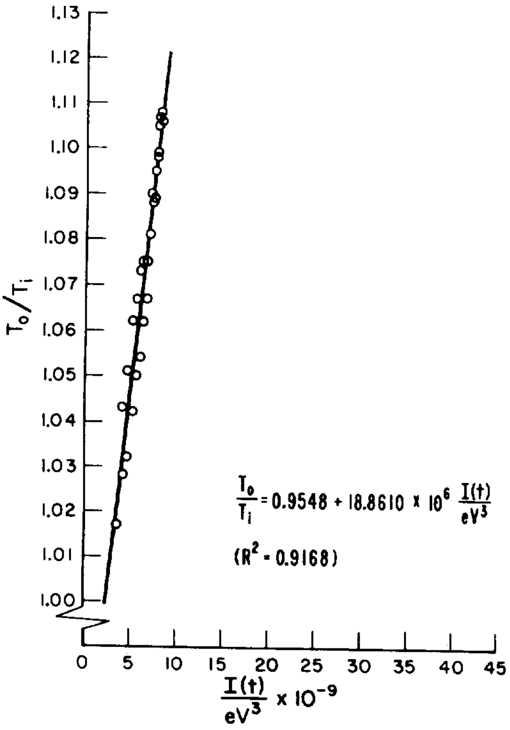

Fig. 4. Prediction equation for the ratio of the outlet to inlet air temperatures of the collector with air velocity of 4.722 km/hr

Prediction curves for different air velocities had different slopes and these slopes were systematically changed as the air velocity was varied. The intercepts of the prediction equations were close to value 1 which can be obtained theoretically when solar insolation is zero.

From the equation predicting the outlet air temperature of the collector, an equation which expresses collector efficiency can be derived. The prediction equation of outlet air temperature for an air velocity of 4.722 Km/hr is given as follows:

$$\frac{To}{Ti} = 0.955 + 18.861 \times 10^6 \frac{I(t)}{ʒv^3} \quad . \qquad (4)$$

Substituting Equation (4) into the To of the efficiency equation (5)

$$E = \frac{MCp(To - Ti)}{AgI(t)} \qquad (5)$$

where,

E = efficiency

M = mass air flow rate (Kg/hr)

Ag = gross cross-sectional area of the collector (m^2)

a simple efficiency line plotted against 1/I(t) is derived. The efficiency equation is

$$E = \frac{18.861 \times 10^6 MCpTi}{Agʒv^3} + \frac{(0.955 - 1)TiMCp}{AgI(t)} \qquad (6)$$

where M, Ag, Cp, ʒ, and v are constant and the values of Cp and ʒ are determined for the average temperature of the outlet and inlet air temperatures which are measured from the experiment. Therefore, the efficiency equation is rewritten:

$$E = 20.806 \times 10^{-4}\ Ti - 0.5972 \frac{Ti}{I(t)} \qquad (7)$$

where the inlet air temperature, Ti, is in degrees

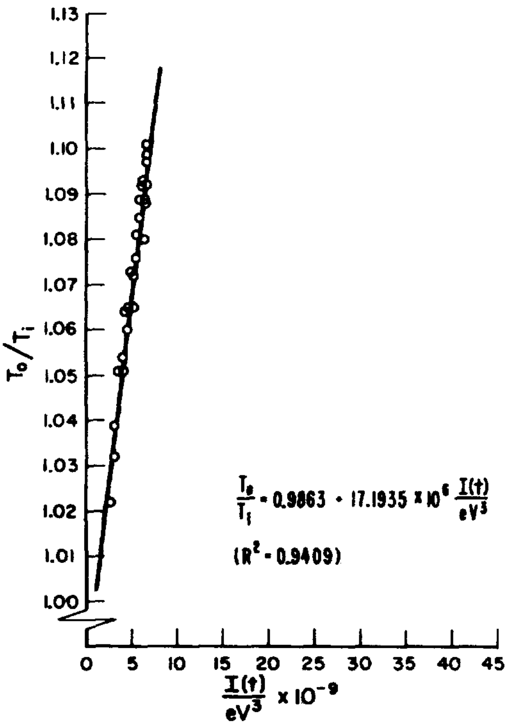

Fig. 5. Prediction equation for the ratio of the outlet to inlet air temperatures of the collector with air velocity of 5.038 km/hr

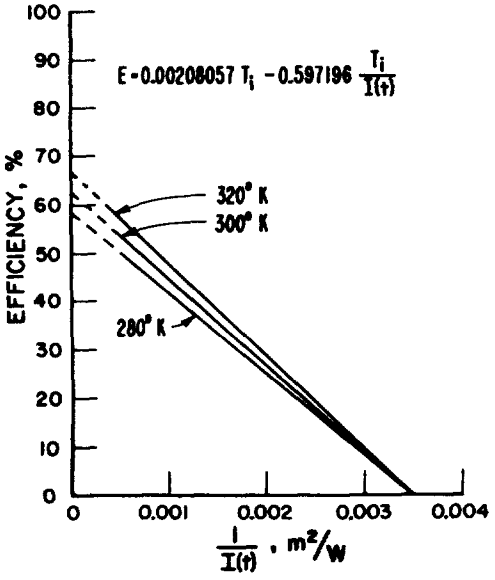

Fig. 6. Group of efficiency curves for the different inlet air temperatures

Kelvin.

In this equation, efficiency is a function of Ti and I(t). However, if a specific value is given for Ti the efficiency can be expressed in terms of solar inlolation. Therefore, an efficiency curve can be drawn from the relationship between collector efficiency and the reciprocal of solar insolation. Figure 6 shows a series of efficiency lines for different inlet air temperatures for an air velocity of 4.722 Km/hr. From Figure 6, it was found that the efficiency increases as solar insolation increases. Also, the efficiency increased as the inlet air temperature increased within the range of normal operating temperature. But the efficiency increase in relation to inlet air temperature increase was so small as about 3 per cent while the inlet air temperature increased from 300 to 320°K and the solar insolation was 1000 w/m^2.

IV. Conclusions

Prediction equations for flat-plate solar collector outlet air temperature were developed using dimensional analysis. In accordance with the Buckingham Pi theorem seven independent Pi terms were developed. Among them five Pi terms were cancelled out since they were constant or very insignificant for influencing to the outlet air temperature. Simplified relationship involving two Pi terms were

$$\frac{To}{Ti} = f\left(\frac{I(t)}{\rho v^3}\right).$$

The following conclusions may be presented from this study:

1. The ratio for the outlet air temperature to inlet air temperature increased linearly as the variable $I(t)/\rho v^3$ increased.
2. The ratio between outlet air temperature and inlet air temperature was only dependent on solar insolation for a given constant air flow rate.
3. The equation predicting the outlet air temperature for an air velocity of 4.722 Km/hr was

$$To = 0.955\, Ti + 18.861 \times 10^6 \frac{I(t)Ti}{\rho v^3}$$

4. From this equation the following equation predicting the collector efficiency was derived:

$$E = 20.806 \times 10^{-4}\, Ti - 0.597 \frac{Ti}{I(t)}$$

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