Development of an Empirical Model For Assessment of Solar Air Heater Performance

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ABSTRACT

Solar flat plate collectors are used for meeting the hot air requirement in a number of applications ranging from domestic to industrial sectors. However, the varying degree of uncertainties of available solar radiation along with varying weather conditions often acts as restriction to their wider use. The varying input conditions like solar radiation, ambient temperature and relative humidity have diverse effect on the output of the flat plat collector used for hot air generation and poses difficulty in terms of reliability in providing the output as per users' requirement. This study refers to a method of predicting the output of flat plate collectors under varying working conditions. The model suggested here defines a relationship between the output in terms of instantaneous efficiency and the inputs, namely, solar radiation, ambient temperature, fluid inlet temperature and the mass flow rate. The relationship is based on the behavior of a given flat plate collector under certain sets of input parameters and can be used to estimate the efficiency of the collector at various mass flow rates. Further, this model can be suitably extended to estimate the mass flow rate for providing a particular output under specific set of input parameters.

Key words: Flat plate collector, mass flow rate, efficiency, solar air heater

INTRODUCTION

In the context of present energy crisis, use of renewable energy sources plays an important role in energy conservation efforts. Solar energy, being a major source among all renewable energy sources, has enough potential for thermal applications. In practice, various types of devices are being utilized to trap and use solar thermal energy. However, it is difficult to operate such devices to provide constant output continuously due to varying operating conditions or region specific uncertainties associated with solar radiation.

The most common examples of using solar thermal energy are the solar water heating systems and the solar air heating systems. Water heating systems utilize solar radiations to heat up water whereas the air heating systems use the solar radiation to heat up the air. Hot water is required in various purposes such as domestic, industrial, commercial establishments, educational institutes etc. These requirements can be met by using solar water heating systems [5,6,10]. Different types of commercial systems such as flat-plate type, evacuated tube type etc are available for such applications and experimental study comparing their performances are also conducted by researchers [21].

Similarly, solar air heaters are also used for many purposes. Uses of solar air heaters are reported for drying of fruits, vegetables and other agricultural and marine products [2,3,8,16,18]. It may also be suitably used for providing industrial process heat requirements, room heating and other similar applications.

The performance of either a solar water heating system or an air heating system is governed by the behavior of the collector used to trap solar thermal energy. Among different types of collectors used in solar thermal applications, flat plat collector is the most common, which is featured by its constructional simplicity and economy. A flat plat solar air heater is a flat plate collector used to generate hot air. As shown in Figure 1, it comprises of an absorber plate, a transparent cover at the top and a parallel plat at the bottom which forms the air passage. The absorber plate is painted black with selective coating and the transparent cover is usually formed by one or more numbers of glass cover. The system is properly insulated to reduce the heat loss from the sides as well as from the bottom. Solar radiation falling on the absorber plate through the glass cover is utilized to heat up the air flowing in the air passage. The circulation of air is usually forced by a fan or a blower and a temperature gradient exists in the air stream flowing from inlet to the outlet.

With the advancement of technology, research and development works related to use of solar thermal energy is primarily oriented towards improvement of efficiency. Various research works are reported in the areas of improving the performance of solar air heaters. This in-

Nomenclature

A_c	Gross area of the collector (m^2)
A_P	Area of the absorber plate (m^2)
c_p	Specific heat of the fluid ((kJ/kg-K)
$D_{A,}$ E_A	Constants in the power equation for absolute value of slope
D_B, E_B	Constants in the power equation for intercept
η_i	Instantaneous efficiency
f	Friction factor
F'	Collector efficiency factor
F_R	Collector heat removal factor
h_e	Effective heat transfer coefficient between the absorber plate and air stream (W/m^2-K)
h_{fb}	Heat transfer coefficient between bottom plate and air stream (W/m^2-K)
h_{fp}	Heat transfer coefficient between absorber plate and air stream (W/m^2-K)
h_r	Radiative heat transfer coefficient (W/m^2-K)
I_T	Instantaneous/hourly solar flux on the top of the collector (W/m^2)
L	spacing between the covers or absorber plate and cover (m)
M	number of glass covers
$\dot{m}$	Mass flow rate (kg/s)
T_a	Ambient temperature (K)
T_{fi}	Temperature of the working fluid at the inlet (K)
T_{fo}	Temperature of the working fluid at the outlet (K)
$(\tau\alpha)_{av}$	Average value of the product of transmissivity and absorptivity for beam and diffuse radiation
U_l	Overall loss coefficient (W/m^2-K)

Greek symbols

α	Absorptivity of the absorber plate
β	slope or tilt (degrees)
ε_c	emissivity of cover for long wave length radiation
ε_p	emissivity of absorber surface for long wave length radiation
η_i	Instantaneous efficiency
σ	Stefan – Boltzmann constant (W/m^2-K^4)
τ	Transmissivity of the glass cover system
$(\tau\alpha)_{av}$	Average value of transmissivity– absorptivity product for beam and diffuse radiation

Subscripts

a	Ambient	*s*	Side
av	Average	*t*	Top
A	Slope	*T*	Total
b	Bottom	*fi*	inlet fluid
B	Intercept	*fo*	output fluid
c	Collector	*i*	Instantaneous
co	Cover	*e*	Effective
p	Absorber plate	*r*	Radiative

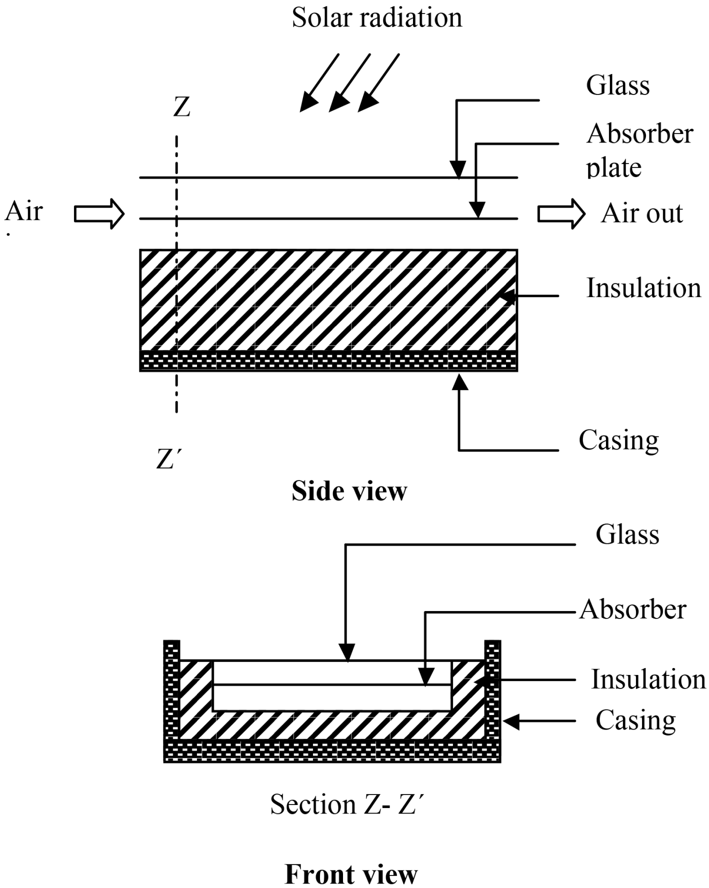

Figure 1. Schematic diagram of a typical solar air heater.

cludes using different types of collectors in terms of geometry, material and configuration [3,11,19]. Similarly works have also been reported in the field of efficiency improvement of solar flat plat collectors [1,4,7,16]. The effect of changing glass cover, single and double pass circulation, incorporation of barriers dividing the air channel on the collector performance, efficiency and exergy analysis are also reported [12,14,20]. Economics of some industrial applications of solar air heater as well as case studies of technical feasibilities are also reported by researchers [8,15]. There are still certain issues concerning the operation of solar air heater as per users' suitability.

From users' perspective, two distinct operating modes of flat plat solar collector may be visualized, viz., (i) hot air required at constant temperature and (ii) hot air required at maximum efficiency of the system. For example, supply of hot air at constant temperature is necessary for drying of crops and vegetables whereas operation of the collector at the best efficiency is required in case of hybrid system or integrated renewable energy systems. Ideally, for the first case, the operation may lead to the reduction of collector efficiency while the second case of operation may lead to the variation of the air temperature at the outlet far beyond the required or acceptable range. It is difficult to operate a solar flat plat collector naturally in either mode continuously due to the varying (temporal and spatial) nature of input solar radiation. The situation thus demands for a mechanism or a method which will predict the behavior of the flat plate collector under varying input conditions so that some measures can be appropriately taken for getting the intended output.

Table 1. Major input parameters for solar flat plate collector

(a) Design parameters	(b) Environmental parameters	(c) User controlled parameters
Dimension of the collector (Gross area A_c, Length, Width, Thickness), Dimension and type of absorber plate such as area (A_p), thickness, materials, geometry, absorptivity (α) and emissivity (ε_p), Coss sectional area of the air duct, Number of glass covers (M), Transmissivity (τ) and emissivity (ε_c), Spacing between the covers or absorber plat and cover (L)	Solar radiation (I_T), Ambient temperature (T_a), Inlet and outlet air temperature in open loop mode, (T_{fi}, T_{fo}), Wind speed, Relative humidity of ambient air	Mass flow rate ($\dot{m}$), Slope or tilt (β), Inlet and outlet air temperature in closed loop mode (T_{fi}, T_{fo})

The temperature of air at the outlet as well as the efficiency of a collector depends on number of parameters. These parameters can be classified as (a) design parameters, (b) environmental parameters and (c) user controlled parameters. The performance of the flat plat collector varies with the changes in either one or all of these parameters (Table 1). As mentioned earlier, a flat plate solar collector in the forced circulation mode consists of a device (blower or fan) to facilitate the flow of working fluid from inlet to the outlet. The rate of flow has an effect on the output temperature as well as on performance of the flat plate collector. This flow rate can be termed as user controlled parameter as it can be adjusted through blower. Solar radiation and ambient temperature, which are controlled by nature, are treated as environmental parameters. The environmental parameters cannot be manipulated as per users' choice while the design parameters, such as, gross area of the collector and area of the absorber plate, remain fixed for a particular collector. Thus, for getting collector output as per users' choice, possible scope lies in user controlled parameters and suitable ways should be explored for manipulating these parameters in order to compensate the variations of the nature controlled environmental parameters. A precise relationship among the input and output parameters reflecting their physical dependency will be very much helpful for decision making process in output specific applications. Keeping in view of the above, an attempt has been made to develop a mathematical relationship to predict the performance of a solar air heater.

MODELING APPROACH

In the present study, a relationship among the input and output parameters is explored with the background knowledge of collector performance for a wide range of operating conditions. The input parameters consist of design parameters, environmental parameters and user controlled parameters. Flat plate collectors having known design parameters such as gross collector area, area of the air flow duct, area and type of the absorber plate are considered for this investigation. The environmental parameters considered are the solar radiation, ambient temperature and fluid inlet temperature in open loop mode. Similarly, user controlled parameter, i.e., the mass flow rate of air is considered. The output parameter is the instantaneous efficiency (η_i) which depends on both environmental and user controlled parameters. A collective set of environmental parameters (T_{fi}, T_a and I_T), user controlled parameter ($\dot{m}$) and a fixed set of design parameters (such as A_p, A_c, τ, α, ε_p, ε_c, M, L) decides the behavior of the collector. For a fixed set of design parameters, the instantaneous efficiencies are experimentally observed under given operating conditions (environmental and user controlled parameters). A model is formulated with the available theory on heat transfer along with available experimental data to predict performance of solar air heater. The theoretical relationship is compared with the trend of experimental investigation to identify important parameters in terms of slope and intercept of corresponding plots. Further, these slopes and intercepts are studied independently at varying flow rates and fitted into a power curve to obtain two characteristic power equations, namely, characteristic slope equation and characteristic intercept equation. Characteristic slope equations and characteristic intercept equations are collector design specific and are useful for predicting the performance.

DEVELOPMENT OF THE MODEL

As discussed earlier, the model under the present study deals with the development of a relationship between the instantaneous efficiency, $\eta_{i,}$ and the temperature parameter $[(T_{fi} - T_a)/I_{T]}$ with respect to mass flow rate, $\dot{m}$. Experimental data for a collector will be prerequisite for developing the relationship. The relationship then may be used to estimate the behavior of the collector at various required mass flow rates. The procedure is briefly highlighted below.

The instantaneous efficiency of a collector can be expressed following the Hottel-Whillier-Bliss procedure [17,20] as,

$$\eta_i = \frac{F_R A_p}{A_c}\left[(\tau\alpha)_{av} - \frac{U_l\left(T_{fi} - T_a\right)}{I_T}\right] \tag{1}$$

The collector heat removal factor F_R refers to the thermal resistance faced by solar radiation in reaching the collector fluid and is given by the ratio of the actual heat gain rate to the gain if the fluid temperature through the absorber plate were at T_{fi} everywhere. Typical values of F_R fall in the range of 0 to 1 [17]. F_R can be expressed as,

$$F_R = \frac{\dot{m}c_p}{U_l A_p}\left[1 - exp\left\{-\frac{\acute{F} U_l A_p}{\dot{m}c_p}\right\}\right] \tag{2}$$

where $\acute{F}$ is the collector efficiency factor.

Eq. (2) implies that F_R is a function of mass flow rate, specific heat, overall loss coefficient, absorber plate area and collector efficiency factor. The variation of F_R with respect to these parameters can be investigated. It is observed from the Eq. (2) that for a constant mass flow rate, F_R is dependent on specific heat, overall loss coefficient, and absorber plate area and collector efficiency factor. For a particular collector, its geometry remains the same, i.e., it will have constant absorber plate area as well as gross collector area. Again, the specific heat of air varies with temperature. For the temperature range from 10 to 93.3^0 C, c_p varies from 1.0048 to 1.0090 kJ/kg-K and may be considered as constant at an average value of 1.0069 kJ/kg-K [20]. The collector efficiency factor F can be expressed in terms of effective heat transfer coefficient (h_e) between the absorber plate and air stream and overall heat loss coefficient (U_l) as

$$\acute{F} = \left(1 + \frac{U_l}{h_e}\right)^{-1} \tag{3}$$

where

$$h_e = \left[h_{fp} + \frac{h_r h_{fb}}{h_r + h_{fb}}\right] \tag{4}$$

and

$$U_l = U_b + U_s + U_t \tag{5}$$

U_b, U_s and U_t in Eq. (5) represent the bottom loss, side loss and top loss coefficients respectively. The bottom and side loss coefficients can be expressed as

$$U_b = \frac{k_i}{\delta_b} \tag{6}$$

$$U_s = \frac{(L_1 + L_2)\, L_3\, k_i}{L_1\, L_2 \delta_s} \tag{7}$$

where k_i is the thermal conductivity of insulation (W/m-K), δ_b thickness of the bottom insulation (m), L_1 and L_2 length (m) and width (m) of the absorber plate, L_3 height of the collector casing (m), δ_s thickness of the side insulation (m). The top loss coefficient U_t can be expressed by the correlation suggested by Malhotra et al [13,17] as

$$U_t = \left[\frac{M}{\left(\frac{C}{T_{pm}}\right)\left(\frac{T_{pm}-T_a}{M+f}\right)^{0.0252}} + \frac{1}{h_w}\right]^{-1} + \left[\frac{\sigma\left(T_{pm}^2 + T_a^2\right)\left(T_{pm}+T_a\right)}{\frac{1}{\left\{\varepsilon_p + 0.0425\,M\left(1-\varepsilon_p\right)\right\}} + \frac{(2M+f-1)}{\varepsilon_{co}} - M}\right] \tag{8}$$

$$f = \left(\frac{9}{h_w} - \frac{30}{h_w^2}\right)\left(\frac{T_a}{316.9}\right)(1 + 0.091\,M) \tag{9}$$

$$C = \frac{204.429\,(\cos\beta)^{0.252}}{L^{0.24}} \tag{10}$$

M = number of glass covers
L = spacing between the covers or absorber plate and cover (m)
h_w = wind heat transfer coefficient (W/m^2-K)
T_{pm} = mean absorber surface temperature (K)
T_a = ambient temperature (K)
σ = Stefan – Boltzmann constant (W/m^2-K^4)
β = slope or tilt (degrees)
ε_p = emissivity of absorber surface for long wave length radiation
ε_{co} = emissivity of cover for long wave length radiation

From Eq. (8) it can be seen that U_t depends primarily on the mean absorber surface temperature, ambient temperature, wind heat transfer coefficient and flow conditions. The convective heat transfer coefficients (h_{fp} and h_{fb}) and the radiative heat transfer coefficient h_r are also dependent on the flow condition as well as on the temperature of the absorber and bottom plate. Considering these variations during the observation period as negligible F_R, $(\tau\alpha)_{av}$, U_l and F can be treated as constant for the period of observation.

Modeling Instantaneous Efficiencies of a Given Collector for Specified Mass Flow Rate

Under the above assumptions, for a particular mass flow rate $\dot{m}_i$, the Eq. (1) can be written as below.

$$\eta_i = (-A_i)\,X_i + B_i \tag{11}$$

where A_i represents the negative slope and B_i represents the Y –axis intercept for i^{th} mass flow rate. Expressions for X_i, A_i and B_i are provided below.

$$X_i = \left[\frac{(T_{fi} - T_a)}{I_T}\right] \tag{12}$$

$$A_i = \left(\frac{A_p}{A_c}\right)\left[F_{R_i} U_{l_i}\right] \tag{13}$$

$$B_i = \left(\frac{A_p\,(\tau\alpha)_{av}}{A_c}\right)\left[F_{R_i}\right] \tag{14}$$

Here the subscript i is used to indicate varying mass flow rate.

Modeling Instantaneous Efficiencies of a Given Collector for Varying Mass Flow Rates

By performing experiments at different mass flow rates different sets of values of X_i and η_i are obtained. Plotting the values of η_i against X_i, scatter plots are obtained for particular mass flow rate $\dot{m}_i$ which can be fitted into a straight line represented by the Eq. (11). From this equation, the values of A_i and B_i corresponding to the i^{th} mass flow rate can be determined.

Experimental results in various literatures have shown the variations in the slope and intercepts according to the mass flow rates [9, 18]. It is observed that by increasing mass flow rate the slope as well as the intercept increases. These variations against mass flow rates is best fitted into a power curve defined by the following characteristic equations

$$A = D_A\,\dot{m}^{E_A} \tag{15}$$

$$B = D_B\,\dot{m}^{E_B} \tag{16}$$

where D_A, E_A, D_B and E_B are constants.

Eq. (15) is termed as characteristic slope equation and Eq. (16) is termed as characteristic intercept equation. The constants $D_{A,}$ E_A, D_B and E_B are characteristic model parameters for the collector. Once the characteristic equations (Eq. (15) and Eq. (16)) are defined and characteristic model parameters ($D_{A,}$ E_A, D_B and E_B) are known, A and B for any mass flow rate $\dot{m}$ can be determined and the corresponding efficiency may be represented by the following equation

$$\eta_i = -A\,\frac{(T_{fi} - T_a)}{I_T} + B \tag{17}$$

DATA SOURCE FOR MODEL TESTING

In order to test the model, four flat plate solar thermal collectors (STC1, STC2, STC3 and STC4) were considered. The necessary data (η_i, X_i and respective $\dot{m}$) have been taken from published literature [9,18]. The specification of the collectors taken from literature is provided in Table 2.

Table 2. Different collectors used for testing the model

Sl. no.	Collector	Specification
1	STC1	Finned, 1.8 m × 0.7 m with 1 mm thickness, stainless steel used absorber material, no of glazing 1, air flow area between absorber plate and back plate 0.0175 m^2
2	STC2	V-corrugated (60^0), 1.8 m × 0.7 m with 1 mm thickness and the absorber material used was stainless steel
3	STC3	Flat plate, 1.8 m × 0.7 m with 1 mm thickness and the absorber material used was stainless steel
4	STC4	Flat plate, air heater dimension 2.03 m × 0.57 m

The flow rates considered for finding out the characteristic constant for the model (Eqs. (16) to (21)) are given in the Table 3.

RESULTS AND DISCUSSION

The values of A and B are determined from the efficiency curve for each flow rate (Table 3) and for each collector (Table 2). These values are

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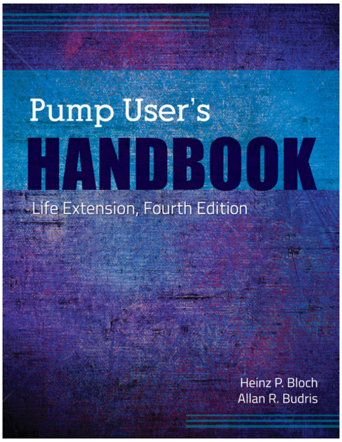

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Table 3. Flow rates used for estimation of characteristic constants in the model

Sl no.	Collector	Flow rate (kg/m^2-s)				
		1	2	3	4	5
1	STC1	0.0116	0.0248	0.042	0.0472	0.056
2	STC2	0.0154	0.0317	0.0387	0.056	
3	STC3	0.0105	0.0317	0.056		
4	STC4	0.042	0.055	0.070		

fitted against $\dot{m}$ into power curves using spreadsheet (Microsoft EXEL). The corresponding regression equations in the form of Eq. (15) and (21) are shown in the Table 4 and Table 5.

Table 4. Characteristic slope equations derived from experimental data of four different collectors

Sl no.	Collector	Characteristic slope equation $A = D_A\, \dot{m}^{E_A}$
1	STC1	$A = 3.3905\, \dot{m}^{-0.206}$
2	STC2	$A = 2.0766\, \dot{m}^{-0.327}$
3	STC3	$A = 4.6368\, \dot{m}^{-0.139}$
4	STC4	$A = 0.0021\, \dot{m}^{-1.981}$

Table 5. Characteristic intercept equations derived from experimental data of four different collectors

Sl no.	Collector	Characteristic intercept equation $B = D_B\, \dot{m}^{E_B}$
1	STC1	$B = 2.3076\, \dot{m}^{0.3579}$
2	STC2	$B = 2.3921\, \dot{m}^{0.365}$
3	STC3	$B = 2.4308\, \dot{m}^{0.393}$
4	STC4	$B = 0.5088\, \dot{m}^{-0.162}$

The equations as obtained in Table 4 and Table 5 are used to predict the efficiency at some selected flow rates (0.0317, 0.0248, 0.0438 and 0.055 kg/m^2-s for STC1, STC2, STC3 and STC4 respectively). The efficiency equations for respective collectors are shown in Table 6.

Using the above equations, efficiencies for some representative X-values are estimated and compared with actual experimental values for each collector. The comparison can be seen in Figures 2-5.

Table 6. Efficiency equations at selected flow rates for four different collectors

Sl. no.	Collector	Flow rate (kg/m^2-s)	Efficiency equation $\eta_i = (-A_i)X_i + B_i$
1	STC1	0.0317	$\eta_i = -6.903122X + 0.670949$
2	STC2	0.0248	$\eta_i = -6.956121X + 0.620518$
3	STC3	0.0438	$\eta_i = -7.162316X + 0.710966$
4	STC4	0.055	$\eta_i = -6.601216X + 0.813969$

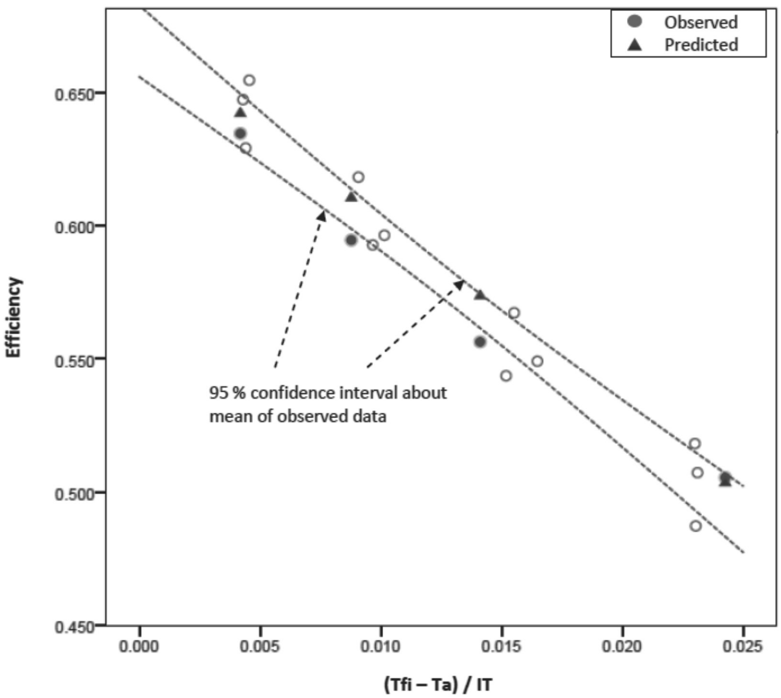

Figure 2.
Observed and estimated efficiencies of STC1 at 0.0317 kg/m^2-s flow rate.

It can be seen from the plots that the model predictions are closer to the experimental values almost for all the four collectors. However, in case of STC4 the deviation of the predictive efficiency from the observed value increases for higher values of *X* parameter. This may be due the fact that only three sets of data were considered for determining D_A, D_B, E_A and E_B in STC4. Also it is observed that the experimental data for *X* parameter which were used to determine the efficiency curve at the flow rate of 0.070 kg/m^2-s, falls mostly in the range of 0.015 to 0.02^0 C/W/m^2

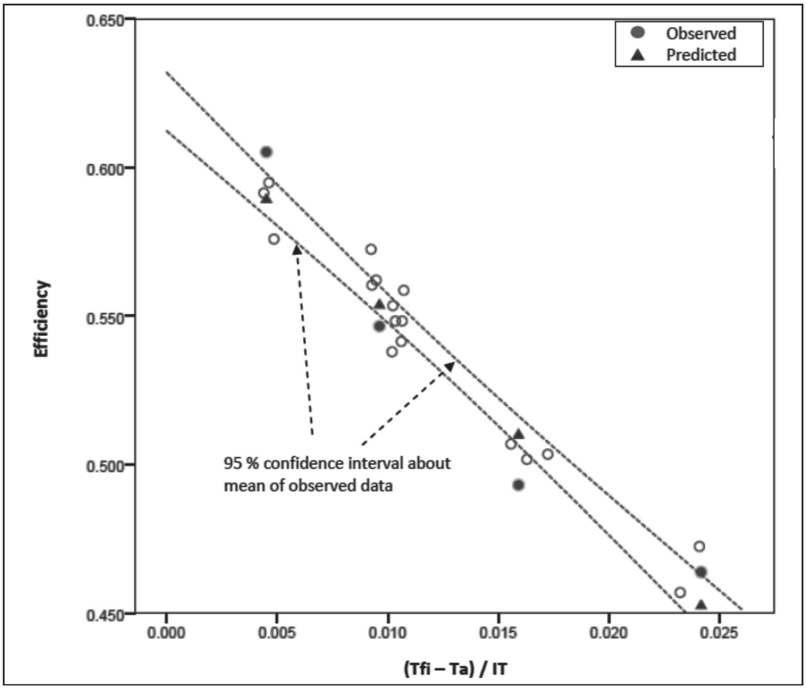

Figure 3.
Observed and estimated efficiencies of STC2 at 0.0248 kg/m^2-s flow rate.

with a span of about 0.05^0 C/W/m^2. So it may be expected that for better estimation by this model, observations with at least 4 to 5 mass flow rates may be done and the *X* parameter should be distributed uniformly over a wide range. The effect of relative humidity on collector performance is not considered in this model.

MODEL VERIFICATION AND VALIDATION

As discussed in Section 2, the model is developed using certain sets of experimental observations and takes into account of four different types of collectors. In general, it is seen that the model predictions reasonably agrees with the observed values. The marginal differences between observed and predicted values might be due to (i) errors in assuming some parameters (c_p, Ut, h_{fp}, h_{fb} and h_r) as temperature independent and (ii) errors in neglecting the effects of wind velocity and

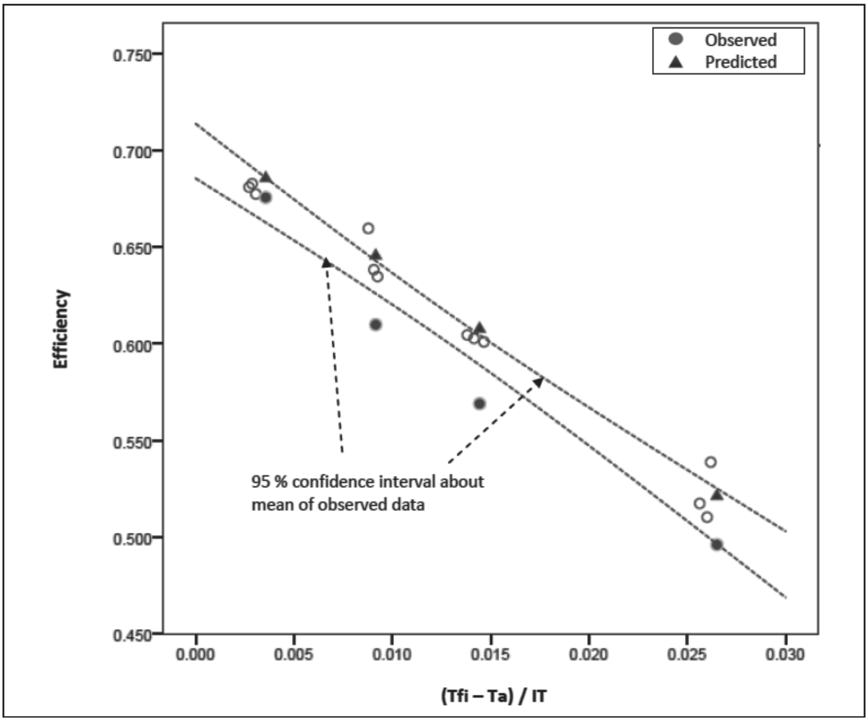

Figure 4.
Observed and estimated efficiencies of STC3 at 0.0438 kg/m²-s flow rate.

relative humidity of air. The required of model prediction is also verified through standard statistical technique (SPSS 16.0) which is incorporated in the Figures 2-5.

CONCLUSIONS

The domestic and industrial applications of flat plate solar air heater have remained limited mainly due to the difficulty associated with getting constant thermal output. The variations of either efficiency or output temperature are caused by related uncertainties. The uncertainties of output will have adverse effect on the quantity or quality of the product in typical applications, viz., drying applications. The model in this study is expected to predict the behavior of the collector in terms of efficiency with respect to varying conditions and mass flow rates. The

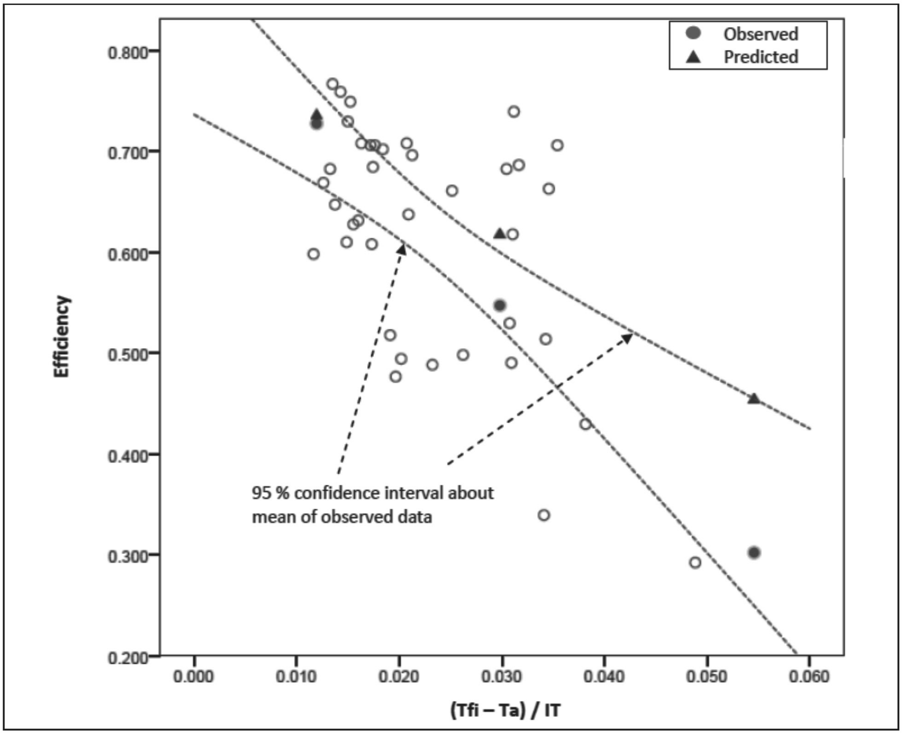

Figure 5.
Observed and estimated efficiencies STC4 at 0.055 kg/m²-s flow rate.

collector heat removal factor and the overall loss coefficient are the characteristics of a collector working under a given condition. The present study correlates these two parameters with measurable characteristic parameters such as slope and intercept of the performance equation. Now, the behavior of the device could be examined using the derived model parameters (D_A, D_B, E_A and E_B). Further, this model would also be useful to estimate the required mass flow rate corresponding to the desired efficiency or output temperature. This will enable to take appropriate decision for a given sets of specific temperature or performance efficiency as per user's choice. Thus, this model would serve as a decision making tool for an automatic control mechanism for providing desired output. In addition to the capability of predicting the performance of a given collector, this empirical model is also useful to compare different flat plat collectors.

The ever increasing demand for energy has become a major concern in India. Continued efforts are being made to exploit renewable energy sources for various applications to reduce the gap between energy demand and supply. Assam, a north eastern state of India, has many tea industries requiring huge amount of thermal energy for different processes. These process heat requirements are generally fulfilled by using conventional energy sources and a suitable solar hot air generator can substantially reduce the consumption of conventional energy. Experimental setups are being prepared to investigate the validity of the model under local operating conditions of Assam in order to explore the possibility of using solar hot air generator in output specific applications.

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