Performance Potential of Flat Plate Solar Air Heaters in Tehran

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Abstract: - Flat plate solar collectors are very efficient and economic devices to be used for space heating in places with abundant supply of solar radiation. In this paper the results of a parametric study on using solar air heaters in Tehran is presented. Simulations were performed for a typical small building by writing a computer program in FORTRAN. It is found that as the mass flow rate of air decreases the outlet temperature increases in the expense of decreasing efficiency. On the other hand, as the air channel depth is changed between 12 mm and 24 mm the useful energy gain is almost unaltered. Moreover, the simulation program is extended to evaluate the performance of solar air heaters on a typical winter day under the climatic condition of Tehran, where solar heating collectors are barely used. It is found that, from the energy point of view, for a model building of 157 m^2 total floor area, solar air collectors of 60 m^2, with tilt angle of 35°, can effectively meet the space heating demand during the day, reducing CO_2 emission by 8 tons annually.

Key-Words: - Solar energy, Flat plate solar collector, Space heating

1 Introduction

In today's rapidly evolving world, fossil fuel reservoirs are diminishing dramatically while the demand of energy is continuously growing. There is also a growing concern over global warming and rising prices. It is inevitable that renewable energy resources need to be utilized more effectively. Solar air heaters can play an important role among heating systems due to minimal use of materials, having zero emission, simplicity and using air directly as the working fluid, which reduces the number of required system components.

Different designs of solar air collectors have been tested and considerable efficiency improvement was obtained by using fins and baffles or corrugated surfaces [1-7]. The effect of collector aspect ratio on the efficiency of upward type baffled solar air heaters was investigated theoretically by H.Yeh et. al. [2]. The results indicated that the collector efficiency of baffled solar air heaters is higher but the improvement of efficiency by increasing the collector aspect ratio is reverse. A numerical study on the natural convection inside the channel between the flat-plate cover and the sine-wave absorber in a cross-corrugated solar air heater was conducted by Gao WF. et. al. [3]. The results showed that to effectively suppress heat loss during natural convection, the characteristic height ratio of the channel should be greater than 2, the characteristic geometric ratio larger than 1 and the tilt angle of the collector less than 40°. Three types of cross-corrugated heaters have been tested by W. Gao et. al. under several different conditions [4]. The results indicate that the collectors having wave-like shape bottom plate along the flow direction has the highest performance. It was also found that coatings on absorber plate can increase the thermal performance of heaters. H. Yeh and C. Ho [5] have investigated the influence of an external recycle on the efficiency of flat plate solar air collector with internal fins. It was found that collector efficiency had improved remarkably.

An experimental study was conducted on a 54 m^2 workshop by Gary Reysa [6] in Montana. Free-convection solar air heating collectors, total area of 15 m^2, were used on the building's south face. It was reported that with this inexpensive and easy-to-build solar air heaters the workshop could be heated to between 16-24°C on sunny winter days. Through the night, the building typically cools to a temperature of 4-8°C above the outdoor temperature. It was observed that the upper vent could supply air into the room at a temperature of 50°C at noon.

A solar air heating system installed at the Enbridge Consumers Gas vehicle repair facility in Toronto is providing all the needed fresh air and saving the company money at the same time [7]. By installing the solar air heater, the company's natural gas consumption is reduced by over 11,000 m^3, which is equivalent to 20 tons CO_2 per year.

In this paper a parametric study of a flat plate solar air heating collector is presented. The effects of air mass flow rate and inlet air temperature on the output air temperature, efficiency of the collector and useful energy gain are investigated. Also, the effect of air channel depth on the mentioned parameters is examined. Moreover, the study was extended to evaluate the seasonal heating potential of the solar air collectors when used for a typical small building.

2 Theoretical analysis

The conventional flat-plate solar air heaters have the simplest design having an air duct above or below the metal absorber plate. A schematic diagram of a flat plate solar air heating collector and heat transfer processes in it is illustrated in Fig.1. Solar radiation passes through the glass cover and is absorbed by the black painted absorber plate. The absorbed heat is transferred to the below channel. The air flows beneath the absorber plate contacting entire surface of the plate for effective heat transfer. In order to reduce heat loses, the system should be well insulated.

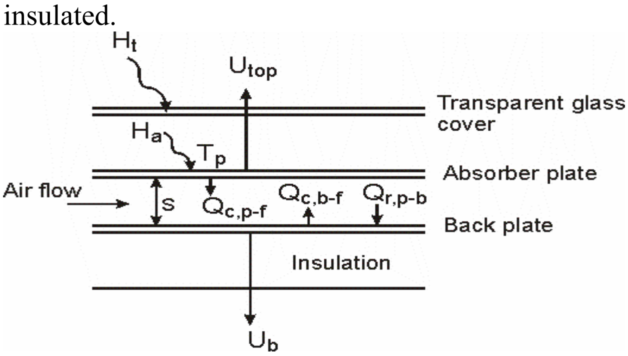

Figure 1. Schematic diagram of flat plate solar heating collector

Flat plate solar air heating collectors are usually fixed and they require no sun tracking. The following assumptions are considered in solving energy balance equations: the temperatures of the absorbing plate, bottom plate and bulk fluids are functions of flow direction only, the sides of the collector are well insulated. The convection heat transfer coefficients of both plates enclosing the air stream are equal. Dust and dirt deposition on the glass cover of the collector is negligible [8].

The steady state energy balance equations are written for differential sections of absorber plate, air stream and back plate [8]. The energy balance on the absorber plate of area (1.δx) gives:

$$H_a(\delta x) = U_{top}(\delta x)(T_p - T_a) + h_{c,p-f}(\delta x)(T_p - T) + h_{r,p-b}(\delta x)(T_p - T_b) \quad (1)$$

where H_a is absorbed radiation, T_p, T_b and T_a are temperature of absorber plate, temperature of back plate and ambient temperature and T is temperature of air. $h_{c,p-f}$ and $h_{r,p-b}$ are convection and radiation heat transfer coefficients from absorber plate to air and from absorber plate to back plate respectively. The radiation heat transfer coefficient is calculated as follows:

$$h_{r,p-b} = \frac{\sigma\left(T_p + T_b\right)\left(T_p^2 + T_b^2\right)}{\left(1/\varepsilon_p\right) + \left(1/\varepsilon_b\right) - 1} \quad (2)$$

where ε_p and ε_b are emissivities of underside and top side of black plate, respectively. σ is Stephan-Boltzmann constant. The radiation heat transfer coefficient can be expressed as a function of air mean temperature in the channel:

$$h_{r,p-b} = \frac{4\sigma\left(T_{air,mean}\right)^3}{\left(1/\varepsilon_p\right) + \left(1/\varepsilon_b\right) - 1} \quad (3)$$

The energy balance on the air stream with the volume of (s.1.δx) is:

$$\left(\frac{\dot{m}}{w}\right)c_p\left(\frac{dT}{dx}\delta x\right) = h_{c,p-f}(\delta x)\left(T_p - T\right) + h_{c,b-f}(\delta x)\left(T_b - T\right) \quad (4)$$

where $\dot{m}$ is mass flow rate of air through collector, w and c_p are width of collector and heat capacity of air, $h_{c,b-f}$ is convection heat transfer coefficient from back plate to air. The convection heat transfer coefficients of both plates for turbulent flow are calculated as follows [8]:

$$Nu = 0.0158Re^{0.8} \quad (5)$$

The following empirical correlations can be used to estimate the thermal conductivity and dynamic viscosity of air [9-10]:

$$k = (0.0015215 + 0.097459T - 3.3322\times10^{-5}T^2)\times10^{-3} \quad (6)$$

$$\mu = (1.6157 + 0.06523T - 3.0297\times10^{-5}T^2)\times10^{-6} \quad (7)$$

while constant value of $c_p \approx 1000$ J/kg.K can be considered. The energy balance on the back plate with area (1.δx) is written as:

$$h_{r,p-b}(\delta x)(T_p - T_b) = h_{c,b-f}(\delta x)(T_b - T) + U_b(\delta x)(T_b - T_a) \quad (8)$$

Solving equations and applying boundary conditions, the temperature distribution equation for air in the duct is found and from that the outlet air temperature equation is obtained:

$$T_{f,out} = T_{f,in} + \frac{1}{U_c}\left[H_a - U_c\left(T_{f,in} - T_a\right)\right] \times \left[1 - \exp\left(-\frac{A_c U_c F'}{\dot{m} c_p}\right)\right] \tag{9}$$

where $T_{f,out}$ and $T_{f,in}$ are outlet and inlet temperature of air, U_c is collector overall heat loss coefficient, A_c is collector area and F' is collector efficiency factor which is evaluated as:

$$F' = \frac{h}{h + U_c} \tag{10}$$

where

$$h = h_{c,p-f} + \frac{1}{(1/h_{c,b-f}) + (1/h_{r,p-b})} \tag{11}$$

The total rate of useful energy gain is evaluated by Hottel-Whillier-Bliss equation for solar collectors as follows:

$$Q_u = A_c F_R\left[H_a - U_c\left(T_{f,in} - T_a\right)\right] \tag{12}$$

where F_R is heat-removal factor

$$F_R = \frac{\dot{m} c_p}{A_c U_c}\left[1 - \exp\left(-\frac{A_c U_c F'}{\dot{m} c_p}\right)\right] \tag{13}$$

The collector efficiency is:

$$\eta_c = \frac{Q_u}{A_c H_t} \tag{14}$$

where H_t is total incident solar radiation in W/m^2. H_a is a function of total solar radiation as follows:

$$H_a = H_t\left(\tau\alpha\right) \tag{15}$$

where τ is the transmissivity of glass cover and α is absorptivity of absorber plate.

3 Methodology

Parametric and case studies concerning flat plate solar air heating collectors are conducted by writing a computer program in FORTRAN. The results of the program are in good agreement with those in the literature [6, 8] having 0.2% relative error. The equations are solved, in a trial and error process, by first, assuming air mean temperature to find the outlet air temperature. Then assumed value is checked with new evaluated air mean temperature. If the evaluated value is not equal to the assumed one, the calculations are repeated with new air mean temperature. This process continues till both air-mean-temperatures become equal. Then with the obtained inlet and outlet temperatures, the useful energy gain and efficiency of the collector are evaluated. For the parametric study, the area of the collector is assumed 1m^2; the product of absorptivity and transmissivity $\tau\alpha$=0.85; overall heat-loss coefficient of the collector U_c=5 W/m^2.K; emissivity of underside of absorber plate ε_p=0.95; emissivity of back plate ε_b=0.95; four mass flow rates of air are chosen to be 0.06, 0.12, 0.18 and 0.24 kg/s and the inclination angle of collector is 35°.

4 Results and discussion

The effects of different inlet air temperatures and solar insolation at four selected air mass flow rates, on outlet air temperature, collector efficiency and useful energy gain are shown in Table 1. The results indicate that as the mass flow rate is increased there is a notable increase in the efficiency of the collector, and thereby useful energy gain until 0.18 kg/s. Above 0.18 kg/s the increase in efficiency is insignificantly small. Thereby, 0.18 kg/s air mass flow rate is chosen as optimum capacity of the needed blower. When ambient temperature is low, the performance remains approximately constant. This occurs because at low ambient temperatures as the rate of solar radiation increases, the rate of useful energy gain increases somehow equally (Eq. 12) leading to approximately constant value of efficiency. The effect of increasing the depth of airflow channel on the other parameters is also investigated at constant 0.18 kg/s air mass flow rate and the results are shown in Table 2. According to the results, increasing the channel depth leads to less energy gain and efficiency of the collector. Thereby, the optimum parameters are 0.18 kg/s mass flow rate and 12 mm depth of air channel.

Moreover, the written program is developed to investigate the potential of using solar energy for space heating in Tehran (35° 45'N, 51° 30', E), having a population of approximately 15 million. Natural gas is widely used as the energy source for space heating, however, solar energy need to be considered for environmental concerns.

The study is conducted under the climatic condition of Tehran for a typical winter day (1st January). A typical small building operating during day time (such as an office), located in northern part of Tehran, with total floor area of 157 m^2 is considered. The walls of the building are constructed with 200 mm red brick and 5 cm plaster. The overall heat transfer coefficient of the wall is 2.184 W/m^2.°C. The height of the walls is 3 m. The daily (6:00-18:00) heating load of the building is evaluated to be 962 MJ. It is assumed that the solar collectors are manufactured with a standard area of 3m^2, with mass flow rate of air and air channel depth chosen to be 0.18 kg/s and 12 mm respectively.

Table 1.Effects of inlet temperature and solar radiation on outlet air temperature, efficiency and useful energy gain of solar collector at different air mass flow rates

T_{fin} (°C)	H_t (W/m^2)	$\dot{m}$ =0.06 kg/s			$\dot{m}$ =0.12 kg/s			$\dot{m}$ =0.18 kg/s			$\dot{m}$ =0.24 kg/s		
		$T_{f,out}$ (°C)	η (%)	Q_u (W/m^2)	$T_{f,out}$ (°C)	η (%)	Q_u (W/m^2)	$T_{f,out}$ (°C)	η (%)	Q_u (W/m^2)	$T_{f,out}$ (°C)	η (%)	Q_u (W/m^2)
5	200	7.2	0.65	134.6	6.2	0.71	147	5.84	0.74	152	5.6	0.75	155.6
	300	8.3	0.65	201.8	6.8	0.71	220	6.26	0.74	229	5.9	0.75	233.3
	400	9.4	0.66	269.1	7.4	0.72	294	6.68	0.75	305	6.2	0.76	311.1
	500	10.5	0.66	336.4	8	0.72	367	7.1	0.75	381	6.6	0.76	388.9
	600	11.5	0.66	403.7	8.6	0.72	440	7.5	0.75	457	6.9	0.76	466.7
	700	12.6	0.67	471	9.2	0.73	514	7.9	0.76	533	7.2	0.77	544.5
	800	13.8	0.67	538.3	9.8	0.73	587	8.3	0.76	609	7.5	0.77	622.3
15	200	16.5	0.47	95.02	15.8	0.51	104	15.6	0.53	108	15.4	0.54	109.7
	300	17.6	0.54	162.3	16.4	0.58	177	16	0.61	184	15.7	0.62	187.5
	400	18.7	0.57	229.6	17	0.62	250	16.4	0.64	260	16.1	0.66	265.2
	500	19.8	0.59	296.9	17.7	0.64	324	16.8	0.67	336	16.4	0.68	343
	600	20.9	0.61	364.3	18.3	0.66	397	17.3	0.68	412	16.7	0.7	420.7
	700	22	0.62	431.6	18.9	0.67	471	17.7	0.69	488	17	0.71	498.5
	800	23.1	0.63	499	19.5	0.68	544	18.1	0.7	564	17.4	0.72	576.2
25	200	25.9	0.27	55.5	25.5	0.31	60.4	25.3	0.31	63	25.2	0.32	64
	300	27	0.41	122.9	26.1	0.44	134	25.7	0.46	139	25.6	0.47	141.8
	400	28.1	0.47	190.4	26.7	0.51	207	26.2	0.53	215	25.9	0.54	219.5
	500	29.2	0.51	257.9	27.3	0.56	281	26.6	0.58	291	26.2	0.59	297.3
	600	30.3	0.54	325.4	27.9	0.59	354	27	0.61	367	26.5	0.62	375.1
	700	31.4	0.56	392.9	28.5	0.61	428	27.4	0.63	444	26.9	0.64	452.9
	800	32.5	0.57	460.5	29.1	0.62	501	27.8	0.64	520	27.2	0.66	530.6

Table 2.Effects of inlet temperature and solar radiation on outlet temperature, efficiency and useful energy gain of solar collector at different air channel depths

$T_{f,in}$ (°C)	H_t (W/m^2)	S=12 mm			S=24 mm		
		$T_{f,out}$ (°C)	η (%)	Q_u (W/m^2)	$T_{f,out}$ (°C)	η (%)	Q_u (W/m^2)
5	200	5.9	74	152.3	5.8	73	150.5
	300	6.3	74	228.5	6.2	73	225.7
	400	6.7	75	304.7	6.6	74	300.9
	500	7.1	75	380.8	7	74	376.2
	600	7.6	75	457	7.5	74	451.4
	700	8	76	533.2	7.9	75	526.6
	800	8.4	76	609.3	8.3	75	601.8
15	200	15.6	54	107.5	15.5	53	106.1
	300	16.1	61	183.6	16	60	181.3
	400	16.5	65	259.8	16.4	64	256.6
	500	16.9	67	335.9	16.8	66	331.8
	600	17.3	68	412.1	17.2	67	407
	700	17.7	69	488.2	17.6	68	482.2
	800	18.1	70	564.31	18	69	557.4
25	200	25.3	32	62.8	25.3	31	61.9
	300	25.7	46	138.9	25.7	45	137.2
	400	26.2	54	215	26.1	53	212.4
	500	26.6	58	291.2	26.5	57	287.7
	600	27.1	61	367.4	27	60	362.9
	700	27.5	63	443.6	27.4	62	438.2
	800	27.9	65	519.7	27.8	64	513.4

The hourly variations of solar radiation and ambient temperatures along the day are shown in Fig.2. The hourly ambient temperatures are taken from Iran Meteorological Organization [11] and incident solar radiation on a tilted surface is evaluated by considering both sky diffuse and beam radiation [8]. As it is shown the highest solar radiation occurs around noon with 930 W/m^2. The maximum ambient temperature is recorded at 2:00 pm with the value of 5°C whilst the minimum temperature of 3°C below zero is recorded at dawn.

The hourly useful energy gains from a 3 m^2 solar collector are shown in Fig.3. The results indicate that total energy gain from each collector is about 47 MJ/day. Consequently, from the needed-energy point of view, 20 unit solar collectors, having total area of 60 m^2, are needed to meet the daily heating demand of the model building which is 960 MJ. As it is obvious, the contribution of solar energy during daytime varies from a very small portion to a large amount, but covering the total demand. Of course, an auxiliary system for heating purpose is needed at night. The efficiency of solar collectors is evaluated to be 74 % in this case.

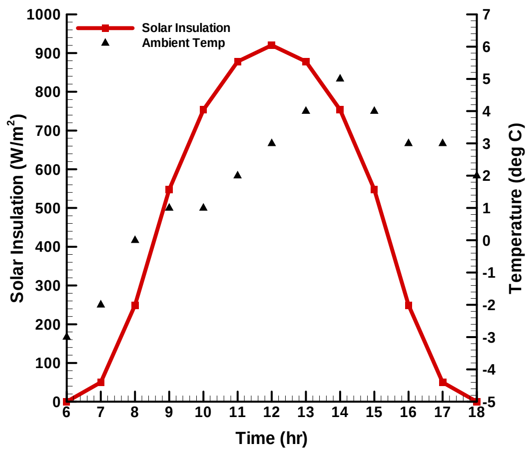

Figure 2. Hourly solar radiation on a tilted surface and ambient temperature

The variations of outlet air temperature are shown in Fig.4. The highest temperature obtained in the afternoon (13:00 pm) but the highest solar radiation occurs at noon. This one hour shift is because of the heat stored in the absorber plate during the day.

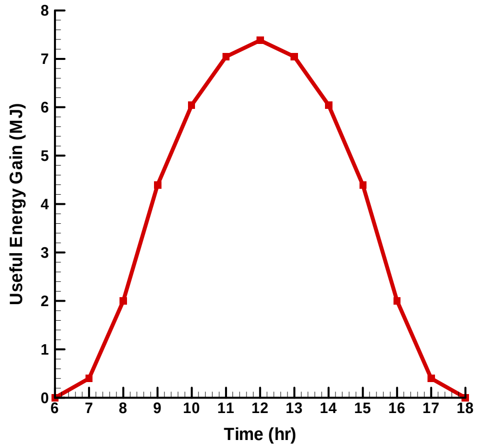

Figure 3. Hourly useful energy gain from solar collector

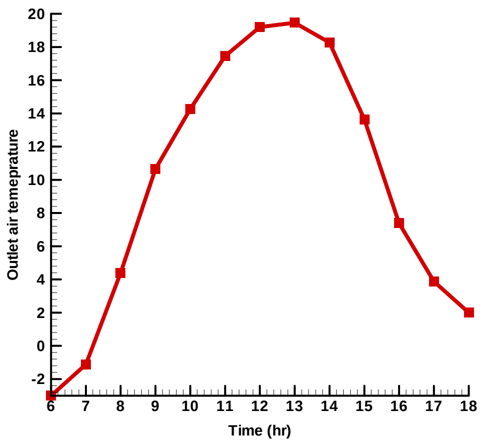

Figure 4. Hourly outlet air temperature variations

To meet the daily heating demand of the model building 25 m^3 natural gas should be burned. Each m^3 natural gas produces 0.001950 ton carbon dioxide. Thereby, to meet daily heating demand of the model building, 8 tones CO_2 is released to the atmosphere annually which will be omitted if solar air heating collectors are used.

5 Conclusion

A computer program is written in FORTRAN to conduct parametric and case studies on flat plate air heating solar collectors. The results of parametric study indicate that among the tested parameters, 0.18 kg/s mass flow rate and 12 mm air channel depth are the optimum values. Moreover, a model building with total area of 157 m^2 in Tehran is considered to investigate the possibility of using flat plate solar air collectors as potential heaters. It is found that even on a cold day of winter (1^{st} of January), 60 m^2 flat plate solar air heating collectors can effectively meet the heating demand of the building with an efficiency of 74%. In addition, it is estimated that by using solar air heating collectors the annual CO_2 emissions for the model house would be reduced by 8 tons. More investigation is needed for evaluating the economic feasibility and possible policy options for the promotion of these heaters.

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