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Thermal energy saving in industrial halls using vertical air solar heaters

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A B S T R A C T

In this paper, an analysis on the thermal energy saving in large industrial halls is performed using air solar heaters. Computations are carried out for latitudes in the range of $35^{\circ} \leq$ Lat. $\leq 40^{\circ}$ at the fixed Longitude of 45°. A large industrial hall with dimensions of length=100 m, width=30 m, and 4 m $\leq$ height $\leq$ 6 m is considered to study. In addition, on the south wall of the hall 25 flat air solar heater with dimensions of length=2 m and height=3m are considered. Several results are obtained in this study. For example, thermal energy audit of the building revealed that the industrial hall located at the latitude of 40° has more energy demand compared with the smaller latitudes. On the other hand, it is demonstrated that application of air solar heaters for such building saves the thermal energy consumption significantly depending on the latitude value.

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1. Introduction

Industrial halls with large and sometimes huge spaces use the large amounts of annual energy. The reason behind this large energy demand is mainly due to external walls, lack of insulation and high rate of air infiltration in such buildings. In the past decade, many different efforts have been performed in order to decrease the annual energy consumption (AEC) for various buildings. These efforts are almost under two categories as follow:

- Improvement the buildings materials and their constructions.
- Partially or fully replacement of the renewable energies in residential and commercial buildings.

Among the renewable energies, solar energy is a more applicable energy which has different applications from space heating and domestic hot water production to electricity production. Therefore, there are many different studies on the solar energy and its applications. It seems that the air solar heater (A.S.H) as a new application for solar energy is investigated less than the other applications. A.S.Hs have different designs. A simple one is a flat collector which is installed on the building walls vertically or on the roofs with specific slope with respect to earth direction. A.S.Hs almost apply for space heating of residential and non-residential buildings. Among the pervious published researches, some of them are worth mentioning. A comparative performance study of some thermal storage materials used for solar space heating is performed by Khalifa and Abbas [1], numerically. They demonstrated that a storage wall 0.08-m-thick made from the hydrated salt $CaCl_2.6H_2O$ maintained the zone temperature close to the comfort temperature with the least room temperature fluctuation compared to the 0.02-m-thick concrete wall and the 0.05-m-thick wall made from paraffin wax. Nowzari et al. [2] conducted on the finding the best configuration for a solar air heater by design and analysis of experiment. It was found that the double-pass solar collector with a quarter-perforated 10D cover (3 cm) yields the maximum average efficiency at a mass flow rate of 0.032 kg/s. Acır and Ata [3] have investigated on the heat transfer enhancement in a new solar air heater using circular type turbulators. They demonstrated that the heat transfer enhancement in the solar air heaters having turbulators was significantly higher than obtained in conventional plain tube. Design and thermal performance evaluation of a novel solar air heater is studied by Saxena et al. [4]. It was found that thermal efficiencies of the novel solar air heater range from 18.04% to 20.78% of natural convection and 52.21% to 80.05% with forced convection. A parametric investigation on thermo-hydraulic performance of wire screen matrix packed solar air heater is presented by Verma and Varshney [5]. Different results have been obtained in their studied. For example , The performance of packed bed solar air heater is governed by the geometry of the packing element and high porosity matrices found to exhibit better thermo-hydraulic performance as compared to matrices with low porosities for wide range of mass flow rates. A feasibility study on solar-wall systems for domestic heating is investigated by Wang et al. [6] using CFD tools. Some different results are obtained in their studies. For example, i) the location of the heat store in the internal wall of the flat is effective using the proposed panel wall structure. ii) the solar energy collectable from roof top solar thermal panels in Scotland exceeds the need for domestic hot water. Kulkarni et al. [7] investigated on the multi-objective optimization of solar air heater with obstacles on absorber plate. The optimization results show that the objective functions are significantly affected by the design variables, and the constructed surrogate models show good prediction accuracies for the objective functions.

2. Materials and methods

In this study, in order to analyze the A.S.Hs effect, an industrial hall with dimensions illustrated in figure 1 is considered. It should be mentioned that the hall length is 1000 m. The applied materials for this hall are summarized in table 1.

First of all, in order to apply the solar heaters in this industrial hall, a thermal energy audit should be performed. Thermal energy audit is basically calculation of annual energy consumption for this hall.

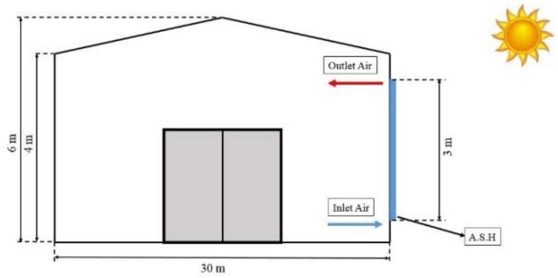

Figure 1. Schematic of the industrial hall and an A.S.H

Table 1. Description of the applied materials

Element	Description
Wall	35 cm hollow brick
Door	t=10 cm, A=15 m^2, Iron, N=2
Window	A=2 m^2, Single glass, Iron frame, N=50
Roof	1 cm Polystyrene insulate + 1 mm Iron plate

Therefore, total heat loss of the building should be computed.

Generally, heat loss of buildings is due to following items;

- Transmission losses or heat transferred through the confining walls, glass, ceiling, floor, or other surfaces, which is calculated as [8]

$$Q_1 = U.A.(T_{in} - T_{out}) \qquad (1)$$

Here, A is surface are (m^2), T_{in} is indoor comfort temperature (°C), T_{out} is mean external temperature (°C) in winter season (mean temperature of six cold month), and U is overall heat transfer coefficient (W/m^2°C) which is computed as [8]

$$U = \frac{1}{R_{total}} = \frac{1}{R_{film-in} + \sum_{i=1}^{n} R_i + R_{film-out}} \qquad (2)$$

in which, R_{total} is total thermal resistance of the wall (m^2 °C/W), R_i conductive resistance (m^2 °C/W), $R_{film-in}$ and $R_{film-out}$ film resistance of inner and outer sides of the wall (m^2 °C/W), respectively, and n is number of wall layers. It should be mentioned that all of the parameters in equations 1 and 2 are calculated based on the CIBSE Guide [9].

- Infiltration losses or energy required to warm outdoor air leaking in through cracks and crevices around doors and windows [8],

$$Q_2 = (0.33) ACH.V.(T_{in} - T_{out}) \qquad (3)$$

Here, ACH is the air exchange rate (1/hr), V is volume of the under consideration space (m^3), and Q_2 is the heat loss due to air infiltration (W).

- Heat loss into ground [8],

$$Q_3 = U_g.A_g.(T_{in} - T_g) \quad (4)$$

In which, U_g is overall heat transfer coefficient through ground (horizontal air film and 3 m of soil, $W/(m^2\ ^\circ C)$), A_g is ground surface area (m^2), T_g is ground temperature ($^\circ$C) [10], and Q_3 is heat loss into ground (W).
Therefore, ignoring the latent heat losses and internal heat gains, the total heat loss (Q_{total}) can be obtained as,

$$Q_{total} = \sum_{i=1}^{3} Q_i \quad (5)$$

Based on heating load calculation, it is possible to estimate the AEC using the following equation [11],

$$AEC = \frac{Q_{total}}{(T_{in} - T_{out})}.HDD.(24).\frac{1}{\eta} \quad (6)$$

in which, AEC is annual energy consumption (KWh/year), HDD is standard heat degree days per years, and η is the seasonal efficiency of heating system. Table 2 indicates the HDD values for three Latitudes of 35°, 37°, and 40° in the constant longitude of 45°. In the present study, fully controlled gas fired boiler with unit heaters system is assumed as the hall heating system. Therefore, the seasonal efficiency of heating system is assumed to be 75% [11].

Table 2. HDD values for different latitudes and months [10]

Month	HDD-35°	HDD-37°	HDD-40°
Jan	470	669	660
Feb	399	571	593
Mar	310	485	511
Apr	113	277	295
May	15	121	173
Jun	0	10	57
Jul	0	0	11
Aug	0	2	19
Sep	0	34	102
Oct	30	192	259
Nov	220	407	436
Dec	411	597	615

In the second step of solar heating system modeling, the net absorbed solar radiation for vertical A.S.Hs should be calculated. The net absorbed radiation from a A.S.H is assessed by [12],

$$S = I_B R_B (\tau\alpha)_b + I_D (\tau\alpha)_D \left[\frac{1+\cos(\beta)}{2}\right] + \rho_G (I_B + I_D)(\tau\alpha)_G \left[\frac{1-\cos(\beta)}{2}\right] \quad (7)$$

in which, [1+cos(β)]/2 and [1-cos(β)]/2 are the view factors and both of them are equal to 1/2 for a vertical surface (β=90°), β is collector slope, $(\tau\alpha)_B$, $(\tau\alpha)_D$, and $(\tau\alpha)_G$ are transmittance-absorptance product for estimating incidence angle modified for beam radiation, sky (diffuse) radiation, and ground-reflected radiation, respectively, I_B and I_D are beam radiation for an hour and diffuse radiation for an hour ($KWh/m^2/day$), respectively, ρ_G is reflectivity of the ground which is consider as 0.35 in the present study, and S is absorbed solar radiation per unit area ($KWh/m^2/day$). R_B is the beam radiation tilt factor which is determines as below [12],

$$R_B = \frac{\sin(L-\beta)\sin(\delta) + \cos(L-\beta)\cos(\delta)\cos(h)}{\sin(L)\sin(\delta) + \cos(L)\cos(\delta)\cos(h)} \quad (8)$$

in which, L is latitude, δ is declination angle, and h is hour time. The declination angle, δ, is obtained as [12],

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + N\right] \quad (9)$$

in which, N is the number of day in a year. Table 3 shows the monthly averaged declination angles.

Table 3. The computed declination angles

Month	δ
Jan	-20.7°
Feb	-12.3°
Mar	-1.8°
Apr	9.70°
May	18.8°
Jun	23.0°
Jul	21.2°
Aug	13.7°
Sep	3.09°
Oct	-8.45°
Nov	-18.1°
Dec	-22.8°

The value of hour angle, h, of a point on the earth's surface is defined as [12],
h=± 0.25(Number of minutes from local solar noon) (10)
and the sunset hour angle, h_{ss}, is [12],

$$\cos(h_{ss}) = -\tan(L)\tan(\delta) \quad (11)$$

Table 4 shows the obtained results for sunset hour angle, h_{ss}, for under consideration latitudes.
The hourly diffuse radiation, I_D($KWh/m^2/day$), in equation 7 is estimated using an empirical correlation introduced by Liu and Jordan [13] as,

$$\frac{I_D}{\bar{H}_D} = (\frac{\pi}{24}) \frac{\cos(h) - \cos(h_{ss})}{\sin(h_{ss}) - (\frac{2\pi h_{ss}}{360})\cos(h_{ss})} \quad (12)$$

Furthermore, the value of hourly beam radiation, I_B ($KWh/m^2/day$), is determined using the following concept,

$$I = I_B + I_D \quad (13)$$

in which, I is hourly total radiation (KWh/m^2/day) and is computed using the Collars-Pereira and Rabl [14] empirical equation as,

$$\frac{I}{H} = (\frac{\pi}{24})(a + b\cos(h))\frac{\cos(h) - \cos(h_{ss})}{\sin(h_{ss}) - (\frac{2\pi h_{ss}}{360})\cos(h_{ss})} \quad (14)$$

Table 4. Sunset hour angle

Lat.	Month	h_{ss}
35°	Jan	74.5
	Feb	81.1
	Mar	88.7
	Apr	96.8
	May	103
	Jun	107
	Jul	105
	Aug	99.8
	Sep	92.1
	Oct	84
	Nov	76.7
	Dec	72.7
37°	Jan	73.3
	Feb	80.4
	Mar	88.6
	Apr	97.4
	May	104
	Jun	108
	Jul	107
	Aug	100
	Sep	82.3
	Oct	83.5
	Nov	75.6
	Dec	71.4
40°	Jan	71.4
	Feb	79.3
	Mar	88.4
	Apr	98.2
	May	106
	Jun	110
	Jul	109
	Aug	101
	Sep	92.5
	Oct	82.8
	Nov	74
	Dec	69.2

in which,

$$a = 0.409 + 0.5016\sin(h_{ss} - 60) \quad (15a)$$

and

$$b = 0.6609 - 0.4767\sin(h_{ss} - 60) \quad (15b)$$

$\overline{H}_D$ and $\overline{H}$ in equations (12) and (14) are called the monthly average daily diffuse radiation on horizontal surface (KWh/m^2/day) and the monthly average total isolation on a terrestrial horizontal surface (KWh/m^2/day) [12], respectively. In the present study, the NASA data [10] are used for assessing the value of $\overline{H}$. Table 5 presents values of $\overline{H}_D$ and $\overline{H}$ for different latitudes.

The values of $(\tau\alpha)_B$, $(\tau\alpha)_D$, and $(\tau\alpha)_G$ in equation (7) are computed as [11],

$$(\tau\alpha)_{B\&D\&G} = 1.01\tau(\frac{\alpha}{\alpha_n})\alpha_n \quad (16)$$

where, τ is collector transmittance, α is the fraction of solar energy reaching surface that is absorbed, and α_n is the absorptance of the plate at normal incidence which is consider as 0.91 in this study. The fraction of α/α_n in equation (16) is determined using the following equation [12],

Table 5. Values of $\overline{H}_D$ and $\overline{H}$, (KWh/m^2/day), [10]

Lat.	Month	$\overline{H}_D$	$\overline{H}$
35°	Jan	0.89	2.66
	Feb	1.17	3.49
	Mar	1.54	4.59
	Apr	1.97	5.41
	May	2.08	6.67
	Jun	1.92	7.68
	Jul	1.94	7.31
	Aug	1.69	6.73
	Sep	1.41	5.65
	Oct	1.25	3.93
	Nov	0.97	2.84
	Dec	0.83	2.33
37°	Jan	0.82	2.52
	Feb	1.06	3.46
	Mar	1.46	4.54
	Apr	1.93	5.36
	May	2.14	6.42
	Jun	1.93	7.64
	Jul	1.83	7.52
	Aug	1.60	6.82
	Sep	1.32	5.62
	Oct	1.19	3.76
	Nov	0.92	2.62
	Dec	0.77	2.13
40°	Jan	0.76	2.04
	Feb	1.06	2.82
	Mar	1.53	3.65
	Apr	2.01	4.42
	May	2.34	5.27
	Jun	2.40	6.12
	Jul	2.31	6.01
	Aug	2.01	5.42
	Sep	1.56	4.57
	Oct	1.17	3.26
	Nov	0.85	2.20
	Dec	0.70	1.72

$$\frac{\alpha}{\alpha_n}=\begin{cases}1+2.0345\times10^{-3}\theta_e-1.99\times10^{-4}\theta_e^2+\\5.324\times10^{-6}\theta_e^3-4.799\times10^{-8}\theta_e^4\\ \\59.68-0.1388\beta+0.001497\beta^2\\ \\90-0.5788\beta+0.002693\beta^2\end{cases} \quad (17)$$

in which,

$$\theta_e=\begin{cases}\cos^{-1}[-\cos(L)\sin(\delta)+\sin(L)\cos(\delta)\cos(h)]\\ \beta\\ \beta\end{cases} \quad (18)$$

The first, second, and third rows of equations (17) and (18) are used for computing of $(\tau\alpha)_B$, $(\tau\alpha)_D$, and $(\tau\alpha)_G$, respectively. Finally, in order to determine the collector transmittance, the following equations are carried out [12],

$$\tau=\tau_\alpha\tau_r \quad (19)$$

$$\tau_\alpha=\exp(-\frac{KL}{\cos(\theta_2)}) \quad (20)$$

$$\tau_r=\frac{1}{2}(\frac{1-r_2}{1+r_2}+\frac{1-r_1}{1+r_1}) \quad (21)$$

in which [12],

$$\theta_2=\sin^{-1}(\sin(\theta_{e,B})/n \quad (22)$$

$$r_1=\frac{\sin^2(\theta_2-\theta_1)}{\sin^2(\theta_2+\theta_1)} \quad (23)$$

$$r_2=\frac{\tan^2(\theta_2-\theta_1)}{\tan^2(\theta_2+\theta_1)} \quad (24)$$

In the upper equations, τ_α is absorber transmittance, subscript r indicates the reflection losses, K is the extinction coefficient, L is the thickness of the glass cover, r_1 and r_2 are the perpendicular and parallel components of unpolarized radiation, respectively, θ_2 is refraction angle and n is the ration of refraction index which is 1.526 for glass. It should be mentioned that in the present study, the value of KL is considered as 0.037.

3. Results & Discussion

Figures 2, 3, and 4 show the computed results of energy consumption of the industrial hall at three latitude of 35°, 37°, and 40°, respectively. The results for each Latitude are presented for three different scenarios. In other words, three various working period (w.p) of 8 hr, 10 hr, and 16 hr are considered for this industrial hall. In order to relate the monthly values of the AEC with absorbed solar energy, monthly values of the solar energy absorbed by A.S.Hs are illustrated in each individual figure by red line. First of all, the results show higher energy demand for industrial hall at higher latitude. Although, at Lat.=35°, in Jun, Jul, Aug, and Sep there is zero energy demand for heating, at Lat.= 37°, only in Jul there is no energy demand. On the other hand, there is energy demand for whole of the months at Lat.=40°. Comparison between the energy demand of the industrial hall and maximum absorbed solar energy (Max. S.E) reveals that; i) between the Feb and Nov at Lat.=35°, more or less, the absorbed solar energy is sufficient for heating application of the industrial hall under w.p= 8 hr to 10 hr. However, for w.p=16 hr, the solar energy is sufficient only between Apr and Oct; ii) at Lat.=37°, between Apr and Oct, the absorbed solar energy is sufficient under w.p=8 hr and 10 hr while the provided solar energy under w.p=16 hr is enough only between May and Sep; iii) Examination of the energy data at Lat.=40° reveals that under 8 hr ≤w.p≤ 10 hr , the absorbed solar energy covers the energy demand of the industrial hall between Apr and Oct, completely. However in this latitude, the provided solar energy is enough between May and Oct under w.p=16 hr.

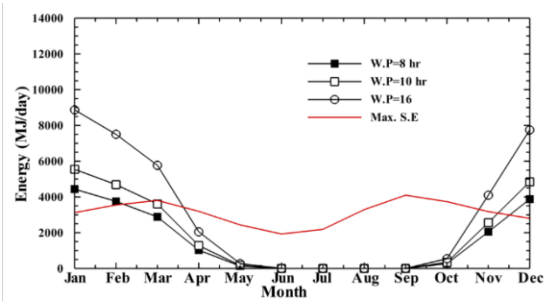

Figure 2. Monthly energy consumptions for Lat.=35° under various w.p and maximum monthly solar energy

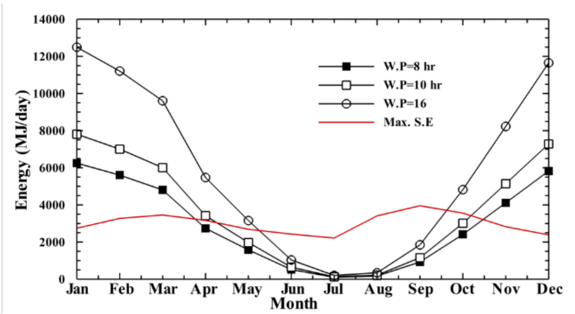

Figure 3. Monthly energy consumptions for Lat.=37° under various w.p and maximum monthly solar energy

It is worth mentioning that during the months that the absorbed solar energy is not sufficient for heating applications of the industrial hall, however, it provides the significant portion of the energy demand. For example, in Jan, under w.p=8 hr, the provided solar energy is 70.4%, 48.5%, and 43.9% of total thermal energy demand at Lat.= 35°, 37°, and 40°, respectively. This portion decreases to 56.3%, 38.8%, and 35.1% under w.p=10 hr at Lat.= 35°, 37°, and 40°, respectively. Finally, it can be seen that absorbed solar energy provides 31.2%, 24.2%, and 21.9% of the energy demand for this industrial hall under w.p=16 hr at Lat.= 35°, 37°, and 40°, respectively.

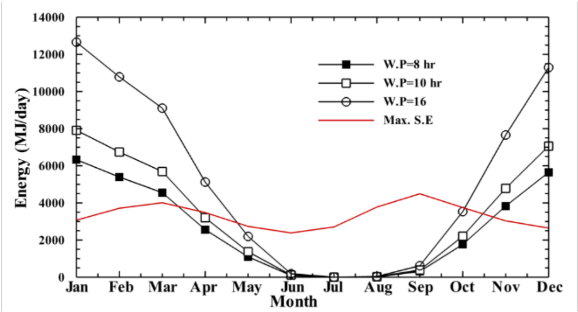

Figure 4. Monthly energy consumptions for Lat.=40° under various w.p and maximum monthly solar energy

4. Conclusions

In the present paper, solar energy potential was assessed for a large industrial hall heating application at 35°≤ Lat. ≤ 40°. A large industrial hall was considered for study of solar energy capacity in heating of the hall. In addition, 25 A.S.Hs were assumed to be installed on the south wall of the hall. Several results were obtained in this study. For example; i) at the under consideration Latitude range, A.S.Hs play an important role for heating application of an industrial hall. ii) the obtained results revealed that using the 25 A.S.Hs, depending to the w.p, fossil fuel energy saves at least 31.2% to 70.4%, 24.2% to 48.5%, and 21.9% to 43.9% at latitudes of 35°, 37°, and 40°, respectively

Nomenclature	
A	radius of
B	position of
C	further nomenclature continues down

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