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Feasibility of a solar-assisted winter air-conditioning system using evaporative air-coolers

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Abstract
The paper presents a winter air-conditioning system which is suitable for regions with mildly cold but dry winters. The system modifies the evaporative air-cooler that is commonly used for summer air-conditioning in such regions by adding a heating process after the humidification process. The paper describes a theoretical model that is used to estimate the system's water and energy consumption. It is shown that a 150-LPD solar heater is adequate for air-conditioning a 500 ft^3/min (14.4 m^3/min) air flow rate for four hours of operation. The maximum air-flow rate that can be heated by a single solar water-heater for four hours of operation is about 900-cfm, unless a solar water heater large than a 250-LPD heater is used. For the 500 ft^3/min air flow rate the paper shows that the 150, 200, 250 and 300 LPD solar water-heaters can provide air-conditioning for 4, 6, 8 and 10 hours, respectively, while consuming less energy than the equivalent refrigerated-type air-conditioner.
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Keywords: Hot and dry climate, Winter air-conditioning, Evaporative air cooler, Solar energy.

1. Introduction

Evaporative air coolers (EACs), which are used for air-conditioning in hot-and-dry climates, have considerably low energy consumption compared to refrigerated systems. Because they do not need any refrigerant, EACs have another important advantage over refrigerated systems which are associated with the ozone-layer depletion problem. A study performed at the University of Arizona [1], that compared the combined electrical and water consumption of evaporative coolers with the electrical consumption of central refrigeration air conditioners, found that the typical EAC consumed about 1500 kWh of electricity per summer, costing about $150. The cooler's water consumption added an average of $54 over the course of the summer, giving an electricity-and-water total cost of $204. By comparison, the central air conditioners consumed an average of 6000 kWh of electricity per summer costing about $600. The $400 saved annually by the evaporative cooler makes it an attractive summer air-conditioning option for hot-and-dry climates. In Sudan, air conditioning is the main electrical demand in summer which adds a large peak load to the electrical grid. According to the national electricity utility, the residential sector consumes more than 50% of the generation while the shares of industry and agriculture are only 16% and 4%, respectively [2]. Although the country has one of the fastest growing economies in Africa, its power generation is still limited and the supply is plagued by frequent blackouts and rationing measures. By minimizing the air-conditioning load, EACs have an important benefit for both consumers and the utility. EACs are the favoured residential air-conditioning systems for most of the population in Central Sudan because of their lower initial and running costs. However, the conventional EAC cannot be used during the winter season. Being at the border of the Sahara desert, the winter in Central Sudan is dry but mildly cold. Because of the low humidity level, the EAC would reduce the temperature below the comfort zone. Therefore, EACs are seldom used in winter. The technology of evaporative cooling is well established, and the published literature on the use of conventional EACs for summer air-conditioning is large [3-6], but this is not the case with their use for winter air-conditioning. An evaporative air-cooler that can be used for both summer and winter air-conditioning is the ventilator supplied by GREENHECK [7]. The system, which incorporates direct and indirect evaporative cooling modules, adds a sensible energy recovery wheel. The role of the sensible wheel is to transfer heat between the exhaust air stream and the fresh air stream. Thus, the wheel minimizes energy consumption by pre-cooling the fresh air stream in summer and pre-heating it in winter. Further heating of the out-door air in winter is provided by a post-heating module. Although the system provides a low-cost alternative to refrigerated air-conditioning, its design departs considerably from that of the simple air-cooler commonly used in Sudan.

El-Awad and Ahmed [8] conducted a laboratory test that assessed the effectiveness of a modified evaporative air-cooler for winter air-conditioning in Central Sudan. The conventional system was modified by placing a heat exchanger in the delivery duct of an ordinary 4000 ft^3/min (110 m^3/min) air-cooler. Hot water was passed through the heat exchanger. By adjusting the flow rate of the hot water, test showed that the system could bring the ambient air, initially at 20°C and 30% humidity, to a more comfortable condition of 24.4°C and 38% humidity. The present paper describes a theoretical model that is used to assess the adequacy and economic feasibility of residential-size solar water heaters for supplying the energy needed for the heating process. The model's estimates show that for air-conditioning a 500 ft^3/min air flow rate for a minimum of four hours of operation at least a 150 litres per day (LPD) is needed. The maximum air-flow rate that can be heated by a single solar water-heater is about 900 cubic feet per minute (cfm), unless a solar water heater large than a 250-LPD heater is used. For a flow rate of 500 ft^3/min, the paper shows that solar water-heaters of 150, 200 and 250 LPD can provide air-conditioning for 4, 6, 8 and 10 hours, respectively.

2. Weather condition in Central Sudan and the need for winter air-conditioning

Extending from latitude 4° to latitude 22°, Sudan has a variety of climatic conditions. Central Sudan (CS) borders the Sahara desert and, therefore, has a hot and dry climate most of the year. Table 1 shows that the climate condition passes through three main seasons, summer (March – July), autumn (July – October) and winter (November – March) [9]. As the figures on the table show, the temperature seldom falls below 20°C throughout the year while the air humidity exceeds 40% only during the rainy season. Even during the rainy season, humidity rarely reaches 70% at any hour of the day.

Table 1. Climate conditions in Central Sudan [9]

Month	Temperature				Relative humidity		Wet Days (+0.25 mm)	Average sunlight (hours)
	Average		Record					
	Min	Max	Min	Max	Am	Pm		
January	15	32	5	40	37	20	0	11
February	16	34	7	44	28	15	0	11
March	19	38	9	45	21	11	0	10
April	22	41	12	47	18	10	0	11
May	25	42	16	47	24	13	1	10
June	26	41	19	48	38	18	1	10
July	25	38	18	47	57	33	5	9
August	24	37	18	43	67	41	6	9
September	25	39	16	45	55	30	2	10
October	24	40	17	45	38	21	1	10
November	20	36	13	42	34	19	0	11
December	17	33	7	40	38	21	0	11

There is a high degree of discomfort from heat during the summer months when the day-time temperature normally exceeds 40°C. However, Central Sudan, which is the most populated part of the country, is blessed with adequate surface and underground water resources even though it lies in the semi-arid border of the Sahara. Therefore, during summer evaporative air coolers are used for air-conditioning in residential as well as commercial and government buildings. Figure 1, which shows the monthly consumption of electricity in Sudan, shows that residential air-conditioning consumes a big portion of the generated power. The rainy season from July to October moderates the ambient temperature and air humidity. Therefore, the need for air-conditioning is minimum during this season.

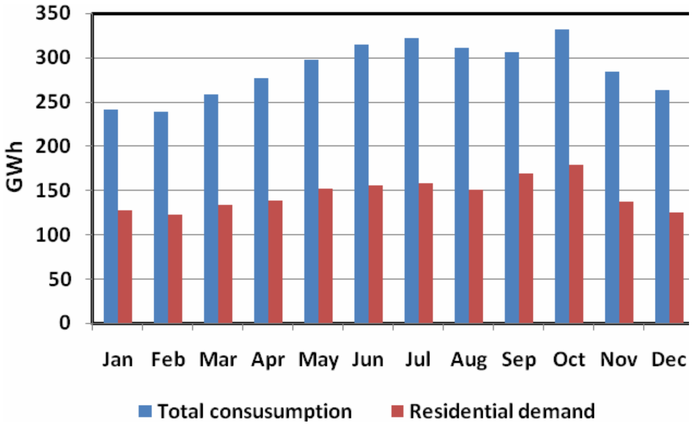
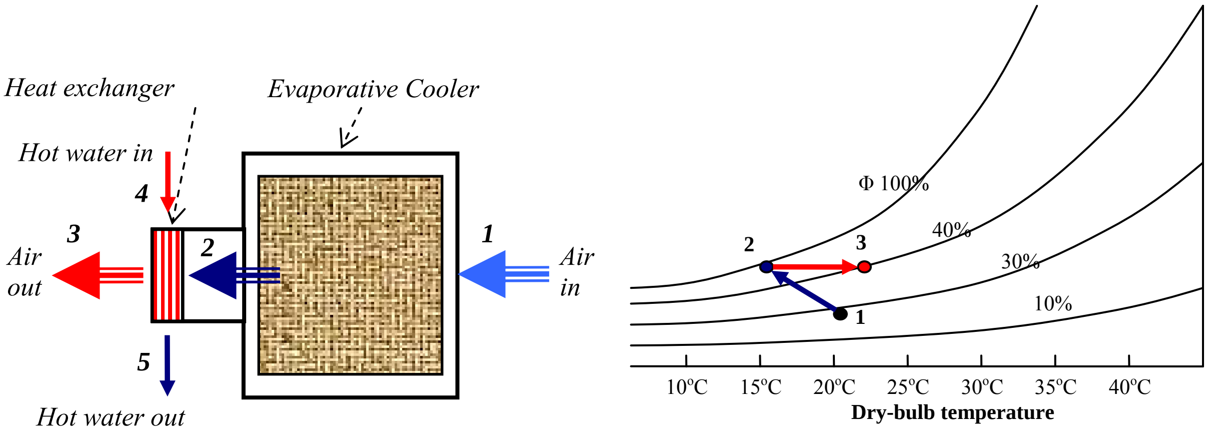


Figure 1. Annual electricity consumption in Sudan [2]

While summer air-conditioning has been a common practice for decades, this is not the case with winter air-conditioning. Although the temperature in CS seldom falls below 15°C during winter, the very low humidity level causes health problems and uncomfortable work conditions. The conventional EAC is not suitable for winter air-conditioning because it would lower the temperature to an inconvenient level. For human comfort winter air requires humidification with a slight increase in temperature. The low air humidity gives a reasonable margin for evaporative humidification even in winter. What is then required is a mild degree of heating. Figure 2a shows a schematic diagram of the proposed air-conditioning system. The system consists of a conventional EAC followed by a heat-exchanger through which passes a stream of hot water. The temperature of air that is drawn inside the air cooler by the cooler's induction fan is initially reduced by water vaporization from T_1 to T_2. Then, the air temperature is raised in the heat exchanger from T_2 to T_3 by the heat transfer from the hot water. The psychrometric chart of Figure 2b shows the humidification process (1-2) followed by the heating process (2-3).



(a) (b)

Figure 2. The evaporative winter air-conditioning system

3. Theoretical model of the system

This section describes a theoretical model that has been developed in order to study the adequacy and economic feasibility of different sizes of solar water heaters for different air flow rates. For a given air flow-rate and inlet condition, the model estimates the flow rate of hot water needed to condition the air to a predetermined temperature and humidity. The hot-water flow rate is used to estimate the time for a given hot-water heater capacity. The water flow rate and time are then used to determine the energy added and, if an electric heater is used, the cost of energy. The condition of the delivered air, as determined by the values of T_3 and Φ_3 on Figure 2, depends the air flow-rate and the amount of heat transferred to it. The amount of heat transferred to the air depends on the temperature and flow rate of the hot water through the heat exchanger. The temperature achieved by atmospheric water-heaters, whether solar powered or electric powered, is in the 70-80^{o}C range (practical consideration may dictate a lower temperature). The hot water flow rate should then be adjusted to obtain a comfortable condition.

While point 2 is determined by the humidification effectiveness of the EAC and the ambient air condition, point 3 is determined by the thermal energy that is available to the heating process. The flow rate of hot water needed for the heating process is estimated from the energy balance. Using the notation of Figure 2, and neglecting heat losses, this can be written as follows:

$$\dot{m}_{WH} C_W \left[T_3 - T_2\right] = \dot{m}_A C_A \left[T_5 - T_4\right] \tag{1}$$

where, $\dot{m}_A$ and $\dot{m}_{WH}$ refer to mass flow rates (kg/h) of air and hot water, respectively, C_A and C_W refer to the specific heats of air and water, respectively, and T refers to the temperature at different points as shown on Figure 2. Replacing the mass flow rates by volume flow rates and rearranging, (1) becomes:

$$\dot{V}_{WH} = \frac{\rho_A C_A \left[T_3 - T_2\right]}{\rho_W C_W \left[T_4 - T_5\right]} \dot{V}_A \tag{2}$$

where, ρ refers to the density (kg/m^3) and $\dot{V}$ to the volume flow rate (m^3/h).

With the exception of T_2, all quantities appearing in (2) are determined by the measurable inlet and outlet conditions of air and those of the water. The air temperature (T_2) can be obtained directly from the psychrometric chart following a constant-enthalpy line. However, in order to computerize the present model, it is calculated using the principles of psychrometry from the following equation:

$$T_2 = \left\lfloor C_A T_1 - \left(\omega_2 - \omega_1\right) h_{fg} \right\rfloor / C_A \tag{3}$$

where, ω_1, ω_2 refer to the specific humidity of inlet and outlet air, respectively, and h_{fg} is the latent heat of vaporization of water at normal atmospheric pressure. The specific humidity is calculated from [10]:

$$\omega = 0.622 \frac{P_v}{P - P_v} \tag{4}$$

where, P and P_{v} are the atmospheric pressure and the water-vapour pressure, respectively. The vapour pressure is obtained at specified dry-bulb temperature and relative humidity from:

$$P_v = \Phi P_g \tag{5}$$

where, P_{g} is the saturation pressure at the given dry-bulb temperature. The computerized model obtains P_{g} from the following relationship [10]:

$$P_g = \exp\left\{70.4346943 - \left(7362.6981/T\right) + \left(0.006952085 \times T\right) - 9.0 \times \log\left(T\right) \times 101.325\right\} \tag{6}$$

where, T in (6) is in Kelvin. The air density appearing in (2) is also calculated, using the ideal-gas equation of state, from:

$$\rho_A = P / R_A T \tag{7}$$

where, R_{A} is the gas constant of air (0.287 kJ/kg.K) and T is its temperature in absolute degrees.

The time (t), in hours, given by a water heater of a given capacity (Q) , in liters per day, is calculated from:

$$t = \frac{Q}{1000 \times \dot{V}_{WH}} \tag{8}$$

If additional heating is required, it has to be provided by the electric heater. Taking the total air-conditioning time to be t_{AC}, the cost of electricity per kWh to be C_e, then the daily cost of electricity (C) incurred by the auxiliary heater is given by:

$$C = \dot{m}_{WH} C_W \left[T_3 - T_2\right](t_{AC} - t)C_e \tag{9}$$

An estimate of the amount of water needed for humidification ($\dot{V}_{WE}$), in m^3/h, is also obtained from:

$$\dot{V}_{WE} = \rho_A \dot{V}_A \left[\omega_2 - \omega_1\right] / \rho_W \tag{10}$$

In order to computerize the theoretical model, it was entered in a Microsoft Excel sheet which estimates the water and energy consumption of the system given the air-flow rate, solar-heater capacity, air-conditioning period, hot-water inlet and outlet conditions, cost of electricity per kWh, and the energy rating of the EAC and the equivalent refrigerated system. The following values for the constants involved were used in the sheet: $\rho_W = 1000$ kg/m^3, $C_w = 2.18$ kJ/kg.K, $C_A = 1.004$ kJ/kg.K, $h_{fg} = 2442.3$ kJ/kg. In the following section, the model is used to assess the adequacy of solar water heaters of residential sizes to provide hot water for different sizes of air-coolers at variable air-conditioning periods.

4. Water consumption and adequacy of residential solar water heaters

El-Awad and Ahmed [8] conducted an experimental test to evaluate the effectiveness of the proposed air-conditioning system. The testing rig consisted of a 4000-cfm air cooler and an insulated tank that stored the hot water. A car-radiator of suitable dimensions was placed at the front opening of the air-cooler duct and used as a heat exchanger to transfer heat from the hot water to the air flow. The test was conducted at a hot-water temperature (T_{WH}) of 87°C when the ambient temperature (T_1) was 20.5°C and the relative humidity (Φ_1) was 31%. Three readings with different flow rates of the hot water were taken. Table 2 shows the dry-bulb temperature (T_3) and relative humidity (Φ_3) of the discharged air for the three readings. The table also shows the model estimations of the hot-water flow rate ($\dot{V}_{WH}$) assuming a water-discharge temperature of 21°C. For test No 1, which gave the closest condition to comfort, the model estimate for the required water flow rate is 0.298 m^3/h. This figure indicates that a 300 litre per day (LPD) solar water heater can provide enough hot water for only one hour of air-conditioning.

Table 2. The model's estimations of the water flow rate for the tests reported by [8]

Test No	T_3 °C	Φ_3 %	$\dot{V}_{WH}$ (m^3/h)
1	24.4	38.0	0.298
2	28.0	28.0	0.357
3	32.0	23.4	0.499

The model's estimates for the flow-rates of the heating water ($\dot{V}_{WE}$) and the humidification water ($\dot{V}_{WE}$) are shown on Table 3 for three sizes of air coolers available in the local market: 4000, 3000, and 2000 cfm (equivalent to 113.3, 85.0 and 56.6 m^3/min, respectively). EACs are usually made to allow operation at two speeds giving the full flow-rate (normal speed) or about half the full flow-rate (low speed). The model's estimation of the water consumption are shown on Table 3 for both speeds.The figures on the table reveal that the heating water flow rate is considerably higher than the water flow rate needed for the evaporation process. Therefore, the discharged water is too much to be directed to the cooler sink, which otherwise could have been a convenient place for it. The water, which the experiment showed that it leaves at ambient temperature, can be stored and either used for normal household needs or re-circulated to the solar heater at the appropriate time.

Table 3. Estimated rates of water consumption (l/h)

	4000 cfm		3000 cfm		2000 cfm	
	Normal speed	Low speed	Normal speed	Low speed	Normal speed	Low speed
$\dot{V}_{WH}$ (l/h)	276	138	207	104	138	69
$\dot{V}_{WE}$ (l/h)	16	8	12	6	8	4

Table 4. Estimated useful time (in hours) of residential-size solar heaters for different air flow rates

	500 cfm	1000 cfm	1500 cfm	2000 cfm
100-LPD	2.69	1.34	0.90	0.67
150-LPD	4.03	2.01	1.34	1.01
200-LPD	5.37	2.69	1.79	1.34
250-LPD	6.71	3.36	2.24	1.68
300-LPD	8.06	4.03	2.69	2.01

Table 4 shows the model's estimates for the air-conditioning time for different air flow-rates and five sizes of solar water heaters. The air flow rates are 500, 1000, 1500 and 2000 cfm (equivalent to 850, 1700, 2550, 3400 m^3/h, respectively). These air flow-rates, in respective order, are those needed for air-conditioning spaces of 28, 55, 85 and 112 m^3 [11]. The five sizes of residential solar water heaters considered are those with 100, 150, 200, 250 and 300 LPD capacities. The inlet air condition was taken as 20.5^{o}C, 31% relative humidity and the outlet air condition as 24.4^{o}C and 38% humidity, which were the values of the laboratory test no. 1 (Table 2). The figures on the Table 4 show that the 100-LPD water heater gives less than 2.7 hours of operation even with the lowest air flow-rate. If we require a minimum of four hours of operation, then the figures on Table 4 suggest that, for air-conditioning a 500-cfm air flow rate, at least a 150-LPD solar heater is needed. For the system to be useful for more than five hours of operation a 200-LPD or a 250-LPD heater is needed. The 250-LPD heater can give nearly 7 hours of operation with the 500-cfm air flow-rate, but gives less than 2 hours with the 2000-cfm air flow-rate.

The figures of Table 4 indicate that the maximum air-flow rate that can be heated by a residential-size solar water heater for about four hours of operation is about 900-cfm, unless a solar water heater larger than the 250-LPD heater is used. However, solar water heaters are expensive equipment. Typically, the 150, 200 and 250 LPD heaters cost about $400, $500 and $625 respectively [12]. Considering the high cost of solar water heaters, the initial cost of the system can be reduced by adding an auxiliary electric heater. Unlike solar water heaters, the installation costs of electric heaters are low. Depending on the cost of energy, a combined solar-electric system can be more feasible than a purely solar one. Adding an electric water heater also improves the system's flexibility since it can be used at times when the solar heater cannot produce an adequate water flow rate at the required temperature. Since the solar water heater cannot be used in the early morning hours, the auxiliary electric heater can be used to prepare the hot water in the morning. In the following section, the theoretical model is used to determine the energy consumption of a combined solar and electric heating of the water so as to assess the economic feasibility of the proposed winter air-conditioning system.

5. Energy consumption and economic feasibility

Both the initial end energy costs of a conventional EAC are considerably lower than those of an equivalent refrigerated system. However, the proposed winter air-conditioning system adds a solar water-heater and an auxiliary electric heater to the conventional EAC. Although the solar water heater does not increase the energy cost of the normal EAC, it does add a significant installation cost to the owner. On the other hand, the initial costs of electric water heaters are much lower than those of the equivalent solar heaters, but their running costs are much higher. Therefore, for the system to be economically feasible, the net saving of electrical energy cost should at least compensate for cost of the solar and electrical water heaters that are sufficient for air-conditioning a given space for a reasonable length of time. The figures on Table 1 show that Central Sudan has eleven sun-light hours during the day that can be utilized to minimize the cost of energy needed for the heating process. Unlike summer-time, there is a surplus of electricity during winter which is available for the auxiliary electric heaters (Figure 1).

The capacity of the solar heater depends on the rate of water consumption needed for the heating process, which depends on the size of the air-cooler, and the required air-conditioning duration. In what follows, the theoretical model is used to estimate the energy consumption and cost for air-conditioning a single room of 3×3×3 m^3. Based on the figures shown on Table 4, a 500-cfm air flow rate is adequate for this space. The energy consumption of a 500-cfm air-cooler is typically 0.1 kW. The energy costs of the proposed system, with a 100-LPD solar water heater, are shown on Table 5 for air-conditioning periods of 4, 6, 8 and 10 hours per day. The figures on the table show the time needed by the auxiliary electric heater, the consumption of the electric heater in kWh per day, and the total cost of electricity needed for the heating process. House owners are charged at a rate of 0.2 SDG (0.08 $) per kWh for the first 200 kWh in the month and 0.26 SDG (0.1 $) per kWh for the monthly consumption exceeding the first 200 kWh. The figures on the table use the rate of 0.26 SDG/kWh.

Table 5. Energy cost for a 500-cfm air flow rate with a 100-LPD solar heater and an auxiliary electric heater

Running time per day	4 hours	6 hours	8 hours	10 hours
Time required for electric heater (hour)	1.31	3.31	5.31	7.31
Energy consumption of electric heater (kWh)	3.75	9.46	15.16	20.87
Energy cost of electric heater (SDG)	0.97	2.46	3.94	5.43
Total energy cost of solar-assisted system (SDG)	1.08	2.61	4.15	5.69
Energy cost of equivalent refrigerated system	0.78	1.17	1.56	1.95

The additional water heating required by the system costs 0.97, 2.46, 3.94 and 5.43 SDG per day for the periods of 4, 6, 8 and 10 hours, respectively. Adding the cost of energy required by the EAC itself, the total energy costs for the 4, 6, 8 and 10 hours are 1.08, 2.61, 4.15 and 5.69 SDG per day, respectively. The corresponding refrigerated system (10,000-Btu window-type) requires 0.75 kW. For 4, 6 and 8 hours per day the energy cost is 0.78, 1.17, 1.56 and 1.95 SDG respectively. Therefore, the energy cost for the modified EAC with 100 LPD solar heater is higher than that of the refrigerated system even if used for only four hours of operation.

However, the system can save energy if a larger solar heater is used. Tables 6 and 7 show the savings of the proposed system in SDG per day for four sizes of the solar water heater; 150, 200, 250 and 300 LPD. The savings are given at electricity cost of 0.26 SDG/kWh and 0.2 SDG/kWh, respectively. The system with the 150-LPD heater saves energy with both electricity rates if run for a maximum of 4 hours per day. If run for 6 hours per day at least a 200 LPD solar heater is required to save energy. For the system to be run for 8 hours without additional energy cost, a 250 LPD heater is needed. A 300-LPD solar heater is not required unless the daily air-conditioning period approaches 8 hours or more. The figure on Table 6 and Table 7 also show that there is an optimum number of operating hours for each size of the solar heater that maximize its energy savings. The optimum number of hours for each heater size were found by using the Excel Solver. For the 150, 200, 250 and 300 LPD heaters, the estimated optimum running times are 4.03, 5.37, 6.71 and 8.06, respectively.

Table 6. Savings of the system in SDG per day for the cost of 0.26 SDG/kWh

Size (LPD)	Running hours			
	4	6	8	10
150	0.68	-0.45	-1.59	-2.74
200	0.68	0.55	-0.60	-1.74
250	0.68	1.01	0.40	-0.75
300	0.68	1.01	1.35	0.25

Table 7. Savings of the system in SDG per day for the cost of 0.20 SDG/kWh

Size (LPD)	Running hours			
	4	6	8	10
150	0.52	-0.34	-1.23	-2.11
200	0.52	0.42	-0.46	-1.34
250	0.52	0.78	0.31	-0.57
300	0.52	0.78	1.04	0.19

The 500-cfm EAC costs about $200 alone. Taking the total cost of the electric heater, heat exchanger, piping and installation at about $200, the systems costs about $800, $900 and $1025 with a 150, 200 and 250 LPD heater, respectively (based on the costs of solar water heaters given by [11]). The cost of the refrigerate-type air conditioner of equivalent capacity (10,000 Btu) is about $400. Since the installation cost of the solar-powered system is more than that of the equivalent refrigerated system by at least $400, the economic feasibility of the proposed system depends on its energy savings compared to the refrigerated system. However, it should be mentioned that the economic feasibility of the present system comes from its energy savings throughout the year and not just during winter. During summer, the EAC saves about 0.26×(0.75 – 0.1) SDG per hour, or about 1.3 SDG per day, if run for 8 hours per day. For four months of operation the EAC saves about 162 SDG ($62). Adding the saving of the proposed system with a 150-LPD heater during winter, which is about 33 SDG ($13) per season (60 days, 6 hours per day), the system saves about 195 SDG ($75) per year. These conservative figures indicate that the modified EAC can recover its additional cost in about 5 years.

Since the initial cost of a single 4000-cfm air cooler is less than that of four separate 500-cfm air-coolers, the proposed system is expected to be economically more feasible when a single 4000-cfm air cooler is used instead of separate 500-cfm units. This is particularly true if a solar water heater larger than a 250-LPD solar heater is available. Another factor that should to be taken into consideration is that the solar heater can be used so as to save energy needed for water heating almost all the year round. Assuming that only a 50% of the heater capacity per day is used for 200 days per year, the cost of energy saved by the solar heater, in US dollar, for different sizes of the heater are shown on Table 8. Electrical energy cost is taken as 0.26 SDG/kWh and 0.2 SD/kWh and fuel cost as 20 SDG/10^6 kJ and 10 SDG/10^6 kJ. The figures on the table show that, if the solar water-heater is used to replace electric heating, then the solar heater can recover its initial cost in less than a year. Even at the lowest fuel cost, the figures on the table clearly show that a good portion of the heater cost can be recovered in the first year alone.

Table 8. Annual savings ($) of water-heating cost for different sizes of solar-heaters

Cost of energy	150 LPD	200 LPD	250 LPD
Electricity at 0.26 SDG/kWh	627	836	1045
Electricity at 0.20 SDG/kWh	482	643	804
Fuel at 20 SDG/10^6 kJ	174	232	289
Fuel at 10 SDG/10^6 kJ	87	116	145

The energy consumption of the proposed system can also be minimized by proper operational arrangements of the solar and electric heating. For example, the figures on Table 1 show that humidity is higher at night than during the day time. Therefore, the humidification process may not be necessary during the night and the early morning hours, which helps to minimise the sensible heating load in this period. Switching the water pump off during this time also helps in this respect by reducing the electric energy consumption.

6. Conclusion

The proposed modification of the conventional summer air-cooler to be used for winter air-conditioning encourages the continued use of this energy-efficient system in the future. An important advantage of the proposed system is that part of the heating can be obtained by utilising solar energy. By using this clean and renewable energy source, the system also maintains the main advantage of evaporative air-coolers over refrigerated systems with regard to the environmental impact. The paper describes a theoretical model of the system that is used to assess the adequacy of residential solar water heaters and the feasibility of the system under the conditions of Central Sudan. The model's estimates show that, for air-conditioning a 500-cfm air flow rate for a minimum of four hours of operation, at least a 150-LPD solar heater is needed. For periods longer than four hours either a solar water heaters of a larger capacity or an auxiliary electric heater should be used. For the system to be used for 8 hours without additional energy cost, a 250 LPD heater is needed. At local energy costs, the optimum number of running hours for air-conditioning a 500-cfm air flow rate with 150, 200, 250 and 300 LPD heaters are 4.03, 5.37, 6.71 and 8.06 hours, respectively. At local equipment costs, the modified EAC with a 150-LPD solar heater and an auxiliary electric heater can recover its additional initial cost in about 5 years.

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References

[1] Saturn Resource Management, Inc. Retrieved February 24, 2009 from the World Wide Web: http://www.srmi.biz/Tips.Low_Cost_Cooling.Evap_coolers_cost_less_than_AC_.htm

[2] The National Electricity Corporation (NEC), Sudan, http://www.necsudan.com/data/home.php.

[3] Borofka J.L., Caron C.T., Kanz K.M., Yanovsky S.A. A comprehensive analytical study of low powered cooling in hot desert climates. University of St. Thomas, School of Engineering, St. Paul, Minnesota. Available: http://courseweb.ssthomas.edu/cmgeorge/mali-cooler/ .

[4] Roberts P. Evaporative air conditioner study, Joint project between Yarra Valley Water and Water Services Association of Australia, Available: yvw.com.au/NR/rdonlyres/823F5570-98A1-442E-BB67-63781C813576/0/EACR.

[5] Raskovic P.O., Vuckovic G.D., Vuklic M.V. Improving eco-sustainable characteristics and energy efficiency of evaporative fluid cooler via experimental and numerical study, *Thermal Science*, vol 12, no. 4, 89-103, 2008.

[6] Qureshi B.A., Zubair S.M. A comprehensive design and rating study of evaporative coolers and condensers. Part I. performance evaluation. International Journal of Refrigeration, no. 29, 645-658, 2006.

[7] GREENHECK Co. http://www.greenheck.com/pdf/energy/ HRECatalogFebruary2005.pdf .

[8] El-Awad M.M., Ahmed M.M. A Preliminary Investigation into the Use of Evaporative Air Coolers for Winter Air-Conditioning in Khartoum, the International Conference and Exhibition on Green Energy & Sustainability for Arid Regions & Mediterranean Countries (ICEGES 2009), Le Royal Hotel Amman, Amman, Jordan, November, 10-12, 2009.

[9] Sudan Embassy in Sanaa (Yemen), http://www.esudany.com/hogo.html.

[10] Cengel Y.A., Boles M.A. Thermodynamics an Engineering Approach. 4th edition. McGraw Hill, 2002. Consumer Energy Center: http://www.consumerenergycenter.org/.

[11] Consumer Energy Center: http://www.consumerenergycenter.org/.

[12] Altawfeer : http://www.altawfeer-solar.com

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