

A SOLAR-ASSISTED WINTER AIR-CONDITIONING SYSTEM FOR HOT AND DRY CLIMATES USING SUMMER AIR-COOLERS

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ABSTRACT

The paper presents an energy-efficient 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 presents a theoretical model that estimates the system's water consumption and energy needed for the heating process. Based on the results obtained, the paper shows that a 150-LPD solar heater is adequate for air-conditioning a 500 ft³/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.

INTRODUCTION

Evaporative air coolers (EACs) have considerably low energy consumption compared to refrigerated systems. A study performed at the University of Arizona, that compared the combined electrical and water consumption of evaporative coolers, also called swamp 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 [1]. The cooler's water consumption added an average of \$54 to a municipal water bill 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 the hot-and-dry climates and particularly for Sudan, which until recently had a total electricity generation of less than 2000 MW.

The current electrical generation in Sudan is about 3000 MW, half of which is produced by hydro-electric power plants.

The residential sector consumes more than 50% of the generation while the shares of industry and agriculture are only 16% and 4%, respectively [2]. Air conditioning is the main electrical demand in summer which adds a large peak load to the electrical grid and causes frequent blackouts and brownouts. By minimizing the air-conditioning load, evaporative air coolers have an important benefit for both consumers and the national electricity utility. Although refrigerated air-conditioning systems have replaced EACs in large modern buildings, EACs are likely to remain the favoured residential air-conditioning systems because of their low initial and running costs. Because they do not need any refrigerant, EACs have another important advantage over refrigerated systems which are associated with the global problem of ozone-layer depletion.

NOMENCLATURE

C	[\$/kWh]	Cost of unit energy
C_p	[kJ/kg.K]	Specific heat at constant pressure
h	[kJ/kg]	Specific enthalpy
\dot{m}	[kg/s]	Mass flow rate
P	[kPa]	Pressure
Q	[litre]	Heater capacity
R	[kJ/kg.K]	Gas constant
T	[K]	Temperature
t	[hour]	Time
\dot{V}	[m ³ /hour]	Compressor's volume displacement
Special characters		
Φ	[%]	Relative humidity
ρ	[kg/m ³]	Adiabatic efficiency of compressor
ω	[-]	Specific humidity
Subscripts		
A		Air
g		Saturation property
v		Water vapour
W		Water

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Although the technology of evaporative cooling is well established [3-6], and the published literature on the use of conventional EACs for summer air-conditioning is large, this is not the case with their use for winter air-conditioning. The nearest to the idea of using summer air-coolers for winter air-conditioning is the ventilator supplied by GREENHECK [7] which can be used for both summer and winter air-conditioning. The system, which adds heat recovery to evaporative cooling, incorporates direct and indirect evaporative cooling modules and 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 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 commonly used simple air-cooler.

El-Awad and Ahmed [8] conducted laboratory tests that assessed the effectiveness of a modified evaporative air-cooler for the mildly cold but dry winter of Khartoum. The conventional system was modified by placing a heat exchanger in the delivery duct of an ordinary 4000 ft³/min (110 m³/min) air-cooler. The tests were performed by passing hot water through the heat exchanger. By adjusting the flow rate of the hot water, tests 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 presents a theoretical model that is used to assess the adequacy of residential-size solar water heaters for supplying the energy needed for the heating process. Based on the results obtained, the paper shows that for air-conditioning a 500 ft³/min air flow rate for a minimum of four hours of operation at least a 150 litres per day (LPD) solar heater is needed. The maximum air-flow rate that can be heated by a single solar water-heater is about 900-cfm, unless a solar water heater large than a 250-LPD heater is used.

CLIMATE AND WINTER AIR-CONDITIONING REQUIREMENTS IN KHARTOUM

Composed of three towns that embrace the banks of the Blue Nile, the White Nile, and the main River Nile, Greater Khartoum (GK) is the most populated city in Sudan. Being at the border of the Sahara desert, GK has a hot and dry climate most of the year. Table 1 shows that the climate condition in GK area 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 and the air humidity does not exceed 40% except during the rainy season. Even during then, humidity rarely reaches 70% at any hour of the day. There is a high degree of discomfort from heat during the summer months when the day-time temperature normally exceeds 40°C. The rainy season from July to October moderates the ambient temperature and, as air humidity is also moderate, air-conditioning is seldom required during this season.

Table 1: Climate conditions in Khartoum [9]

Month	Temperature				Relative humidity		Wet Days (+0.25 mm)	Average sunlight (hours)
	Average		Record		am	pm		
	Min	Max	Min	Max				
Jan	15	32	5	40	37	20	0	11
Feb	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
Aug	24	37	18	43	67	41	6	9
Sept	25	39	16	45	55	30	2	10
Oct	24	40	17	45	38	21	1	10
Nov	20	36	13	42	34	19	0	11
Dec	17	33	7	40	38	21	0	11

Because of its unique location, GK is blessed with adequate 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. EACs have been an effective air-conditioning method, which also suited the limited electricity generation capacity of the country. While summer air-conditioning has been a common practice for GK residents for decades, this is not the case with winter air-conditioning. Although the temperature in GK seldom falls below 15°C during winter, the very low level causes health problems and uncomfortable work conditions. However, low income and habit pushed winter air-conditioning to a low-priority need. The recent availability of electricity from hydro-power and the increase in per capita income are bound to make winter air-conditioning a common practice.

While the cost of energy of a refrigerated air-conditioner, which can be used for both winter and summer air-conditioning, is much higher than can be afforded by the majority low-income families, the conventional EAC is not suitable for winter air-conditioning because it would lower the temperature to an inconvenient level. For human comfort the winter air requires a slight increase in temperature coupled with some humidification. The low air humidity gives a reasonable margin for evaporative humidification even in winter. What is then required is a mild degree of heating. The psychrometric chart of Figure 1, which shows the condition of ambient air as point 1 and the targeted room condition as point 3, shows a humidification process followed by a heating process.

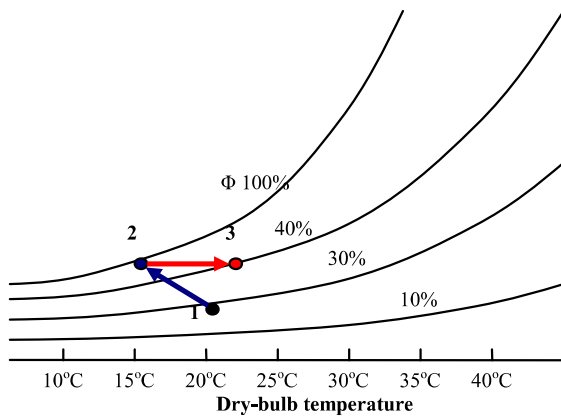


Figure 1 The winter air conditioning process.

THE EVAPORATIVE WINTER AIR-CONDITIONING SYSTEM

Fig. 2 shows a schematic diagram of the proposed air-conditioning system. The system consists of a conventional evaporative air cooler 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. Table 1 shows that there are eleven sun-light hours during the day which can be utilized to minimize the cost of energy needed for the heating process. An auxiliary electric water heater is needed when the solar-heated water quantity is not adequate.

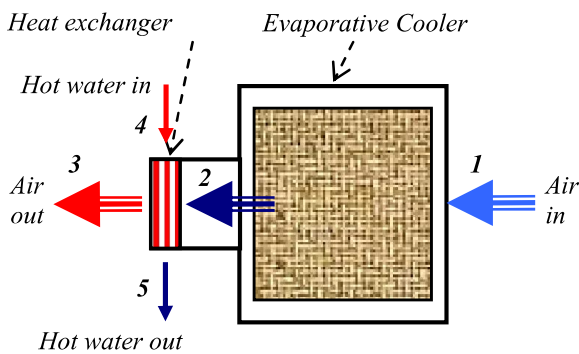


Figure 2 The evaporative winter air-conditioning system.

Fig 3 shows the residential and the total monthly consumption of electricity in Sudan. Unlike summer-time, there is a surplus of electricity during winter which is available for the heating process. The degree of comfort, as determined by the values of T_3 and Φ_3 on Fig. 1 and Fig 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°C range. 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 can be made available to the heating part of the process. If the sole source of energy for the heating part is solar energy, then point 3 would be determined by the capacity of the solar water heater.

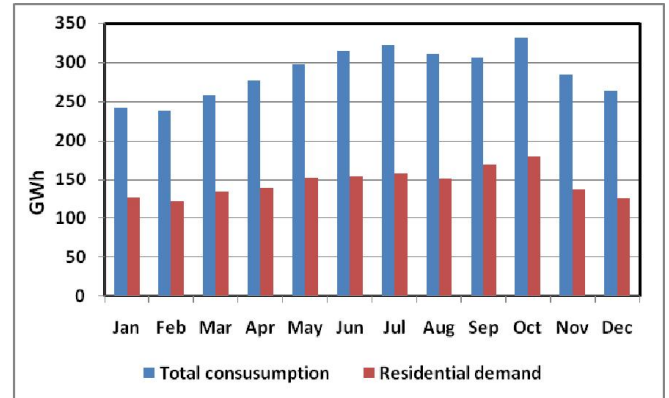


Figure 3 Annual electricity consumption in Sudan [2].

Although the addition of a 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 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. Air coolers and solar water heaters of different capacities exist in the local market. The commonly used air coolers have air-flow rates ranging from 2000 to 4000 cubic feet per minute (cfm). The capacities of residential solar water heaters range from 50 to 300 liter per day. The present work aims to determine the economically feasible combination of solar and electric heating for a given air flow rate taking into consideration the cost of energy fixed by the local utility

THE SYSTEM SIMULATION MODEL

A theoretical model of the system has been developed in order to study the adequacy and economic feasibility of different sizes of solar water heaters for different air flow rates, while avoiding the limitations and cost of the experimental tests. 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 then used to estimate the time for a given hot-water heater capacity. The flow rate of hot water needed for the heating process is estimated from the energy balance. Using the

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notation of Fig. 2, and neglecting heat losses, this can be written as follows:

$$\dot{m}_{WH} C_{pW} [T_3 - T_2] = \dot{m}_A C_{pA} [T_5 - T_4] \quad (1)$$

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

$$\dot{V}_{WH} = \frac{\rho_A C_{pA} [T_3 - T_2]}{\rho_W C_{pW} [T_4 - T_5]} \dot{V}_A \quad (2)$$

where, ρ refers to the density (kg/m³) and \dot{V} to the volume flow rate (m³/h).

With the exception of T_2 , all quantities appearing in (2) are determined by the known inlet and outlet conditions of air and those of the water. The air temperature (T_2) can be obtained directly from the psychrometric chart (Fig. 2) 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:

$$T_2 = [C_{pA} T_1 - (\omega_2 - \omega_1) h_{fg}] / C_{pA} \quad (3)$$

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]:

$$\omega = 0.622 \frac{P_v}{P - P_v} \quad (4)$$

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:

$$P_v = \Phi P_g \quad (5)$$

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

$$P_g = \exp\{70.4346943 - (7362.6981/T) + (0.006952085 * T) - 9.0 * \log(T)\} * 101.325 \quad (6)$$

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

$$\rho_A = P / R_A T \quad (7)$$

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:

$$t = \frac{Q}{1000 \times \dot{V}_{WH}} \quad (8)$$

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:

$$C = \dot{m}_{WH} C_{pW} [T_3 - T_2] (t_{AC} - t) C_e \quad (9)$$

An estimate of the amount of water needed for humidification (\dot{V}_{WE}), in m³/h, is also obtained from:

$$\dot{V}_{WE} = \rho_A \dot{V}_A [\omega_2 - \omega_1] / \rho_W \quad (10)$$

In order to computerize the present 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/m³, $C_{pW} = 2.18$ kJ/kg.K, $C_{pA} = 1.004$ kJ/kg.K, $h_{fg} = 2442.3$ kJ/kg. Using the sheet with the values of T_1 , Φ_1 , T_3 , Φ_3 as in the laboratory test reported by El-Awad and Ahmed [8] in which T_1 , Φ_1 , T_3 , and Φ_3 were 20.5°C, 31%, 24.4°C and 38% respectively, the model's estimates of ω_1 , ω_2 and T_2 are 0.0046, 0.0072, and 14.3°C, respectively. These estimates compare well with the respective values reported by El-Awad and Ahmed [8].

WATER CONSUMPTION AND ADEQUACY OF RESIDENTIAL SOLAR HEATERS

The model's estimates for the flow-rates of the heating water (\dot{V}_{WH}) and the humidification water (\dot{V}_{WE}) are shown on Table 2 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 m³/min, respectively). 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 used for normal household needs.

Table 2 Estimated rates of water consumption (l/h)

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

It should be mentioned that the model's estimate of the heating water flow rate for the 4000-cfm air cooler at low speed, which is 138 l/h, is higher than the 87 l/h flow rate measured in the experiment by almost 60%. Table 3 shows the model estimates for the air-conditioning time for different air flow-rates and different sizes of solar water heaters. The air flow rates are 500, 1000, 1500 and 2000 cfm (equivalent to 850, 1700, 2550, 3400 m³/h, respectively). These air flow-rates, in respective order, are those needed for air-conditioning spaces of 28, 55, 85 and 112 m³ [11]. Four sizes of residential solar water heaters are considered with 100, 150, 200, 250 and 300 LPD capacities. The inlet air condition is taken as 20.5°C, 31% relative humidity and the outlet air condition as 24.4°C and 38% humidity, which are the values of the laboratory test reported by El-Awad and Ahmed [8].

Table 3 Estimated useful time for solar heaters in hours

	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

The figures on the Table 3 show that the 100-LPD water heater gives less than 2.7 hours of operation even with the smallest air flow-rate. If we require a minimum of four hours of operation, then the figures on Table 3 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. Although the 250-LPD heater can give nearly 7 hours of air-conditioning with the 500-cfm air flow-rate, it can give less than 2 hours with the 2000-cfm air flow-rate. The figures also show that the maximum air-flow rate that can be heated by solar energy is about 900-cfm, unless a solar water heater large than the 250-LPD heater is used.

Considering the high cost of solar water heaters, the cost-effectiveness of the system can be improved 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.

CONCLUDING REMARKS

By modifying the conventional summer air-cooler to be used for winter air-conditioning, the proposed system encourages the continued use of the energy-efficient air-coolers in the future. An important advantage of the proposed system is that part of

the heating, if not all, is 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. Existing EACs can be easily converted for winter air-conditioning use by adding a solar water heater and a heat exchanger. Conversion is technically simple and can be undertaken by the technicians of local workshops. The previous laboratory tests [8] demonstrated the ability of the proposed system to bring the condition of winter air to a comfortable state. However, the present study showed that the system requires an auxiliary electric heater to provide air-conditioning for more than four hours with a residential-size solar water heater. Therefore, for the system to be economically feasible, its energy saving compared to an equivalent refrigerated system must outweigh the additional installation costs.

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