



COMPUTER SIMULATION OF SOLAR COOLED BUILDINGS IN KHARTOUM

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ABSTRACT

The transient state heat transfer formulation has been used to determine the air conditioning cooling load for two selected one room buildings in Khartoum: one made from brickwork and the other from wood. This formulation has been achieved by applying an explicit finite difference numerical techniques and adopting thermal network of electrical analogy to solve the transient conduction heat transfer equations. A computer program was developed to analyse the thermal network and to determine the cooling load for the wall, roof, window, ventilation and the total cooling load for each building for a typical hot summer day in Khartoum.

A solar cooling system comprising mainly of a flat plate solar collector, a Lithium Bromide-Water absorption air conditioner, a storage and auxiliary tanks was integrated in the building and the energy equation for each component was obtained. A general simulation program for the solar cooled buildings has been developed and it was found that about 65% of the total cooling load demanded by the brick building could be supplied by energy from the solar collector, the other 35% portion had to be met by the auxiliary tank compared with 70% of the total cooling load demanded by the wood building which could be supplied by energy from the solar collector.

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KEYWORDS

Explicit; numerical; simulation; solar cooling; transient.

INTRODUCTION

The transient thermal response of buildings to variable solar radiation intensities and different outdoor temperatures produces the thermal storage effect of the structure. Usually, this effect is not taken into account when calculating the air conditioning cooling and heating loads. Therefore, only quick but approximate value of load is given and this could lead to an appreciable error in energy estimates even for small commercial buildings. In the present work, the transient conduction heat transfer is solved by using an explicit finite difference numerical techniques since it is easy to formulate and the solution for the unknown quantity can be directly given (Welty, 1974; Lienhard, 1981). Two buildings were selected to compare the transient and the steady state air conditioning cooling loads and also to act as an integral part of a solar cooling system. The buildings under theoretical tests were chosen as small offices (4mx4mx4m) and all walls were assumed being exposed to the

external weather. All walls for one office were made of common brick (22 cm thick), the roof and floor were made of concrete slab (10 cm each) with addition of 10 cm screed layer for the roof to minimise the heat gain. The (1.5 m x 1.5 m) window was made of a single clear glass and the effect of the door was neglected. The walls and the roof of the other building were made of wood, while the window and the floor were similar to those used in the first office. The conduction path of all structure of the two buildings was approximated by a lumped parameter network which gives a finite difference approximation to the one dimensional transient partial differential equations of conduction heat transfer. This finite difference approximation could be obtained by using either mathematical or physical (heat balance) approach. The latter approach was chosen since it is flexible and can easily accommodate any heat transfer complications such as variable heat transfer properties, internal heat generation, different node sizes and shapes plus heat transfer by convection and radiation.

Operation of absorption air conditioners with energy supplied from flat plate collector and storage tank system is the most common approach to solar cooling (Butz *et al.*, 1974; Winn *et al.*, 1974). In this work, the main components of the solar cooling system for the building are the solar collector, the storage tank, an auxiliary heated tank, a LiBr-H₂O absorption air conditioner and the building itself. A general simulation program for the solar cooled buildings was developed by modelling each component of the cooling system and theoretical results were obtained. The results were discussed and some important conclusions were drawn.

THEORETICAL ANALYSIS

The theoretical analysis is shown in the appendix.

RESULTS AND DISCUSSION

The cooling load profiles for the different walls, roof, window, ventilation and the total cooling load for the brick building are shown in Fig (1) and Fig (2). Since the initial temperatures of the building structure nodes of the thermal network were assumed based on steady state heat transfer, it was expected that some errors would arise from this assumption. To make these errors quite negligible, the programmes calculating the cooling load were run for a period of three days using the same data and it is clear that from Fig (1) and Fig (2) that the results of the second and third days are similar. From Fig. (1), it is clear that the roof of the brick building gives the maximum cooling load as compared to other surfaces since the roof has relatively higher sol-air temperatures. The maximum transient total cooling load for the brick building was 5.5 kW compared to 8.2 kW using steady state calculations. Therefore a decrease of almost 33% can be noticed. Also, the maximum transient total cooling load for the wood building was 7.2 kW compared to 8.6 kW using steady state formulation which marked a decrease of 16%. So, the decrease of the transient cooling load was almost twice in the brick building as compared to that of the wood building. This reflects clearly that the thicker the wall, the heat storage effect will be more pronounced and therefore affects the total cooling load appreciably. The variation of inside air temperature with time is shown in Fig (3) and Fig (4) for the brick and wood buildings respectively. It can be seen that sharp and abrupt fluctuations occur at certain time steps. The main reasons for these fluctuations could be discussed as follows: The inside building temperature, T_b , is described by equation (10) and it is a function of three distinct terms. The first term gives the amount of heat supplied by either the storage or auxiliary tank, the second term is the instantaneous heat gain or loss from the building while the third term gives the amount of cooling introduced to the building from the absorption air conditioner utilising either the heat coming from the storage or auxiliary tanks. If T_b is above 22.5 °C and below 25 °C, the control function governing the cooling term, F_3 , would be set to zero, so the building temperature is only a function of the total cooling load and the instantaneous heat gain. If the cooling load is increased, the inside temperature of the building would increase and vice versa. Therefore, a sharp and unpredictable fluctuations in T_b could happen. If T_b was above 25 °C, the cooling term would be activated and here some kind of a simple property control system was simulated in the program for the cooling term. This was achieved by setting the mass flow rate of the fresh air passing through the cooling coil of absorption air conditioner to be proportional to the outside

ambient air temperature and the result proved to be quite good. From Fig (3) and Fig (4), it could be noticed that the variation of inside air temperatures with time for both buildings is quite acceptable and lie within the thermal comfort zone of the psychrometric chart.

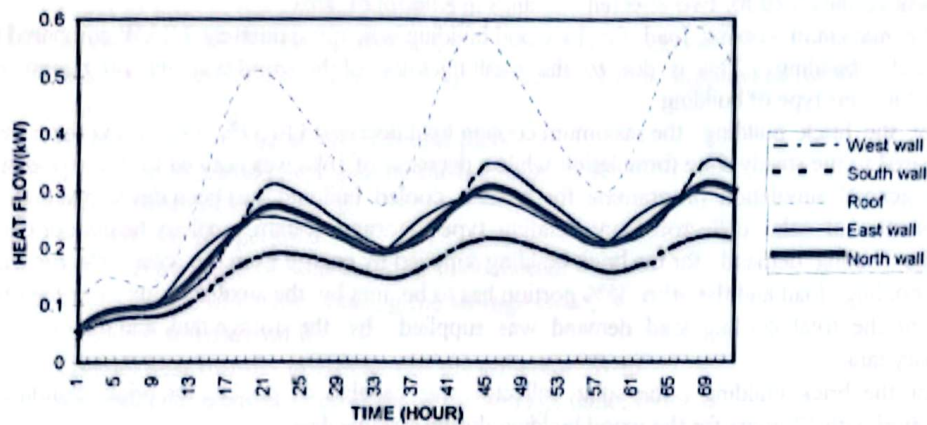


Fig.(1) Cooling load profiles for walls and roof (brick building)

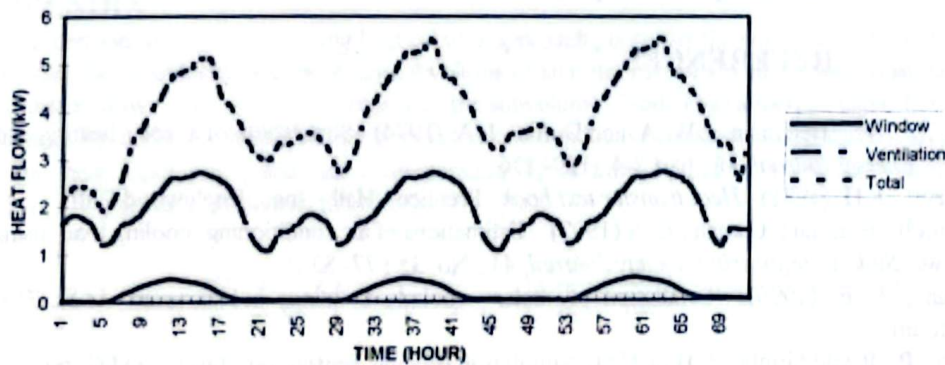


Fig. (2) Cooling load profiles for window, ventilation and total cooling load (brick building)

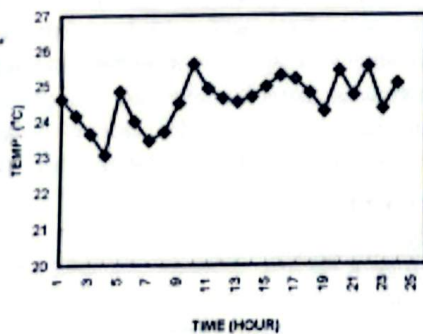


Fig. (3) Variation of inside air temperature with time (brick building)

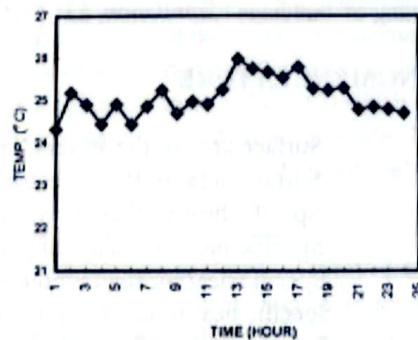


Fig. (4) Variation of inside air temperature with time (wood building)

CONCLUSIONS

- 1- An explicit numerical technique utilising thermal network of electrical analogy was used to calculate the transient cooling load for two selected buildings in Khartoum area.
- 2- The maximum cooling load for the wood building was approximately 7.2 kW compared to only 5.5 kW for the brick building. This is due to the small thickness of the wood building and therefore inside insulation is needed for this type of building.
- 3- For the brick building, the maximum cooling load decreased to 33% when using the transient formulation as compared to the steady state formulation while a decrease of 16% was noticed for the wood building.
- 4- A general simulation programme for a solar cooled building has been developed and can be used for any combination of solar collectors, any building type, storage system, auxiliary heating or cooling system.
- 5- The cooling demand for the brick building supplied by energy from the solar collector was about 65% of the total cooling load and the other 35% portion has to be met by the auxiliary tank. For the other wood building, 70% of the total cooling load demand was supplied by the storage tank and the other 30% was met by the auxiliary tank.
- 6- For the brick building, the solar collector was capable of cooling the brick building for about 11 hours compared with 12 hours for the wood building during a single day.
- 7- The maximum fluctuation for the inside air temperature for both brick and wood buildings was 1.5°C and the fluctuations during any single time step was less than 0.5°C.

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NOMENCLATURE

A_s	Surface area of the storage tank, m^2
A_c	Surface area of the collector, m^2
C_{pa}	Specific heat of fluid in the auxiliary tank, $kJ/kg K$
C_{pf}	Specific heat of fluid in the collector, $kJ/kg K$
C_{ps}	Specific heat of fluid in the storage tank, $kJ/kg K$
C_{pb}	Specific heat of air within the building, $kJ/kg K$
F_R	Solar collector efficiency
$F, F1, F2, F3, F4, F5$	Control functions
H	Solar radiation intensity incident on the plane of the collector, W/m^2

m_f	Mass of fluid in the collector , kg
m_s	Mass of fluid in the storage tank , kg
m_b	Mass of air within the building , kg
m_A	Mass of fluid in the auxiliary tank , kg
M_a	Mass flow rate of fresh air through the cooling coil , kg/sec
M_s	Mass flow rate of hot water in storage or auxiliary tank supplied to the air conditioner , kg/sec
Q_A	Heat supplied by the auxiliary heater , kW
Q_{TOT}	Total instantaneous heat gain by the building , kW
T_{ij}	Temperature of node ij , °C
T_a	Ambient air temperature , °C
T_i	Inlet temperature of fluid entering the collector , °C
T_s	Temperature of air surrounding the storage tank , °C
T_{amb}	Ambient air temperature , °C
U_c	Overall heat transfer coefficient of the collector , W/m ²
U_s	Overall heat transfer coefficient of the storage tank , W/m ²
ΔT_{HE}	Design temperature drop through the air conditioner , °C

APPENDIX

To apply an explicit method in practice , using heat balance approach , consider the nodal subvolume of Fig. (A1). This element can be considered as an arbitrary subvolume of an outer part of a building wall. Assume one dimensional heat transfer flow and node i to represent the subvolume . Node i has a thermal capacity C_i and connected by resistances R_{q1} and R_{q2} which stand for convective and conductive resistances respectively. If node i is exposed to a solar heat input , q_i , and has a temperature T_i^t at time t , then for a time interval Δt , the temperature of node i ($T_i^{t+\Delta t}$) could be shown as follows :

$$T_i^{t+\Delta t} = \frac{\Delta t}{C_i} \left[q_i + \frac{T_{q1}^t}{R_{q1}} + \frac{T_{q2}^t}{R_{q2}} - T_i^t \left(\frac{1}{R_{q1}} + \frac{1}{R_{q2}} \right) \right] + T_i^t \quad (1)$$

If node i is connected to n number of nodes , then equation (1) becomes :

$$T_i^{t+\Delta t} = \frac{\Delta t}{C_i} \left[q_i + \sum_{j=1}^n \frac{T_j^t}{R_{ij}} - T_i^t \left(\sum_{j=1}^n \frac{1}{R_{ij}} \right) \right] + T_i^t \quad (2)$$

The explicit method was used to solve the transient response of the two buildings and the network approach of electrical analogy was adopted . The errors expected in the calculated results , when using this method , is not more than $\pm 5\%$. The conduction path of the four walls , roof , and floor were approximated by a lumped parameter network which gives a finite difference approximation to the partial differential equations concerned . A complete view of the thermal network of the whole brick building is shown in Fig. (A2) which consists of eight parallel circuits ; all of which terminate at node (36) which represents the inside room air node . For more details of the thermal network of the buildings , the reader is referred to (Osman , 1996 ; Magzoub and Osman , 1997).

The following variables are used to solve the thermal network : Ambient air temperatures , thermal resistances and thermal capacitances and sol - air temperatures . The air conditioning cooling load is calculated by evaluating the following items : Direct solar radiation through windows , heat transmission through structure , internal heat gains , infiltration and ventilation . The loads are evaluated by determining the nodal temperature at each time step . Figure(A3) shows a schematic diagram of the solar cooling system and the different component of this system was modelled as follows :

The solar collector was modelled in a manner proposed by Whiller and Hottel (1955) in which the useful heat gained by the collector , Q_u , is given by :

$$Q_s = F_R A_c (H - U_L (T_i - T_a)) \quad (3)$$

The tilt angle is set to be equal to the latitude and taken as 15 °N, which is the latitude of Khartoum. When the collector fluid outlet temperature, T_o , is less than the storage tank temperature, T_s , there will be no flow of fluid through the collector and as a control function F is set equal to zero. Then, the temperature of the fluid in the solar collector is given by the solution of the following energy equation

$$m_c C_{pf} \frac{dT_o(t)}{dt} = A_c H - A_c U_L (T_o - T_a) \quad (4)$$

It is assumed that when T_o is greater than T_s by a prescribed amount, ϵ , then the collector pump was set into action and as a control function $F = 1$ and the amount of useful energy delivered to the storage tank, Q_s , is given by equation (3). When the pump is in work, the temperature of the fluid entering the collector is assumed equal to the temperature of the storage tank and the outlet temperature of the collector, T_o , is:

$$T_o(t) = T_s + \frac{Q_s(t)}{m_s C_{pf}} \quad (5)$$

Smith and Gupta (1975) gave the following energy equation for the storage tank:

$$m_s C_{ps} \frac{dT_s(t)}{dt} = F Q_s(t) - F_1 (M_s C_{ps} \Delta T_{HX} + U_s A_s (T_s(t) - T_a)) \quad (6)$$

The energy equation for the auxiliary tank is given by:

$$m_a C_{pa} \frac{dT_a(t)}{dt} = F_2 (Q_s - M_s C_{ps} \Delta T_{HX}) \quad (7)$$

A lithium bromide - water absorption air conditioner with a coefficient of performance of 0.65 was selected. The total load on the cooling coil was modelled by simply multiplying the energy transferred from either the storage or the auxiliary tank to the absorption machine by 0.65 so,

$$\text{the cooling coil load} = 0.65 (F_1 + F_2) M_s C_{ps} \Delta T_{HX} \quad (8)$$

By neglecting ducting and fan power gains, the building heat gain was obtained by subtracting the fresh air load, $M_a \Delta h$, from the total cooling coil load so,

Q - heat gained by building =

$$0.65 (F_1 + F_2) M_s C_{ps} \Delta T_{HX} - M_a \Delta h \quad (9)$$

The energy balance of the building accounts for the heat supplied by either the storage or the auxiliary tank, the instantaneous heat gain or loss from the building and the cooling load supplied by the absorption air conditioner. Therefore, the energy equation for the building takes the form:

$$m_b C_{pb} \frac{dT_b(t)}{dt} = (F_1 + F_2) M_s C_{ps} \Delta T_{HX} + Q_{TOT} - F_1 (0.65 (F_1 + F_2) M_s C_{ps} \Delta T_{HX} - M_a \Delta h) \quad (10)$$

The inner node temperature of the building was assumed to be kept within a comfortable range 22.5 to 25°C. The energy equation for each component was integrated. The coefficients and control functions were assumed constant over the time step during which the integration were taking place. At the end of the integration period, the coefficients were recalculated and the control functions were reset for the next period of integration.

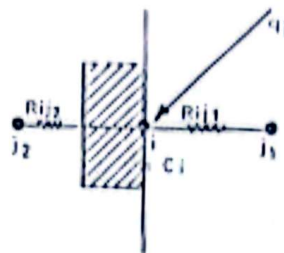


Fig. (A1) Illustration of heat balance approach

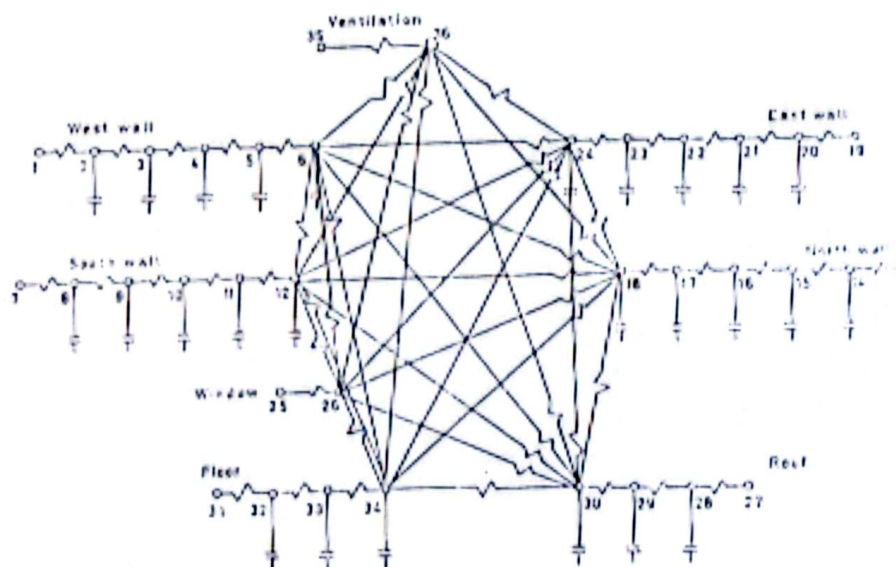


Fig. (A2) Brick building thermal network

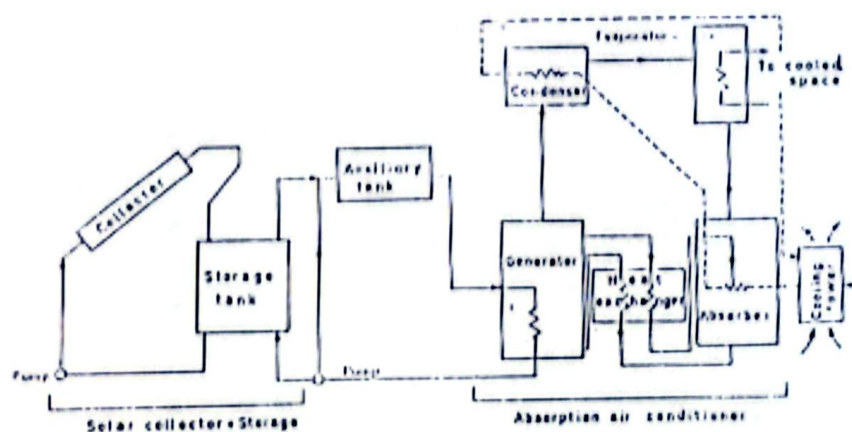


Fig. (A3) Schematic of a solar operated absorption air conditioner