Solar powered absorption cooling systems for Southern Africa

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This project was concerned with establishing the technical and economic effectiveness of solar powered absorption cooling systems for Southern African climatic conditions. Solar cooling systems consist of a solar collector array, water storage tank, absorption chiller and cooling tower for heat rejection. In this study, a complete system utilising solar energy without an auxilliary boiler was designed and optimised.

South Africa has experienced a significant growth in middle-to-high income families in the last decade. With these larger incomes came increased demands for indoor air quality, thermal comfort and consequently increased peak cooling loads during summer months. Added to this, prevailing electricity shortages and ever increasing energy prices, there is now an increased need for cooling systems using working cycles driven by renewable energy such as solar, wind, geothermal or biogas, while at the same time having minimum impact on the environment. Solar energy in particular, had potential to supply a sizeable percentage of the cooling energy demand as solar radiation levels in South Africa were among the world's highest. Most of South Africa's interior receives average insolation, in excess of 5 kWh/m^2/day, with some parts of the Northern Cape averaging 6 kWh/m^2/day [1]. In general, solar cooling was an attractive idea since the cooling loads and availability of solar energy were roughly in place.

The preferred type of thermally driven technology to produce chilled water is absorption cooling. The system, which has simple capacity control, mechanism, easy implementation, high reliability, silent operation, long life and low maintenance cost is a candidate for efficient and economic use of solar energy for cooling applications. In comparison to vapour compression systems, absorption chillers use low temperature thermal energy from the sun. The basic physical process in an absorption system consists of at least two chemical components, one serving as a refrigerant, and another as an absorbent. For air-conditioning applications, absorption systems commonly use lithium bromide-water or ammonia-water working pairs. LiBr-water absorption units are most appropriate for solar applications as low cost solar collectors may be used to power the generator. The NH$_3$-water machine requires high generator temperatures in the range 125 – 170ºC [2], which necessitates the use of medium concentration ratio parabolic collectors, whereas the LiBr-water machines require a temperature in the range 75 – 120ºC, which is easily achieved using flat plate or evacuated tube collectors. The LiBr-water machine has a higher coefficient of performance (COP) than the NH3- water and is cheaper [3, 4]. This is because the NH3-water machine requires a rectifier to prevent water vapour entering its evaporator.

The country seeks to achieve a 15% renewable contribution to the energy mix within the decade. In spite of this, almost the research and development effort concerning solar energy has concentrated on provision of solar domestic water heating and little work done in regards of solar cooling systems. Based on current technologies, market available thermally driven cooling devices and solar collectors, solar air conditioning can lead to significant primary energy savings [5].

The future of solar cooling methods depends on development beyond the cooling process itself. A complete cooling system comprised of a solar collector, storage tank, cooling tower, a LiBr-water absorption system and distribution pumps and controllers was designed, optimised and its technical and economic performance analysed. There are many solar collectors utilised in cooling applications, flat plate, evacuated tube and compound parabolic collectors. In this study a comparison was made between a system using flat plate collectors and another using utilising evacuated tube collectors. The high price of compound parabolic collectors excluded them from the study. The relationships between the various parameters such as solar collector type and array size, storage tank volume and installation and operational costs with system performance were investigated. The system will be constructed and its actual performance verified with the theoretical projections and necessary recommendations made regarding the domestic and or commercial applications of solar absorption cooling systems.

Methodology

The steps taken in this study were as suggested by Tsoutsos et al [6], and are given as:

Collection of the required meteorological data: meteorological data for Durban was used. A typical meteorological year (TMY) was created and the hourly, monthly and annual values of solar radiation, humidity, wind speed and temperature processed.

Cooling load calculation: A suitable building was chosen, and its construction characteristics, desired indoor conditions, together with the weather data were used to come up with a load profile.Use of the building was considered as it significantly contribute to building cooling load.

Design and sizing of the solar absorption cooling system: Using the weather data, and the selected design conditions, the collector, hot water storage tank, absorption chiller and cooling tower could be sized. The appropriate control strategy was chosen and the requisite pumps selected.

Optimisation of the system: The aim was to use least cost energy so the designed system was optimised with that in mind.

Material procurement and construction of the experimental system: Once the system had been optimised, the components were procured and the system was constructed and simulation results validated.

Performance evaluation and economic analysis: The energetic and economical effectiveness of the system was evaluated. The life cycle costs for solar cooling system were calculated and competitiveness with regards to price and thermal efficiency for domestic applications determined.

Analysis of results and making of recommendations: The results were analysed and necessary improvements recommended. A decision was made on whether solar absorption cooling was a viable option for southern Africa climatic conditions. Options for improving technical effectiveness and economic competitiveness were suggested. The costs of the system were compared to average family incomes. Ways of improving research and development efforts in this field were also investigated.

Software description

The TRNSYS simulation software was used for the design and simulation study of the system. This is a quasi-steady, complete and extensible simulation environment

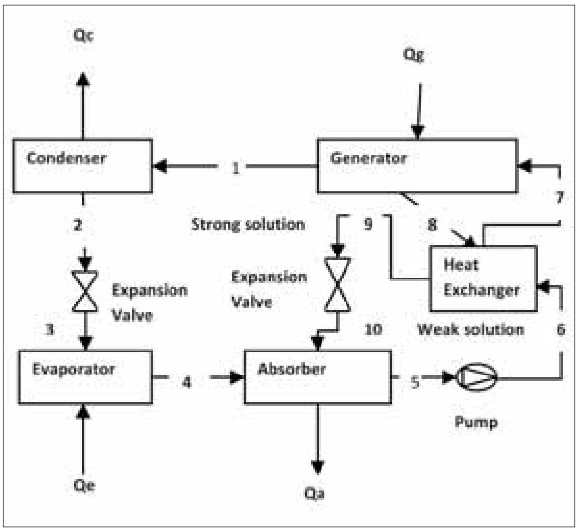

Fig. 1: LiBr-water absorption cycle.

for the transient simulation of systems, including multi-zone buildings developed by the University of Wisconsin. TRNSYS allows one to validate new energy concepts from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behaviour, alternative energy systems wind, solar, PV, hydrogen systems, etc. [7]. The system provides flexibility in solar design and may be used to analyse combinations of different energy systems. In addition, TRNSYS can be easily connected to many other applications, for pre- or post-processing, or through interactive calls during the simulation (e.g. Microsoft Excel, MatLab, COMIS, etc.) [7].

System description

The Solar energy is received by a solar collector and stored in hot water storage tank. The water is then is supplied to the absorption chiller generator to boil off water vapour from a weak LiBr solution at high pressure. The water vapour is passed to the condenser where heat is removed and the vapour cools then to form a liquid. The water at high pressure is passed through an expansion valve and its pressure is reduced on the way to the evaporator. In the evaporator the water is turned into vapour thus providing cooling to the required space. The water vapour is then passed into an absorber and is absorbed by the strong LiBr solution to form a weak solution. The weak solution is preheated by pumping it through the solution heat exchanger, where it exchanges heat with the strong solution leaving the generator.

In the generator the weak solution is separated by the heat emanating from the storage tank and the process is repeated. The heat produced from the condensation and mixing is removed from the system by water from a cooling tower. Since the temperature of the absorber has a greater influence on the efficiency of the system than condensing temperature, the cooling water, is allowed to first flow through the absorber, then to the condenser [8].

To accurately predict the performance of a thermal system that makes use of an absorption chiller, a mathematical model was needed that described the operation of the chiller components. The model used was a steady state suggested by Grossman and Michelson, 1985 as cited by [9]. The structure of the model was:

- A main mass balance is applied to the entire cycle, expressing the conservation of the refrigerant and of the salt.
- Each component of the chiller is modelled with a set of equations representing the energy balances of the internal and external stream, and heat transfer equations.
- The thermo-physical properties of the working fluids are needed to complete the model.

The following assumptions are made in development of the model:

- There are steady state conditions.
- Pressure drops and heat losses in components and tubes are negligible.
- The pump is isentropic.
- Expansion valves are adiabatic.
- There is saturated refrigerant at condenser and evaporator outlets.
- A saturated solution leaves the absorber and generator.

To implement the cycle analysis, mass and energy balance must be performed for each component. Where: x_w is the weak solution concentration, x_s is the strong solution concentration, *m* is the mass flow rate, *Q* is the heat transfer rate, x_s is the efficiency of solution heat exchanger and *h* is the enthalpy.

$$x_5 + x_6 + x_7 = x_w \qquad (1)$$

$$x_8 + x_9 + x_{10} = x_s \qquad (2$$

At the absorber:

$$\dot{m}_4 + \dot{m}_{10} = \dot{m}_5 \qquad (3)$$

$$\dot{m}_5\, x_5 = \dot{m}_{10} x_{10} \qquad (4)$$

The energy balance is given as:

$$Q_a = \dot{m}_4 h_4 + \dot{m}_{10} h_{10} - \dot{m}_5\, h_5 \qquad (5)$$

At the generator:

$$\dot{m}_7 = \dot{m}_1 + \dot{m}_9 \qquad (6)$$
$$(Total\ mass\ balance)$$

$$m_7\, x_7 = m_9\, x_9 \qquad (7)$$
$$(LiBr\ balance)$$

The energy balance is given as:

$$Q_9 = \dot{m}_1 h_1 + \dot{m}_9 h_9 + \dot{m}_7 h_7 \qquad (8)$$

At the condenser:

$$m_1 = m_1 = m_{ref} \qquad (9)$$
$$(Total\ mass\ balance)$$

The energy balance is given as:

$$Q_9 = \dot{m}_{ref}(h_1 - h_2) \qquad (10)$$

At the evaporator:

$$\dot{m}_g + \dot{m}_4 = \dot{m}_{ref} \qquad (11)$$
$$(Total\ mass\ balance)$$

The energy balance is given as:

$$Q_g = \dot{m}_{ref}\, h_4 - h_3 \qquad (12)$$

At solution heat exchanger:

$$\dot{m}_g + \dot{m}_6 = \dot{m}_7 + \dot{m}_g \qquad (13)$$
$$(Tatal\ mass\ balance)$$

The energy balance is given as:

$$\dot{m}_g h_g + \dot{m}_6 h_6 = \dot{m}_7 h_7 + \dot{m}_9 h_9 \qquad (14)$$

The heat exchanger efficiency is given as:

$$g = \frac{h_7 - h_6}{h_7 - h_9} \qquad (15)$$

At the expansion valves:

$$m_2 = \dot{m}_8 = \dot{m}_{ref} \qquad (16)$$
$$(Total\ mass\ balance)$$
$$\dot{m}_9 = \dot{m}_{10}$$

The energy balances are given as:

$$h_2 = h_g \qquad (17)$$

$$h_9 = h_{10} \qquad (18)$$

The equilibrium temperature and enthalpy of LiBr-H_2O solution can be obtained by:

$$T_{sol} = T_{ref} \sum_{i=0}^{g} a_i\, x_i + \sum_{i=0}^{g} b_i\, x_i \qquad (19)$$

$$h_{sol} = \sum_{i=0}^{4} c_i\, x_i + T_{sol} \sum_{i=0}^{4} d_i\, x_i + T_{sol}^2 \sum_{i=0}^{4} e_i\, x_i \qquad (20)$$

where:

The constant coefficients of a_i, b_i,.... . e_i were presented by [2], T_{ref} is refrigerant temperature, and are temperature, T_{sol} and h_{sol} enthalpy of solution respectively.

The COP of the system is given by:

$$COP = \frac{Qe}{Qg} \tag{21}$$

Solar collector

Evacuated tube collectors and flat plate collectors were characterised by different cost and performance, so it was vital to choose the correct collector for each application to optimise the behaviour of the whole system, the energy savings and the finance payback.

The useful energy gained by a solar collector at near normal incidence is given by:

$$q_a = A_C F_R [G_t \tau\alpha - U_L(T_i - T_A)] \tag{22}$$

Where:

F_R = collector heat removal factor.

T_i = collector fluid inlet temperature.

T_a = ambient temperature.

A_c = collector area.

G_t = total incident solar radiation

U_L = overall heat loss coefficient.

T_a = effective absorptance-transmittance product

The thermal efficiency is given as:

$$\eta = F_R \left[\tau\alpha - \frac{U_2\ (T_i - T_a)}{G_t}\right] \tag{23}$$

If the heat loss coefficient is considered as the sum of two terms, a constant factor and a second term dependent on the temperature difference between fluid and ambient air, the efficiency equation can be written as:

$$\eta = F_R\, \tau\alpha - c_1 \frac{(T_i - T_a)}{C_t} - C_2 \frac{(T_i - T_a)^2}{C_t} \tag{24}$$

Thermal storage tank

These are simple and suitable for implementation into overall energy system simulation programmes which permit ong term studies [10]. A storage tank of a diameter, D and length, L was modelled and divided into N nodes (sections) in the longitudinal direction with energy balances written for each node. This resulted in a set of N, differential equations that could be solved to get the time distribution of temperature for each. The degree of stratification depended on tank design, size, location and design of inlets and outlets, flow rates of entering and leaving streams. A collector control function was defined to determine which node received water from the collector [3]. Such as:

$$Ff = \begin{cases} 1\ if\ i = 1\ and\ T_{co} > T_{E\lambda} \\ 1\ if\ T_{E\lambda-1} > T_{co} > T_{E\lambda} \\ 0\ if\ i = 0\ or\ t = N + 1 \\ 0 = if\ otherwise \end{cases} \tag{25}$$

NB: If the collector is operating only one control function can be non-zero.

The liquid returning from the load can be controlled in a similar manner with a load control function F_i:

$$F_i^L = \begin{cases} 1\ if\ i = N\ and\ T_{Lr} > T_{SN} \\ 1\ if\ T_{a\lambda} \geq T_{Lr} > T_{s\lambda} \\ 0\ if\ i = 0\ or\ i = N + 1 \\ 0\ if\ otherwise \end{cases} \tag{26}$$

Return is always to a node closest, but lower, than the collector/load return temperature. The net flow between nodes is upwards or downwards depending upon the magnitudes of the collector and load flow rates and the values of the two control functions. One can conveniently define a mixed-flow rate to represent the net flow into node i from node i-1 excluding the effects of flow, if any, directly into the node from the load.)

$$\dot{m}_{m\lambda} = 0 \tag{27}$$

$$\dot{m}_1 = \dot{m}_c \sum_{j=1}^{i-1} F_j^c - \dot{m}_1 \sum_{j=i+1}^{n} F_j^L \tag{28}$$

$$m_{mi+1} = 0 \tag{29}$$

With these control functions, the energy balance on node i can be expressed as:

$$m_i \frac{dT_d}{dt} = \left(\frac{UA}{C_p}\right) (T_a - T_d) + Ff\, m_t\, (T_{tt} - T_{s,i}) + \begin{cases} if\ \dot{m}_1 > 0: & \dot{m}_1\, (T_{s,i-i} - T_{s,i}) \\ if\ m_{i+1} > 0: & m_{i+1}(T_{S,i} - T_{s,i+1}) \end{cases} \tag{30}$$

System optimisation

A number of simulation runs were carried out to optimise the various factors affecting the system's performance. The parameters to be considered:

- Collector type and slope. A comparison was made between evacuated tube and flat plate collectors and the optimum tilt angle chosen. This is because the amount of energy supplied by the solar collector dependsed on the collector tilt angle.
- Collector area
- Pump flow rate. The pump flow rate significantly affected the collector output temperature hence the amount of useful energy collected.
- Storage tank size.
- Cooling tower type and power.

Economic analysis

The economic problem in solar process design is to find the cheapest system, as a result, economic studies of the system were carried out to determine the most viable system. Solar processes are generally characterised by high initial costs and low operating costs, so the basic economic problem is one of comparing a known investment with estimated future operating costs. The cost of a solar energy system breakdown into two main categories: Investments (costs and delivery costs, construction and installation costs of collectors, storage unit, pumps, and fans and controllers, chillers etc) and operating costs include costs of operation of pumps and fans, interest on loans if system was constructed using borrowed funds, insurance etc. Careful design can minimise the cost of operating the pumps. System performance is much more sensible to collector area variation than any other parameter [3] thus reducing the economic problem to one of determining the size of a solar system with a known load, with storage capacity and other parameters fixed in relationship to collector area. The most widely used and most appropriate method for economic analysis was the life savings method [3, 11]. The analysis takes into account both capital costs and annual running costs over the entire life span of the system. All running costs was discounted to the beginning of the first year of operation of the system.

Results and analysis

The optimum collector type, slope and area, storage tank volume were determined and their effects on system long term economic performance analysed. An optimised solar powered absorption system was be obtained and depending on availability of funding, be constructed and the simulation results verified.

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