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THE DESIGN, DEVELOPMENT AND EVALUATION OF A SOLAR POWERED ADSORPTION COOLING SYSTEM FOR SOUTH AFRICAN CONDITIONS

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ABSTRACT

Solar assisted adsorption cooling is one current research area where scientists study the development of new and safe cooling technologies; so that the conventional vapour compression refrigeration; with its many disadvantages; might be discarded. It has been investigated during the last decade, with some success. One problem facing researchers is to do detail comparisons for the two systems on the cost effectiveness, so that the best option is identified.

This study presents an experimental analysis of a solar assisted adsorption fridge, and compares its cost effectiveness with the conventional vapour compression system, so that a cost effective fridge can be found for South African conditions.

The machine is operated by a solar powered flat plate, with collectors containing the adsorbent. The adsorbent – adsorbate pair chosen for this study is water and silica gel. The cooling machine was designed, developed and tested. Preliminary results show that chilled water at temperatures of 6 ^{0}C and 12 ^{0}C is produced. The cost effective comparisons shows that a solar adsorption cooling machine represent an energy saving machine with a good economic competitiveness.

Keywords: Solar, Adsorption cooling, Cost effectiveness, Silicagel, water, vapour compression, Fridge.

INTRODUCTION

The sun is the main source of energy and more outstanding since it is clean and comes to the earth with no costs. However, mankind does not utilize most of this precious energy effectively.

In recent years there has been a growing interest in studies of solar energy since the potential of this source is almost unlimited. One such study is in solar powered adsorption cooling for food preservation, which will be in competition with the conventional vapour compression method, with the latter incurring higher running costs and using refrigerants that produce toxins, which destroy the ozone layer and causing global warming.

Many experiments on adsorption cooling machines have been tested [2, 3, 5, 6, 8, 9]. At present there is no mass production of adsorption cooling machines because of the following reasons: Long adsorption/desorption time, small refrigeration capacity per unit mass of absorbent, high initial capital costs and low COP values.

In Africa, and South Africa in particular, emerging farmers need their agricultural products preserved in storage or in transit. Adsorption cooling machines would be of benefit to these farmers as they do not require any additional source of energy and are completely autonomous.

NOMENCLUTURE

C	[Euros, €]	capital cost
C_p	[kJ/kg.K]	specific heat
H	[kJ/kg]	heat of desorption
m	[kg]	mass
n	[months]	life period for the system
NPV	[€]	net present value
PB	[years]	pay back period
PVP	[€]	resent Value
Q	[kJ]	energy
R	[%]	annual interest rate
S_j	[€/year]	yearly benefits
Sil	silca gel	
T	[^{O}C]	temperature

Subscripts

c	condenser
e	evaporator
v	vapour

ADSORPTION COOLING CYCLE THEORY

Theoretically, the cycle consists of two isosteres and two isobars that intersect at points defined by the temperatures in the processes: adsorption temperature, condensation temperature, maximum generation temperature and evaporation temperature [1].

The cooling cycle operation principle

During the day-time silica gel is heated in the adsorber. Water vapour evaporates from the silica gel and then is cooled by the condenser and stored in the evaporator.

During the night-time, the adsorber is cooled by ambient air and the temperature of the silica gel reaches a minimum. In this period, the connection between the adsorber and the evaporator is opened to allow silica gel to adsorb the vapour. The adsorption process is exothermic, and heat is taken from the space to be cooled bythe evaporation of the water.

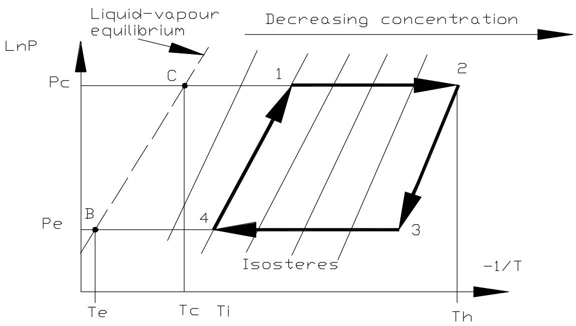

Figure 1 The theoretical Adsorption cooling cycle

The principle of the solid-adsorption refrigerator is explained using a Clapeyron diagram in figure 1 and shows the idealized process using silica gel and water vapour in achieving the refrigeration effect. The cycle begins at point 4 where the adsorbent is at a low temperature T_i and at low pressure P_e, during the daylight period. Point 4 to point 1 represents the initial isosteric heating of the silica gel. The progressive heating of the adsorbent from 1 to 2 at constant pressure causes some adsorbate to be desorbed and its vapour to be condensed at the condenser pressure P_c [5].

When the adsorbent reaches its maximum temperature T_h, desorption ceases. Then the condensate is transferred into the evaporator. During the night, the decrease in temperature from 2 to 3 induces the decrease in pressure from P_c to P_e. Then the adsorption and evaporation occur while the adsorbent is cooled from 3 to 4. During this cooling period heat is removed to decrease the temperature of the adsorbent and to reject adsorption heat.

Energy equations

From the Clapeyron diagram, the total energy gained by the system during the heating period Q_T will be the sum of the energy $Q_{4\text{-}1}$ used to raise the temperature of the silica gel and water vapour from point 4 to 1 and the energy $Q_{1\text{-}2}$ used for progressive heating of the silica gel to point 2 for the desorption of water vapour.

$$Q_T = Q_{4-1} + Q_{1-2} \tag{1}$$

$$Q_{4-1} = (m_{sil}c_{p_{sil}} + m_v c_{p_v})(T_1 - T_4) \tag{2}$$

$$Q_{1-2} = [m_{sil}c_{p_{sil}} + (m_{v_4} + m_{v_2})c_{p_v}/2(T_2 - T_1) + (m_{v_4} - m_{v_2})H \tag{3}$$

The energy necessary for cooling the liquid adsorbate from the temperature at which it is condensed to the temperature at which it evaporates is Q_e.

$$Q_e = (m_{v_4} - m_{v_2})c_{p_v}(T_c - T_e) \tag{4}$$

EXPERIMENTAL SETUP AND PROCEDURES

Experimental equipment

A testing rig for solar adsorption cooling was developed, designed and constructed to study the adsorption cooling system with water/silica gel as working media under South African conditions. The system is composed of a solar adsorber, a condenser and an evaporator as shown in figure 2.

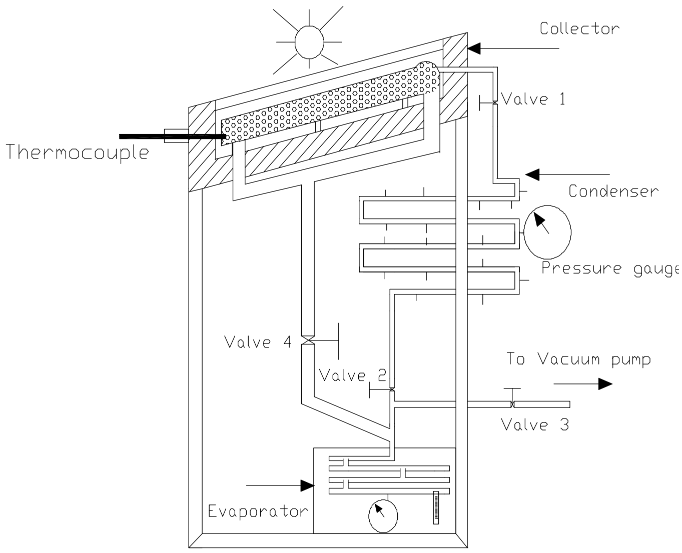

Figure 2 The solar adsorption Fridge.

Experimental procedures

The adsorbent, assumed to be partially saturated, is first heated in the adsorber/collector, with the available solar energy from 8 a.m to 3 p.m, to evaporate the vapour from the silica gel. Then the whole system is evacuated by a vacuum pump for 1 hour until the pressure reached is –85 kPa, with all vacuum valves and adsorber end covers closed. As the adsorber is heated, the periods of silica gel desorption and vapour condensation take place. Silica gel generation and condensation are allowed to continue for four hours after the maximum cycle temperature has been reached. When desorption is completed, the collector box end cover plates are opened to allow ambient air to cool down the adsorber. Valve 1 is then shut. As cooling progresses, valve V_2 is opened to let the condensate into the evaporator coil, which contains a known quantity of water. Subsequently, when the difference of pressure between evaporator and adsorber is lower than 90 Pa, valve V_4 is opened to permit evaporation to begin.

During this stage, heat is absorbed from the space to be cooled. When the adsorbent is saturated, a single cycle of an adsorption cooling is completed.

ECONOMIC ANALYSIS OF THE SOLAR ASSISTED AND VAPOUR COMPRESSION SYSTEMS

The second objective of this study was to compare initial capital, maintenance and running costs for a solar cooling machine with a typical vapour compression machine, so that the best option can be chosen. Different approaches as used by previous studies were of value to this study [7, 10, 11].

For this study, four main methods are used to compare the economic costs: The initial cost, the net present value, the payback, the maintenance and running costs methods.

It is assume that the lifetime for the vapour compression system is the same as that for a solar adsorption system provided the former is maintained regularly.

INITIAL COSTS

Vapour compression cold room

The initial cost method reflects only the initial price, installed and ready to operate, and ignores such factors as expected life, ease of maintenance and efficiency.

The initial cost for the vapour compression cold room includes the compressor, the heat rejecting equipment, room structure with an insulation of thickness 100 mm, made from polystyrene, piping, wiring and specific structures.

The heat rejection equipment for the application considered in this work is a blower coil. The blower coil and the compressor are the main power consumers. Table 1 shows the vapour compression equipment and cold room quotation, from Cold Curve Refrigeration cc, Pretoria, South Africa. Assumed cooling load was 1755 kg, and the room holding temperature of 2 ^{O}C.

The quotation includes the cost of the room structure, installation and refrigeration equipment.

Compressor	Hermetic MP600/350
Condenser	Recoil
Capacity	4 kW @ 5 Suction
Room structure costs	€1958.76
Compressor, condenser, evaporator, fan and installation costs	€3092.78
Total Initial price	€5051. 54

Table 1 Vapour compression cold room costs.

The solar assisted cold room

The initial costs for the solar adsorption system include installation costs, piping, the cold room structure, the evaporator, the heat rejection equipment, instruments and solar energy collection system.

Table 2 is the initial cost analysis of the solar cold room. Figure 3 shows the comparison in initial capital. The initial capital for the solar system almost doubles that of the vapour compression system.

ITEM	SIZE	QUANTITY	PRICE
Cooler room	3 x 3 x 3 m		€1958-76
Glass	1.5 x1.5 m	6	€1030-93
Black Sheet	2450 x 1250 x 1	6	€309-28
Galvanized sheet	2450 x 1225 x 0.5	30	€412-37
Paint	30 L	1	€103-10
Copper tubing	54 x 5.5 x 1.5	15	€824-74
Wika industrial Vacuum gauge	Model 213.40.063	2	€103-10
Wika industrial Vacuum gauge	Model 213.50.063	1	€103-10
Vacuum valve	54 mm	4	€1030-93
Energylite(Insul)	3500 x 1000 x 50	30	€206-18
Silica gel	75 kg	4	€824-74
Wika Machine thermometer	Model	2	€103-1
Labour	@€12-89/ hour	120 hours	€1546-39
Initial Total Cost			€8556-70
10% of unforeseen costs per annum			€855-67
Life time			10 years

Table 2 Solar initial cost

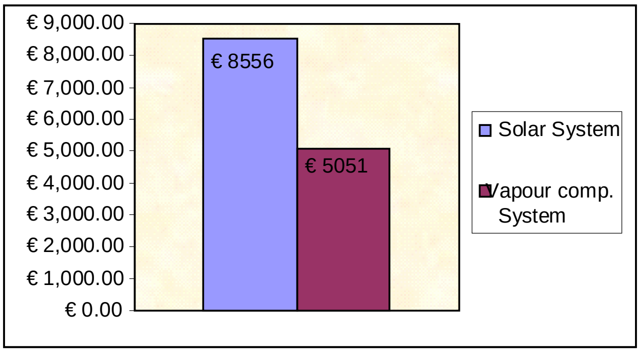

Figure 3 Initial cost comparisons

MAINTENANCE AND RUNNING COSTS

Vapour compression cold room system

Maintenance includes tests, measurements, adjustments, and parts replacement, performed specifically to prevent faults from occurring. The maintenance cost was estimated using the common procedures used in heat, ventilation, air-conditioning and refrigeration projects. The three most common maintenance types applied are: run-to-failure, preventive, and predictive maintenance.

The maintenance cost assumed for this study is preventive, so that the system will works continuously without outages. It is assumed that the two systems are automatic; therefore variables such as local labour rates, their experience, the age of the system, length of time of operation, etc. have been ignored.

For vapour compression system, looking after the machines in terms of servicing and electricity bills is a challenge.

The maintenance cost depends to a large extent on the level of sophistication of the system and the relative ease of access to plant, which is beyond this work.

An assumed cooling load of 1755 kg was used as a base for comparing with the vapour compression system.

For this study, electricity tariffs of 0.041 Euros average per kWh, from Eskom were assumed. An inflation rate of 6% for South Africa was also assumed for each year. Table 3 shows the running cost for the vapour compression system.

Motor fan capacity	0.75 kW	
Compressor capacity	4 kW	
Total capacity	4.75 kW	
Run on time per day	16 hours	
Number of days	365	
Total run on hours per year	16 x 365 = 5840 hours	
Total kilowatt hours (kWh)	5840 x 4.75 = 27740 kWh	
Cost per kilowatt hour	Average @0.0412 Euros	
Cost of electricity after a year	27740 x 0.0412 = €1142 - 89	
Bi-monthly service (exc.parts)	€103-10 average	
Annual service	€103-1 x 6 = €618-60	
Total costs for 1st year	€1142-89+ €618-60 = €1762.00	
Cost per 2nd year	€1867-18	Including 6% inflation
Cost per 3rd year	€1979-21	Including 6% inflation
Cost per 4th year	€2097-96	Including 6% inflation
Cost per 5th year	€2223-84	Including 6% inflation
Cost per 6th year	€2357-27	Including 6% inflation
Cost per 7th year	€2497-70	Including 6% inflation
Cost per 8th year	€2648-62	Including 6% inflation
Cost per 9th year	€2807-54	Including 6% inflation
Cost per 10th year	€2976-00	Including 6% inflation

Table 3 Running costs for the vapour compression system

Solar driven cold room system

Running costs for the solar assisted adsorption cooling is very minimal, and this was ignored. However, 10% of the total cost for the system is budgeted for unforeseen repair problems each year. This is estimated as (0.1 x €8556.7) or €855.67 per year.

Savings or profit comparisons

Figure 4 shows the comparison savings between the vapour compression and the solar adsorption assisted systems respectively.

Savings are the difference in the amount of money coming in to the amount going out.

Using the vapour compression system, it is assumed that 1 kg of the product cooled in the cold room will yield a profit of R1-00 or 0.103 Euros per month. This figure was obtained from Clover South Africa, a dairy products company.

The profit made from the 1755 kg stored in the cold room, for example, is 1755 x 0.103 x 12 = € 2171 per year.

The maintenance and running costs for the vapour compression system was compiled in Table 4. These values are assumed to be the saving for the solar assisted system.

Over the 10 year period, there is almost 3 times in savings for the solar system than in the vapour compression system.

Vapour compression system			Solar system			
Inflow	Outflow	Savings	Outflow	Inflow	Savings	
2171	1762	409	856	1762	907	1st year
2301	1868	433	856	1868	1013	2nd year
2439	1980	459	856	1980	1125	3rd year
2586	2099	487	856	2099	1243	4th year
2741	2225	516	856	2225	1369	5th year
2905	2359	547	856	2359	1503	6th year
3080	2500	580	856	2500	1644	7th year
3265	2650	614	856	2650	1794	8th year
3460	2809	651	856	2809	1953	9th year
3668	2978	690	856	2978	2122	10th yr

Table 4 Running and maintenance costs

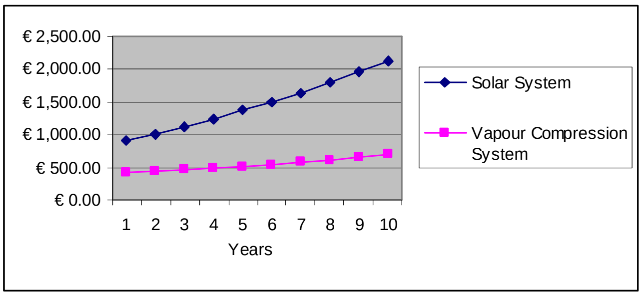

Figure 4 Savings comparison

PAYBACK PERIOD

PB is a measure of the approximate number of years that are required for the total value of savings to equal the total required investment [10]

The payback period is determined by the equation:

$$PB = \frac{\log\left(\frac{Ci}{100E} + 1\right)}{\log\left(1 + \frac{i}{100}\right)} \qquad (5)$$

Where payback period is in years; *C* is the capital cost of installed solar cooling equipment (Euros), i is the change of energy prices relative to general inflation (6%), *E* is the energy saving (€ per year).

The solar assisted system

For the solar system C is €8556-70, **i** is 6%, E is €14673-00.

PB = 0.6 years or about 7 months.

The vapour compression sytem

For the vapour compression system, *C is* €5051-55, **i** is 6%, E *is* €5386-46.

PB = 0.94 years or about 11 months.

THE NET PRESENT VALUE

NPV is a standard method for evaluating competing long-term projects in capital budgeting. It measures the excess or shortfall of cash flows, in present value (PV) terms, once financing charges are met. All projects with a positive NPV should be undertaken [4].

The net present value is given by

$$NPV = \frac{S_j}{r}\left(1-\left(1+\frac{r}{12}\right)^{-n}\right)-C_S \qquad (6)$$

where NPV is in Euros, $\mathbf{S_j}$ is yearly benefits (€/year), $\boldsymbol{r}$ is the annual interest rate, assumed 20% for South Africa, **n** the life period for the system in months (10 years = 120 months), C_s is the initial cost of installed solar cooling equipment (€).

The solar assisted system

For the solar system C_s *is* €8556-70, S_j *is* €14674-11.

NPV = €54719-21

The vapour compression system

For the solar system C_s is €5051-55, S_j is €5386-46

NPV = €18175-29

RESULTS AND DISCUSSION

Table 5 and Figures 5 and 6 show measurements recorded on 27 - 30 November 2006.

Time	Condens. T(^{O}C)	Amb. T(^{O}C)	Adsorb. T(^{O}C)	Adsorb. Pres. (kPa)	Absolute Pres.(kPa)
8 a.m	25	25	50	-83	3
9 a.m	30	30	72	-80	6
10 a.m	30	32	94	-76	10
11 a.m	35	33	112	-74	12
12 p.m	36	34	113	-74	12
13 p.m	38	35	113	-74	12
14 p.m	40	35	115	-74	12
15 p.m	37	34	115	-75	11
16 p.m	35	33	67	-84	2
17 p.m	33	32	49	-84	2
18 p.m	30	31	39	-84	2
19 p.m	30	29	29	-84	2
20 p.m	27	27	27	-82	4

Table 5 Temperature measurements

Analysis of the condensation and silica gel generation mode

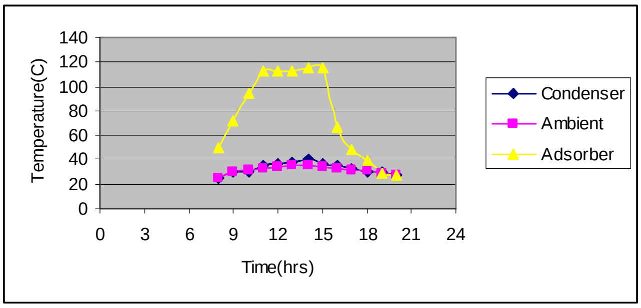

Figure 5 Condensation and silica gel generation curves

From figure 5, it is seen that the condenser tube temperature increases with ambient temperature. Condensation started only at 11:00, and stopped at 16:00. The average difference between the ambient and the condensing temperature recorded was 3 ^{O}C. The graph also shows the adsorber tube surface temperature and ambient temperature variations with time. It is seen from that the adsorber tube surface temperatures depended on variations of solar intensity [10]. The maximum temperature recorded was 115 ^{O}C.

Analysis of the pressure-temperature curve

Figure 6 below represents the recorded working pressures and temperatures, for the tested silica gel/water pair. The graph does not resemble the theoretical (Figure 1) cycle, the reason for this was that small amount of air was leaking into the system, with the result that more pressure was generated inside the adsorber.

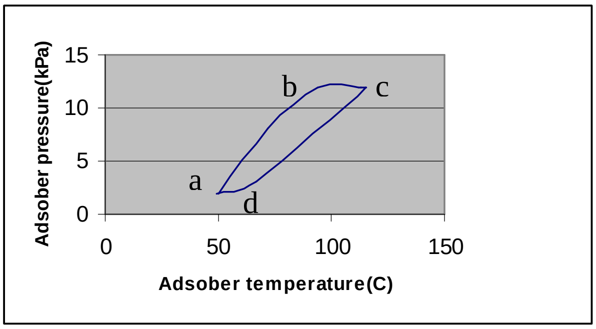

Figure 6 Measured temperature–pressure for the adsorber

Analysis of the evaporation mode

Figure 7 shows that inside the evaporator cabinet, the temperature increased from 13°C to 24°C. This shows that outside heat was leaking into the cooling cabinet, and the cooling capacity of the machine was affected.

When evaporation started after 18:00, the temperature of the evaporator water decreased gradually until it reached a final value at the end of the test. The lowest temperatures obtained in this system varied from 8 to 12 °C from the water initially in the temperature range of 25 °C.

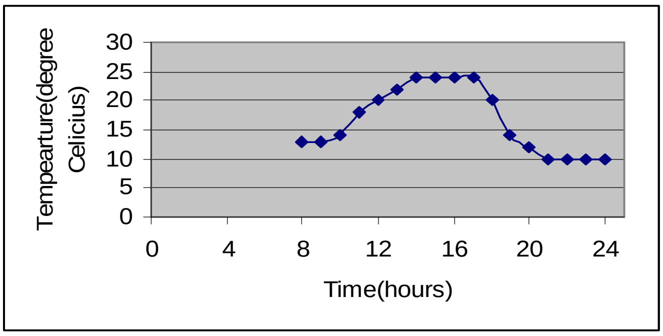

Figure 7 Evaporator temperature versus time

Long time advantages for solar adsorption systems are

- Quietness.
- Electricity-free operation.
- Minimal maintenance.
- The working medium does not destroy the ozone layer, nor produce the greenhouse effect.
- The working cycle can be driven by a low-temperature heat source.

The disadvantages of this system are

- It works on a non-continuous cycle.
- It has a long cycle time.
- It has a low cooling capacity.
- The need for vacuum technology.
- It works perfectly only on sunny days.

CONCLUSIONS

A solar powered adsorption-cooling fridge employing simple apparatus and silica gel-water vapour as an example of the absorbent-adsobate combinations was designed, developed and evaluated.

Test equipment is bound by good workmanship, cost, and the kind of experimental data acquired. Vacuum technology and air leaks were the major problems for this present study.

The presence of air in the system affects the operation of the solar fridge. Desorption pressure did not remain constant as required by theory.

Test results show that only chilled water at temperatures of between 6 ^{0}C and 12 ^{0}C is produced. Vegetables and fruits with preservation temperatures in the range 4 -10 ^{0}C are within the scope of the present system.

The cost effectiveness comparisons show that solar adsorption cooling machines represent energy saving machines with good economic competitiveness.

Further investigations are necessary to improve on the vacuum tightness for the prototype and implement this on a large scale in cold rooms.

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