Entrepreneurial opportunity of using adsorption cooling system

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Abstract:

The paper lucidly presents the principle of operation of adsorption cooling system with the work of compression to be replaced by heat adsorption system. The Clausis Claperyon diagram is drawn in comparison with Pressure-enthalpy (p-h) & temperature-entropy (t-s) Diagrams of Vapour Compression refrigeration system with same capacity thus bringing in the advantage of zero Ozonosphere depletion potential (ODP), zero Greenhouse warming potential (GWP), size, scale and practical applicability as entrepreneurial opportunity. The systems analysis is presented on the basis of performance parameters like coefficient of performance (COP), specific cooling power and thermodynamic analysis. Finally cost analysis is done for both the system based on initial cost, running cost and replacement cost. It is found that though the adsorption cooling system is more costly as compared to conventional Vapour compression refrigeration system (VCRS) but due to long life duration and environmentally friendly operation of the former system makes it a preferred candidate.

Key words:

Adsorption, Compression, Vapour, Refrigeration & Desorption.

Introduction

In today’s modern world the field of refrigeration and air-conditioning is one of the most important aspects of our life whether it may be field of food preservation or comfort living. A majority of the refrigeration and air conditioning devices used today are running on electricity. Majority of the electricity is produced by burning of fuel like coal and natural gas which are non-renewable in nature, thus constitutes the release of greenhouse gasses in the atmosphere which leads to global warming. The overall temperature on the earth surface has raised during the last century due to global warming. This has resulted in the imbalance of the climate around the world this has further increased the demand of the air conditioning and refrigeration. This is like a never ending loop and therefore the time has come that we reduce the consumption of fossil fuels to produce electricity and shift towards clean and renewable energy at least in the field of refrigeration and air-conditioning.

One such option of using clean or green energy is solar energy. It is the main source of energy and available in plenty. The fact that peak cooling requirements coincide with the peak availability of solar energy will only help. In recent years many projects have been developed justifying the use of solar cooling for cooling of residential and commercial buildings.

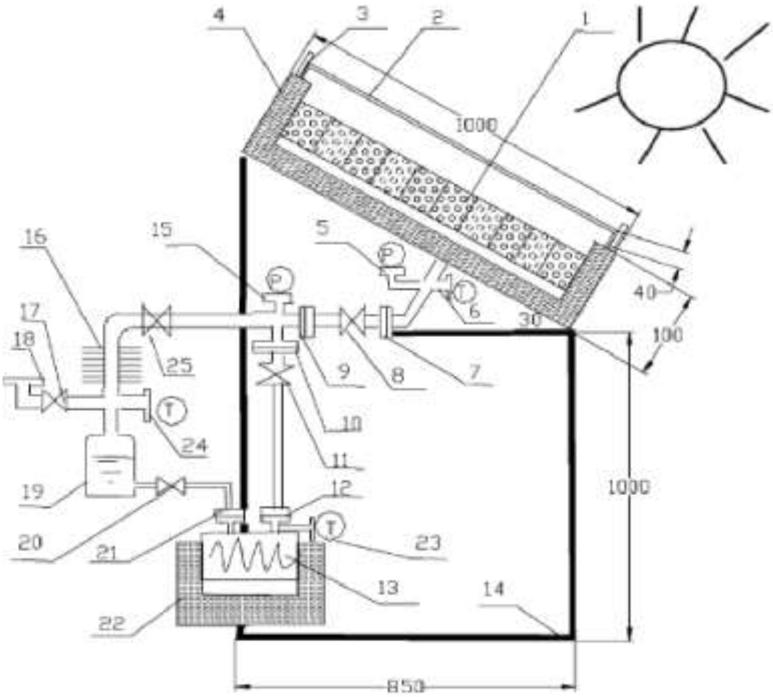

Fig.1: Schematic of the solar solid-adsorption ice maker: (1) adsorbent bed; (2) glass cover; (3) damper; (4) insulated material; (5,15) pressure gauges; (6,23,24) temperature gauges; (7,9,10,12) connecting flanges; (8,11,17,20,25) valves; (13) evaporator; (14) bracket; (16) condenser; (18) refrigerant input pipe;(19) Reservoir; (22) ice box. [1]

Li et al. [1] performed experiments with a solar powered ice maker that had activated carbon–methanol as a working pair. The icemaker, which is shown schematically in Fig. 8, had a COP ranging from 0.12 to 0.14, and produced between 5 and 6 kg of ice per m^2 of collector area. Analysing the temperature gradient within the adsorbent bed, the authors concluded that in order to improve the performance of the system, the heat transfer properties of the adsorber bed must be enhanced. This could be achieved by increasing the number of fins or using composite adsorbent.

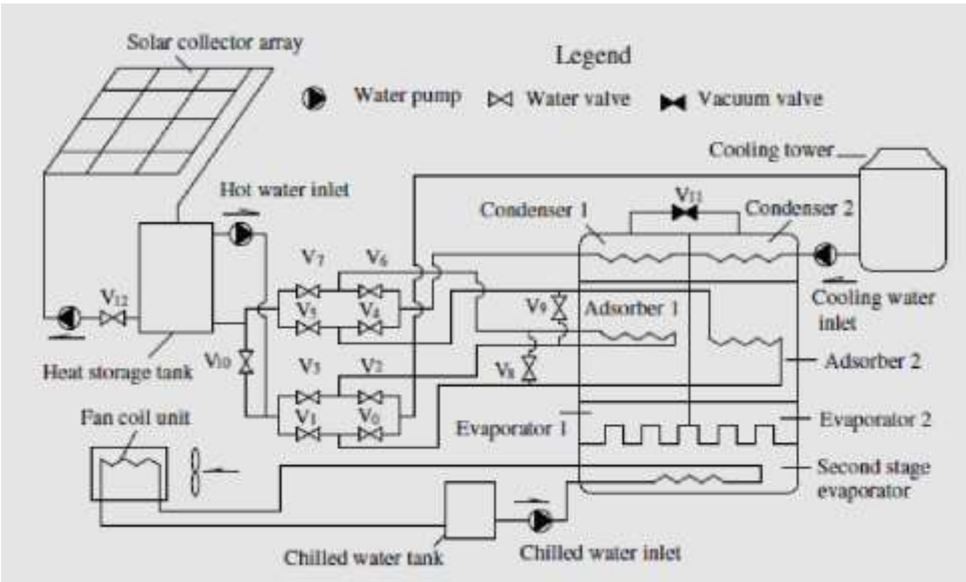

Fig.2: Schematic Diagram of Solar powered Adsorption Chiller.

In 2010 Huilong Luo at el [2], had developed a solar-powered adsorption chiller with heat and mass recovery cycle. The system consists of a solar water heating unit, a silica gel-water adsorption chiller, a cooling tower and a fan coil unit. The adsorption chiller included two identical adsorption units and a second stage evaporator with methanol working fluid. The effects of operation parameters on system performance were tested successfully. Test results indicated that the COP (coefficient of performance) and cooling power of the solar-powered adsorption chiller could be improved greatly by optimizing the key operation parameters, such as solar hot water temperature, heating/cooling time, mass recovery time, and chilled water temperature. Under the climatic conditions of daily solar radiation being about 16–21 MJ/m^2, this solar-powered adsorption chiller can produce a cooling capacity of about 66–90W per m^2 collector area, its daily solar cooling COP was about 0.1 -- 0.13.

Solar cooling can be broadly classified in two main categories, one is solar thermal application and solar electric application. The solar thermal application uses the heat energy gained from solar radiation for pressurisation of the refrigerant and the solar electric application uses the solar photovoltaic module to run the compressor of the conventional Vapour compression refrigeration system. In solar thermal application there are further sub divisions namely solar adsorption cooling, solar absorption cooling and solar decent cooling.

Our focus in this study will be on the comparison of solar adsorption cooling and vapour compression cooling systems. Both the systems are compared on the thermodynamic platform and their detailed working is explained. Pressure-enthalpy (p-h) & Temperature-Entropy (t-s) characteristics are considered for VCR System and Clausius-clapeyron and dhurring diagrams are considered to gauge the performance of the solar adsorption cooling. Performance of both the systems are compared on various performance parameters like Coefficient of Performance (COP), specific cooling power and thermodynamic analysis. Finally cost analysis is done for the life cycle of systems considering initial, running and replacement cost.

Working principle of Vapour compression Refrigeration system:

The vapour compression refrigeration system works on the principle of second law of thermodynamics. According to Clausius's statement the heat cannot flow from the colder body to hotter body on its own there is a need to supply some external work, for the process to complete. That external work is supplied by the compressor.

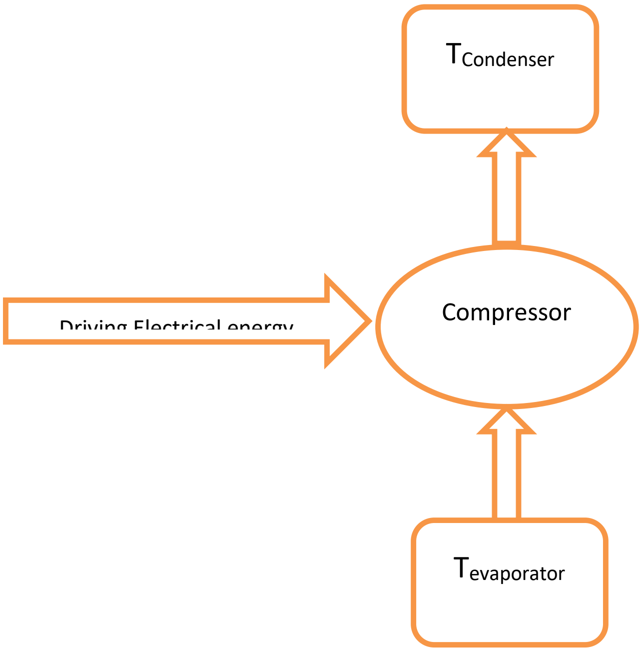

Fig.3: Working Principle of Vapour compression refrigeration system

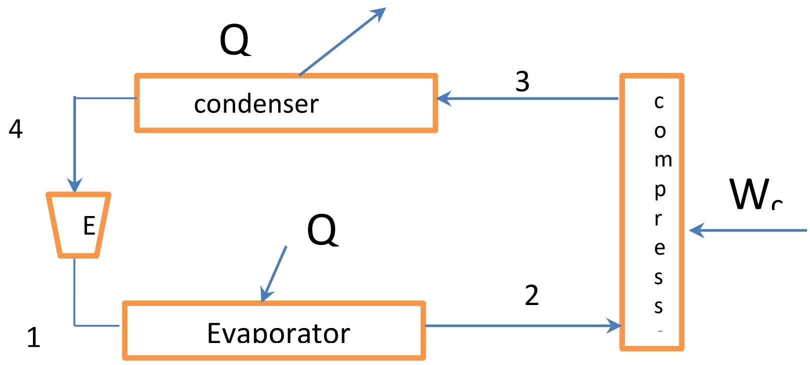

Fig.4: Basic diagram of Vapour compression refrigeration system

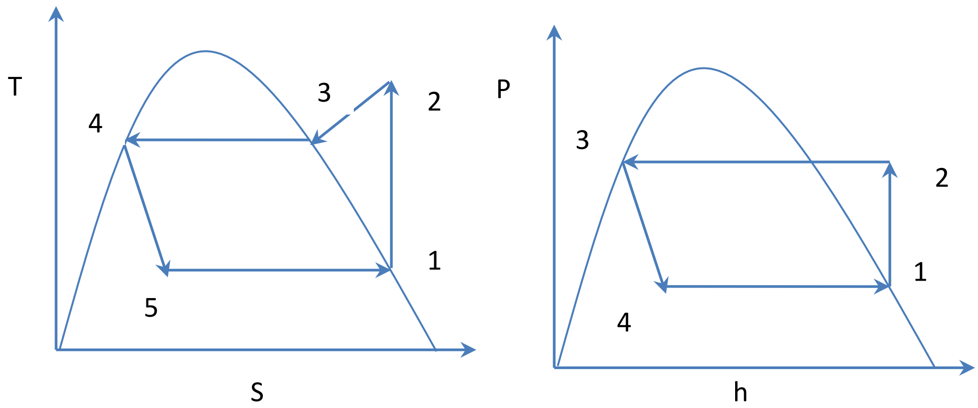

Fig.5: p-h & t-s Diagram for Vapour compression refrigeration system

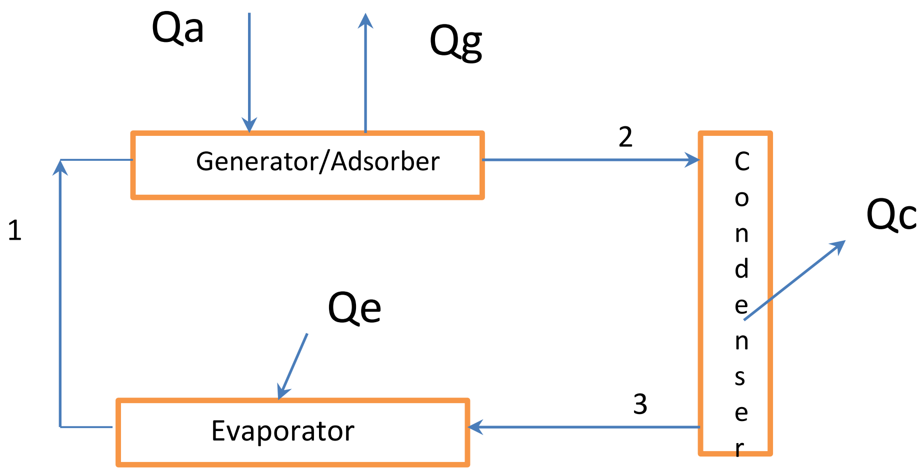

Fig.6: Adsorption refrigeration system

As shown in figure the compressor of the conventional vapour compression refrigeration system is replaced by adsorber/generator for adsorption refrigeration system. The driving energy in case of VCRS is the electric energy where here in case of adsorption system heat energy is the driving energy and compresses the refrigerant by way of constant pressure heating. The heat energy can be of any form either waste heat energy or solar energy or it may be a special heat source in the form of a furnace or a boiler.

Working principle of solar Adsorption refrigeration system:

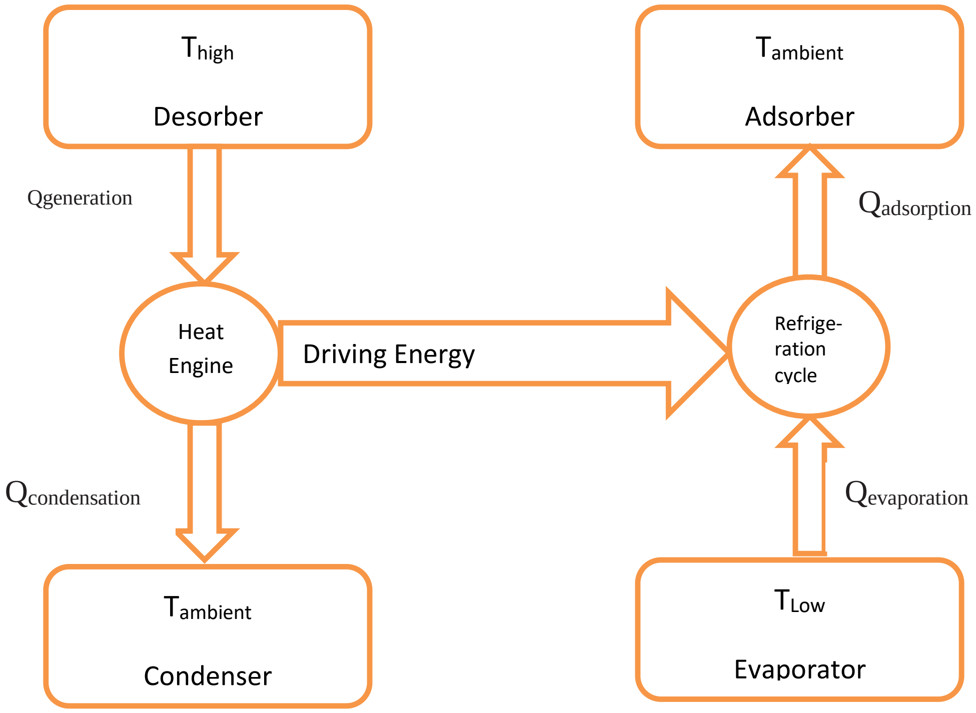

Fig.7: Working Principle of Adsorption Refrigeration cycle

Figure 7 shows adsorption refrigeration cycle which works on three temperature levels namely the desorber, ambient and evaporator temperature having two sources and two sinks. The energy required to drive the thermal compressor is obtained from the source at desorber temperature, this is similar to the compressor work in the Vapour compressor refrigeration system.

Whereas the working principle of the Vapour compression refrigeration system is explained in Figure 2, the electrical energy is used to drive the compressor where the compressor compresses the vapour refrigerant from the evaporator thus increasing its pressure and temperature.

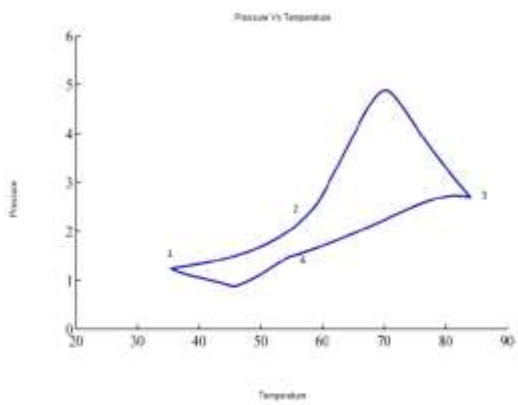

Fig.8: Duhring Diagram

Figure shows the duhring diagram for adsorption cooling system which shows the relation of pressure with the temperature for the whole operation of the system. Here the pressure is in KPa and Temperature is in °C.

1-2 Preheating mode:

During preheating mode the pressure increases and the adsorption bed is made ready to start the desorption process. Heat is supplied to the bed in the form of hot water flowing through the adsorption bed.

2-3 Desorption mode:

Refrigerant water vapours start leaving from adsorption bed to condenser resulting in the decreasing the concentration ratio of the bed. Pressure and temperature reaches the highest value in the whole cycle during this process. Further heat is rejected in the condenser and refrigerant vapours are converted to liquid.

3-4 Pre cooling mode:

Now the stored heat energy in form of sensible heat of the adsorbent bed is released to the cooling water during this pre-cooling mode, this bed is prepared for the adsorption of vapours from the evaporator.

4-1 Adsorption mode:

During this mode the adsorption bed is connected to the evaporator and low pressure triggers the evaporation of the liquid refrigerants and once again the concentration ratio of the bed increases. Cooling is produced in this mode.

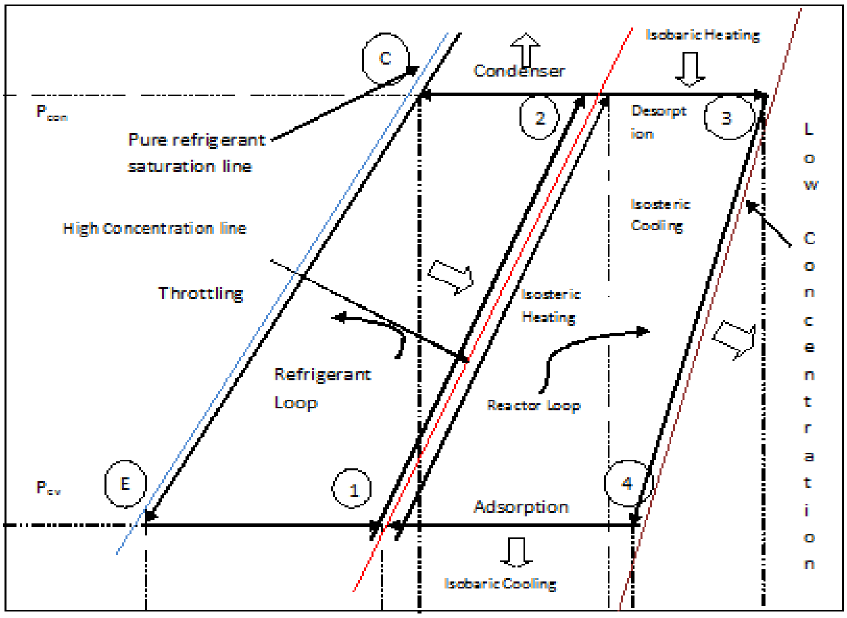

Fig.9: Adsorption Clapeyron Diagram

As shown in figure the detail working of the adsorption refrigeration can be understood by the clapeyron diagram. The system works between condenser pressure and evaporator pressure both the pressures being in vacuum.

Isobaric cooling (Adsorption-Evaporation) Process 4-1:

Evaporation of the refrigerant is triggered by adsorption in the bed at evaporator pressure due to the adsorption the concentration of the refrigerant in the adsorption bed is increasing from low concentration line to the high concentration line at a constant pressure resulting in cooling effect in evaporator shown by process 4-1.

Isosteric heating (constant concentration) Process 1-2:

Once the adsorption bed is saturated with the vapour refrigerant the heat energy is required to remove the vapour refrigerant from the bed this energy is supplied by flowing the hot water through the bed this increases the pressure of the bed to the saturation pressure of the refrigerant and pressure is increases to the condenser pressure shown by process 1-2.

Isobaric heating (Desorption-condensation) Process 2-3:

After the isosteric heating the high pressure vapour refrigerant enters the condenser from the bed where the further heat rejection takes place in the condenser at constant pressure. As more and more vapour refrigerant is taken out from the bed its concentration is reduced to low concentration shown by process 2-3.

Isosteric cooling (Constant concentration) process 3-4:

Now the liquid refrigerant from the condenser enters the evaporator via expansion device thus pressure reduces to the evaporator along the constant concentration line shown by process 3-4 in the figure.

Design procedure for solar adsorption cooling system:

The adsorption cooling system works under vacuum. In our case water is used as a refrigerant. It is found from the table of saturated water and steam temperature table the vapor pressure of the water is 2.5 KPa at a temperature of 20.5°C [3]. The complete working of the adsorption cooling system is divided into two processes that is Adsorption and Desorption both having equal duration of 900 sec each. Whole design is carried out considering 3.5kW of cooling capacity. The adsorbate-adsorbent pair is water-silica gel.

Step 1: calculate the amount of refrigerant required to produce 3.5kW of cooling effect.

The cooling effect produced due to vaporization of 1 kg of water is calculated from equation:

$$Q_c = \frac{q_{eva,ads}}{T_{ads}}$$

Where $q_{eva,ads}$ is the heat of vaporization of 1 kg of water at evaporator pressure and temperature. T_{ads} is the duration of adsorption process in sec

Q_c = 2733.56 w/kg of refrigerant.

For calculating the amount of refrigerant required to produce 3.5kW of cooling.

$$V_{ref} = \frac{Q_{cap}}{Q_c}$$

$= 1.280*10^{-3}$ m^3.

Step 2: calculating the amount of silica gel.

It is found from literatures that the silica gel can absorb 30 % of water of its dry weight in 1 hour when the height of bed is 1m and velocity of air is 0.2 m/sec with relative humidity of 60%.[4,5]

Based on the above data it is possible to find the relation between the absorptivity of the silica gel and bed physical parameters.

$A_{15} = 0.9 * A_{60} * T_{ads}/T_{60}$ (g of water/100 g of silica gel)

= 6.3 g of water/100 g of silica gel

Now to absorb 1280 gm of water refrigerant in 15 min the amount of silica gel required is calculated and comes to 20.31 kg.

Therefore the amount of silica gel required is selected as 21 kg.

Step 3: calculate the heating power to regenerate the silica gel for adsorption/ desorption process:

$Q_{reg} = q_{bed,des} * V_{ref}/T_{des}$

= 5870*1280/900

=8348 W or 8.3 KW.

Step 4: calculate area of solar collector to provide heating power for regeneration of the adsorbent bed

$A_{sc} = Q_{reg} / \eta_{sc} * A_{rad}$

Where A_{rad} average solar radiation for ahmedabad region= 5.76 Kwh/m^2/day [6] = 0.48 kw/m^2

η_{sc} = efficiency of solar collector 50%

$A_{sc} = 35.58\ m^2$

Step 5: Calculate the storage tank capacity for heating and cooling water.

$V_h = 3600*10^{-3} * Q_{reg}/C_{ref} * \Delta T_{ads}$ m^3

= 1.02 m^3

$V_{ch} = 3600*10^{-3} * Q_{eva}/C_{ref} * \Delta T_{eva}$ m^3

=0.602 m^3

Step 6: calculate surface area of evaporator, condenser and adsorber bed

Evaporator surface area:

$A_{eva} = \{- Ln[1-(Q_{eva}/\Delta T_{eva} * K)] * K\}/U_{eva}$ m^2

Consider copper as the material for the construction of evaporator, taking thermal conductivity and heat transfer coefficient of copper:

K =400 W/m K ; U_{eva} = 1000 W/m^2 K

= 1.48 m^2

Condenser surface area:

$A_{cond} = \{- Ln[1-(Q_{cond}/\Delta T_{cond} * K)] * K\}/U_{cond}$ m^2

Consider copper as the material for the construction of condenser, taking thermal conductivity and heat transfer coefficient of copper:

$K = 400$ W/m K ; $U_{eva} = 1000$ W/m^2 K

= 1.68 m^2

Adsorber bed surface area:

$A_{bed} = \{- Ln[1-(Q_{bed}/\Delta T_{bed}*K)]*K\}/U_{bed}$ m^2

Consider aluminum as the material for the construction of adsorber bed, taking thermal conductivity and heat transfer coefficient of copper:

$K = 205$ W/m K ; $U_{eva} = 500$ W/m^2 K

= 2.34 m^2

Step 7: calculate the mass flow rates of chilled water, cooling water and hot water

Mass flow rate of chilled water for evaporator:

$M_{ch} = 3.6*Q_{eva}/C_{ch}*\Delta T_{ch}$ m^3/hr

= 0.32 m^3/hr

Mass flow rate of hot water for adsorber bed:

$M_{hw} = 3.6*Q_{bed}/C_{hw}*\Delta T_{hw}$ m^3/hr

= 0.41 m^3/hr

Mass flow rate of hot water for adsorber bed:

$M_{cw} = 3.6*Q_{cond}/C_{cw}*\Delta T_{cw}$ m^3/hr

= 0.38 m^3/hr

Step 8: Specific cooling power of adsorption cooling system:

Specific cooling power = Q_{eva}/W_s

= 166 W / kg of silica gel

Step 9: Calculating Coefficient of Performance.

C.O.P = Q_{eva}/Q_{reg}

= 0.42

As our main focus is on the adsorption cooling system therefore detail design is not studied for the vapor compression refrigeration system and so all data system parameters and operating conditions and performance equations are extracted from [7,8,9]

Refrigerant: R134a

Evaporator pressure: 200 KPa

Condenser Pressure: 1400 KPa

Refrigerant mass flow rate: 0.025kg/sec

Degree of superheat: 10°C

Degree of subcooling: 5°C

Mass of refrigerant: 1.15 kg

Various detail of Vapour compression refrigeration system (Refrigerant thermo physical properties, material of construction, specifications) at evaporator pressure and condenser pressure:

Condenser Pressure: 1400 KPa	
T_{sat}	52.4°C
T_{cond}	48°C
$h_{expin} = h_{expout}$	120.39KJ/kg
Degree of subcooling	
Material of construction:	
Copper tube with aluminum fins	K= 400 w/m.K ; U= 1000 w/m^2.K
Electric motor efficiency	100%
Outer Diameter	9.5 mm
Inner diameter	8 mm
Length	13 m
Surface area	2.4m^2 (air cooled)

Table1: Condenser Specification

Evaporator Pressure

Evaporator Pressure: 200 KPa		Remark
Refrigerant	R134a	Selected
$T_{eva,in}$	-10 °C	
h_{compin}	253.05 KJ/kg	
Entropy S_{compin}	0.9698 KJ/kg.K	Calculated
Material of construction:		
coil type with internal fins of copper	K= 400 w/m.K ; U= 1000 w/m^2.K	
Outer Diameter	17 mm	
Inner diameter	15.5 mm	
Length	0.9m or 900 mm	
Surface area	0.8 m^2	

Table 2: Evaporator Specification

Thermophysical properties of refrigerant R134a

Molar mass	102 kg/Kmol				
Normal boiling point	-26°C				
Critical temperature	101°C				
Critical pressure	4.06 MPa				
properties at saturation(0°C)					
Pressure	Liquid			Vapour	
	0.29MPa			0.29MPa	
Volume	Liquid			Vapour	
	0.77 m^3/Kg			69.31 m^3/Kg	
Specific heat capacity	Liquid			Vapour	
	C_p=1.34 KJ/Kg.K		C_V=0.88KJ /Kg.K	C_p=0.90KJ/Kg.K	C_V= 0.76 KJ/Kg.K
Viscosity	Liquid		Vapour		
	271.08*10^{-6} Pa.S		10.73*10^{-6} Pa.S		
Thermal Conductivity	Liquid	Vapour			

	0.092 W/m.K	0.012W/m.K	
Surface tension	0.012 N/m		
Heat of vaporization	198.6 KJ/Kg.K		
Ozone Depletion Potential(ODP)	0		
Global Warming potential (GWP)	1300		

Table3: Thermophysical Properties of refrigerant R134a [10]

Based on the above mentioned parameters for the vapour compression refrigeration system, a simple ideal design steps are discussed in the following section:

Design procedure for vapour compression refrigeration system

Assumptions:

1. Changes in kinetic and potential energy are neglected while considering the different components
2. Compression process is considered isentropic process
3. Heat loss from evaporator is negligible
4. No heat transfer and pressure drop in connecting pipe lines
5. Steady flow process in all components

Step 1: calculate refrigeration capacity

$Q_{eva} = m_r(h_{eva,out} - h_{eva,in}) \text{ kW}$

$= 3.317 \text{ kW}$

Step 2: work input to compressor:

$W_c = m_r(h_{com,out} - h_{com,in}) \text{ kW}$

$\eta_{comp} = 88\%$

$h_{com,out} = 301.74 \text{ KJ/Kg}$

$W_c = m_r(h_{com,out} - h_{com,in}) \text{ kW}$

$= 1.21 \text{ kW}$

Step 3: Heat rejected by condenser

$Q_{con} = m_r(h_{con,in} - h_{con,out})$

$= 4.53 \text{ kW}$

Step 4: Pressure drop at expansion device

Considering throttling process ie. Constant enthalpy process $h_{expin} = h_{expout}$

The exit quality of the refrigerant is two phase , so using the dryness fraction to find the quality of the refrigerant at exit of the expansion device.

$h_{out} = h_f + Xh_{fg} \text{ kj/kg}$

where h_f enthalpy of saturated liquid refrigerant, h_{fg} = latent heat of vaporization at evaporator pressure.

$h_{expin} = h_{expout} = 120.39 \text{KJ/kg}$

Step 5: Calculating the Coefficient of performance (COP)

COP= $Q_{eva}/ W_c = m_r(h_{eva,out} - h_{eva,in})/ m_r(h_{com,out} - h_{com,in})$

COP = 2.72

Cost analysis for Vapour compression system and solar adsorption cooling system

Cost analysis for Vapour compression system and solar adsorption cooling system for capacity of 3.5 kW		
Type of system	VCRS	SARS
Initial cost	30,000 Rs	5 lacs
Running cost per year	18000 Rs	Negligible as compared to vcrs
Replacement cost(5 years)	30,000	Nil
Environmental pollution		

Conclusion:

Comparison for Various parameters for Vapour compression refrigeration system and solar adsorption refrigeration system		
System parameters	VCRS	SARS (Silica -Water)
Refrigeration capacity	3.5kW	3.5kW
Refrigerant mass	0.6 kg	1.280Kg
Adsorbent mass(Silica gel)	-------------------	21Kg
Heating power/Compressor work	1.21kW	8.3kW
Solar collector area	-------------------	35.58m^2
Evaporator surface area	0.82m^2	1.48 m^2
Storage tank Volume(Hot water)	-----------------	1.02m^3
Storage tank Volume(Chilled water)	-----------------	0.60 m^3
Condenser surface area	2.4 m^2(air cooled)	1.68 m^2
Adsorber bed surface area	-----------------	2.34 m^2
Mass flow rate of refrigerant/Chilled water	0.09m^3/hr	0.32 m^3/hr
Coefficient of Performance(COP)	2.72	0.42
Evaporator Pressure	200KPa	2.5 KPa
Condenser Pressure	1400 KPa	101 KPa
Cooling/heating cycle time	900 sec	Temperature cutoff

Table 4: Comparison of VCRS & SARS.

Solar Adsorption systems are heavy and bulky in size due to lower thermal inertia and coefficient of performance is much lower as compared to the conventional vapour compression refrigeration system. The use of solar collectors to supply the heat of adsorption ie, driving energy further increases the cost and space requirement. As the adsorption systems work under the vacuum pressure there is a great requirement to maintain the pressure below the atmosphere. As seen from the table for the same cooling capacity the evaporator size for the adsorption system is more than 65% as compared to the vapour compression system. Further the necessity to supply cooling continuously for 24 hours leads to the additional chilled water and hot water storage tanks, which increases the cost.

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