PERFORMANCE ANALYSIS OF A SOLAR-THERMAL AIR CONDITIONING (ST-AC) SYSTEM USING THREE STAGE VAPOUR ABSORPTION TECHNIQUE

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Abstract: - The world and our nation are struggling with two serious issues related to energy and climate change. The demand for energy is growing at an alarming rate every year. In the last years, growing demand for refrigeration and air conditioning has caused a significant increase in demand for primary energy. It is estimated that 30% of total energy generated is used for refrigeration and air-conditioning. From a sustainability perspective, directly using solar as a primary energy source is attractive because of its universal availability, low environmental impact, and lower running cost. Thus, solar cooling appears to be more attractive technique due the fact that when the cooling demand is high, the sunshine is strongest. Therefore use of solar energy is achieving more attention due to its potential especially in India as one of the reliable source. Almost all air-conditioning and refrigeration systems in use are vapour compression systems operated by grid-electricity. However, most ways of generating electricity used today has some kind of negative impact on the environment, whether it is emissions of carbon-, sulphur-, and nitrogen dioxide (fossil fuel plants), radioactive waste (nuclear power), destroyed rivers and water falls (hydropower) or noise pollution (wind power). Therefore it is desirable to reduce or at least to prevent the increase of electricity demand. Moreover, Refrigerants being used in traditional vapour compression systems also have harmful effects on human health and the environment. Thus, in this paper Performance Analysis of Solar Air Conditioning System using Three Stage Lithium Bromide -Water Vapor Absorption Technique has carried out that utilizes solar energy since their operating temperature is lower and which is more readily attainable with low-cost solar collectors.

Keyword:- Solar energy, Climate change ,Solar Air Conditioning and Three Stage LiBr-H2 O Vapour Absorption System

1. INTRODUCTION

Nowadays, safe, comfortable and higher standard of living has always been one of the main goals of the human being everywhere in the world. Development of refrigeration and air conditioning has played a vital role in fulfilling this goal. India, being a warm tropical country, most of the refrigeration and air conditioning applications involve cooling of air, water, other fluids or products and it accounts for a significant portion of the energy consumption in many manufacturing industries (such as chemicals, pharmaceuticals, dairy, food etc.), agricultural & horticultural sectors (mainly cold stores), domestic and commercial buildings (such as offices, hotels, hospitals, institutions, airports, theatres, auditoriums, malls, multiplexes, control-rooms, data processing centers, telecom sectors etc). Almost everywhere, traditional refrigeration and air conditioning systems are used and that are affecting the environment primarily in two ways. The first is due to the emissions of chlorofluorocarbons (CFCs) and hydro chloro fluorocarbons (HCFCs) used as refrigerants in these machines. Chlorine atoms in CFCs and HFCs are causing the breakdown of the ozone, which shields the earth from cancer-causing ultraviolet-B solar radiation. By 1985, scientists saw a drastic thinning of the ozone layer over Antarctica, an annual phenomenon dubbed the “ozone hole.” Recognizing these dangers, on September 16, 1987, world leaders from 24 nations signed the Montreal Protocol. Since then, new scientific proofs of the urgency of ozone damage have led all 196 members of the United Nations to ratify the treaty. The production of CFCs is already phased-out and the phasing-out of less active HCFCs is expected to be complete by 2030.

The second environmental concern due to conventional air conditioning is its impact on global warming. Most of the commonly used refrigerants in Vapour Compression Refrigeration (VCR) machines have very high Global Warming Potential (GWP). For example, HFC-134 a, one of the most widely used refrigerant blends, has GWP equivalent to 1320 times of CO2. Greenhouse gases are widely believed to contribute to an increase in the observed average temperature of the earth’s atmosphere , resulting in higher cooling demand and therefore creating a positive feedback loop. Selection of natural refrigerants which are ozone friendly and have lower GWP in air-conditioning and refrigeration systems would significantly benefit goals for environmental progress

1.1 Refrigeration & Air Conditioning Systems:

Refrigeration refers to the cooling of a system below its surrounding temperature whereas the term Air conditioning refers to simultaneous treatment or conditioning of air, control of its temperature, moisture content (humidity), quality and circulation as required by the occupants, a process or products in the region or space.

1.2 Principle of Refrigeration & Air Conditioning Systems:

Refrigeration is the process by which heat energy is transferred from a lower temperature space to a higher temperature space. The fundamentals of the refrigeration phenomenon are governed by the second law of thermodynamics. This is expressed in two equivalent forms which are given below.

1. The Kelvin-Planck Statement: *"it is impossible for a heat engine to produce network in complete cycle if it exchanges heat only with bodies at a single fixed temperature". Or "No process is possible whose sole result is the absorption of heat from a reservoir and the conversion of this heat into work."*

2. The Clausius Statement: "*it is impossible to construct a device which operating in cycle , will produce no effect other than the transfer of heat from a cooler to hotter body". Or "No process is possible whose sole result is the transfer of heat from a cooler to a hotter body."*

In essence, it is impossible to transport heat from a lower temperature to a higher temperature without the input of some form of energy. This is shown in the figure-1

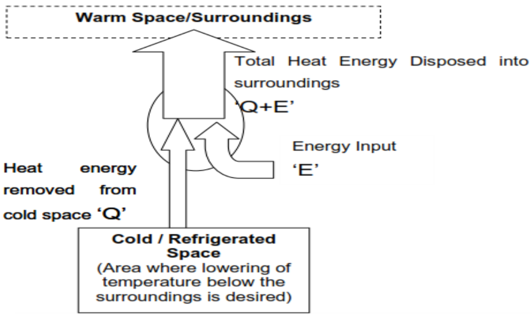

Fig-1, Principle of Refrigeration

1.3 Refrigeration System Efficiency:

The *cooling effect* of refrigeration systems is generally quantified in *tons of refrigeration.* The unit is derived from the cooling rate available per hour from 1 ton (1 short ton = 2000 pounds = 907.18 kg) of ice, when it melts over a period of 24 hours. British measuring units are still popularly used by refrigeration and air conditioning engineers; hence it is necessary to know the energy equivalents.

1 Ton of Refrigeration (1TR) = 3023 kcal/h= 3.51 kW
= 12000 Btu/hr

The commonly used figures of merit for comparison of refrigeration systems are *Coefficient of Performance* (COP), *Energy Efficiency Ratio* (EER) and *Specific Power Consumption* (kW/TR). These are defined as follows:

1.4 Coefficient of Performance of a refrigeration system:

The coefficient of performance (COP) of a system is defined as the ratio of the desired effect derived to the work input provided. The efficiency of refrigeration cycles are compare on this basis.

For a refrigeration system, this is the ratio of heat removed to the energy supplied:

COP = (Net Heat Removed / Net Energy Input)

$$= Q_{removed} / Q_{input} \qquad (1)$$

Energy Efficiency Ratio (EER) is the ratio of heat removal rating (kJ/hr)of a refrigeration system to energy input (kWhr) of the machine .

Higher COP or EER indicates better efficiency.

The other commonly used and easily understood figure of merit is

Specific Power Consumption = $\frac{\text{Power Consumption (kW)}}{Refrigeration\ effect\ (TR)}$

Lower Specific Power Consumption implies better efficiency.

1.5 Working of refrigeration & air conditioning systems:

The most commonly used systems for industrial and commercial refrigeration and air conditioning systems are vapour compression & vapour absorption systems.

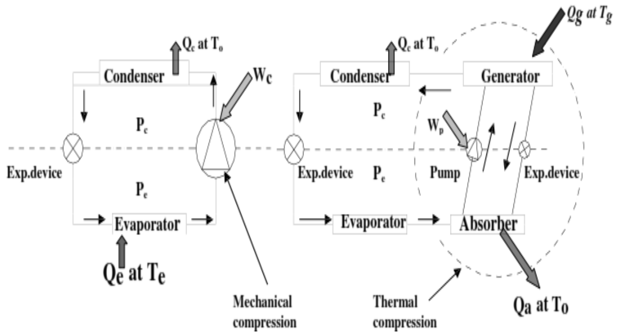

Fig-2, vapour compression & vapour absorption systems

Figure-2 show a continuous output vapours compression refrigeration system and a continuous output vapour absorption refrigeration system. As shown in the figure in a continuous absorption system, low temperature and low pressure refrigerant with low quality enters the evaporator and vaporizes by producing useful refrigeration Qe. From the evaporator, the low temperature, low pressure refrigerant vapour enters the absorber where it comes in contact with a solution that is weak in refrigerant. The weak solution absorbs the refrigerant and becomes strong in refrigerant. The heat of absorption is rejected to the external heat sink at T_0 . The solution that is now rich in refrigerant is pumped to high pressure using a solution pump and fed to the generator. In the generator heat at high temperature Tg is supplied, as a result refrigerant vapour is generated at high pressure. This high pressure vapour is then condensed in the condenser by rejecting heat of condensation to the external heat sink at T_0. The condensed refrigerant liquid is then throttled in the expansion device and is then fed to the evaporator to complete the refrigerant cycle. On the solution side, the hot, high-pressure solution that is weak in refrigerant is throttled to the absorber pressure in the solution expansion valve and fed to the absorber where it comes in contact with the refrigerant vapour from evaporator. Thus continuous refrigeration is produced at evaporator, while heat at high temperature is continuously supplied to the generator. Heat rejection to the external heat sink takes place at absorber and condenser. A small amount of mechanical energy is required to run the solution pump. If we neglect pressure drops, then the absorption system operates between the condenser and evaporator pressures. Pressure in absorber is same as the pressure in evaporator and pressure in generator is same as the pressure in condenser. It can be seen from Fig-2, that as far as the condenser, expansion valve and evaporators are concerned both compression and absorption systems are identical. However, the difference lies in the way the refrigerant is compressed to condenser pressure.

In vapour compression refrigeration systems the vapour is compressed mechanically using the compressor, where as in absorption system the vapour is first converted into a liquid and then the liquid is pumped to condenser pressure using the solution pump. Since for the same pressure difference, work input required to pump a liquid (solution) is much less than the work required for compressing a vapour due to very small specific volume of liquid ($w = -\int_1^2 v.dP$), the mechanical energy required to operate vapour absorption refrigeration system is much less than that required to operate a compression system. However, the absorption system requires a relatively large amount of low-grade thermal energy at generator temperature to generate refrigerant vapour from the solution in generator. Thus while the energy input is in the form of mechanical energy in vapour compression refrigeration systems, it is mainly in the form of thermal energy in case of absorption systems. The solution pump work is often negligible compared to the generator heat input. Thus the COPs for compression and absorption systems are given by:

COP_{VCRS} = (Net Heat Removed / Net Energy Input)

$$= \text{Desired Effect}/W_{\text{input}} = \frac{Q_e}{W_C} \qquad (2)$$

COP_{VARS} = (Net Heat Removed / Net Energy Input)

$$= \text{Desired Effect}/W_{\text{input}} = \frac{Q_e}{Q_g+W_p} \approx \frac{Q_e}{Q_g} \qquad (3)$$

Q_e = Heat absorbed by the refrigerant in evaporator.

Qg= Heat gain by the mixture in generator/ solar energy input

Thus absorption systems are advantageous where a large quantity of low-grade thermal energy is available freely at required temperature. However, it will be seen that for the refrigeration and heat rejection temperatures, the COP of vapour compression refrigeration system will be much higher than the COP of an absorption system as a high grade mechanical energy is used in the former, while a low-grade thermal energy is used in the latter. However, comparing these systems based on COPs is not fully justified, as mechanical energy is more expensive than thermal energy. Hence, sometimes the second law efficiency is used to compare different refrigeration systems. It is seen that the second law efficiency of absorption system is of the same order as that of a compression system.

2. SYSTEM DESCRIPTION:

Solar Energy Centre (NEC) or Nation Institute Of Solar Energy (NISE), Gwal Pahari, Gurgaon, Haryana, (India) is the national Research & Development Institution in the field of solar energy under MNRE, that assist the ministry in implementing The National Solar Mission and to coordinate research, technology, skill development, training and other related works. In this institution, a Solar Air conditioning system which is operated on Three Stage Vapour Absorption technique has been built to meet the cooling demand of its 13 rooms. Which uses Lithium Bromide-Water as the absorbent-refrigerant pair. The water in this solution is the refrigerant and Lithium Bromide is the absorbent. The designed COP of the system is 1.7. The heat source to TSVAS is from solar field.

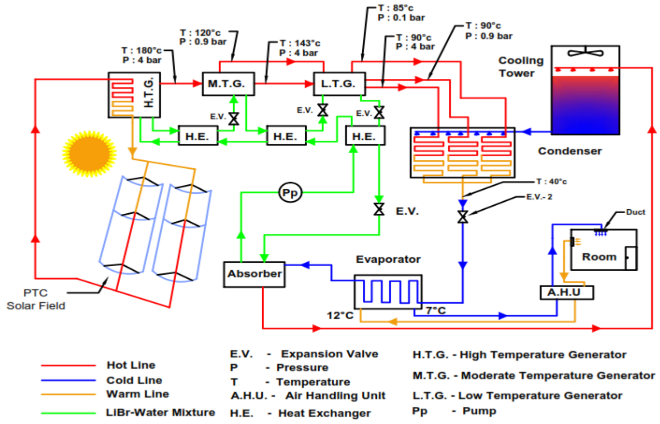

Fig-3, Three Stage Vapour Absorption System (TSVAS)

2.1 System Specifications:

Heat source : Hot water from solar collectors

Collector Type : 48no. Parabolic Trough Collectors

Hot Water Temperature : 210ºC,

Flow : 5 - 6 m^3/hr

Cooling capacity : 100 kW

Chilled water Temperature : 12/7ºC

Cooling water inlet Temperature: 32ºC

Thermal storage : Hot – 30 minutes

: Cold – 30 minutes

COP of cooling system : 1.7

2.2 Generator:

Since the system is stage vapour absorption system, there are three generators used, High Temperature Generator (HTG), Medium Temperature Generator (MTG) and Low Temperature Generator (LTG). The initial concentration ratio of LiBr + Water solution is 50/50. The hot fluid from solar field having a temperature up to 2100C (design temperatures are mentioned here) delivers heat to the HTG and leaves the generator at 2000C.The HTG is maintained at a pressure of 4 bar. In higher temperature the LiBr and water gets separated and the water will start evaporating taking away the heat supplied from the solar field. The water will evaporate at high temperature due to the presence of LiBr and the high pressure in the HTG due to boiling and evaporation of the refrigerant.

The refrigerant vapour leaves the HTG at180ºC, the concentrated LiBr and water in the HTG enters the MTG at 120ºC by giving away the heat in the Heat exchanger. The refrigerant vapour passes through the MTG which acts like a condenser for HTG. The pressure in MTG is maintained at 0.9 bar. The refrigerant gets condensed in the MTG at a temperature of 143ºC. The heat rejected by the refrigerant while condensing is utilized for evaporating the refrigerant from the LiBr and water solution in the MTG. The refrigerant from MTG evaporates at 120ºC. Both the condensed refrigerant at 143ºC and the refrigerant vapour of 120ºC enters the LTG. The concentrated solution of LiBr and water is sent to the LTG through Heat exchanger 2 and enters the LTG at a temperature of 85ºC. The pressure in LTG is maintained at 0.1 bar. The refrigerant vapour from MTG and condensed liquid of HTG will reject heat which is enough for the refrigerant to evaporate from LTG at a temperature of 85ºC and leaves the LTG. The refrigerant vapour of MTG condenses at a temperature of 90ºC. The condensed refrigerant of both HTG and MTG leaves the LTG at 90ºC. The more concentrated LiBr and water which has a concentration ratio of 65/35 is sent to the absorber through Heat Exchanger 3.

2.3 Condenser:

All the three outlets from the LTG go into the condenser and the heat is rejected from the refrigerants of different pressures by the circulation of cooling water in the condenser. The refrigerant leaves the condenser at a temperature of 40ºC.

2.4 Evaporator:

The condensed refrigerants of different pressures get mixed in the evaporator. The evaporator is maintained at 0.01 bar pressure. Due to sudden drop in pressure in this chamber,

flashing occurs and water gets vaporized by taking away the latent heat in the circulated chilled water (12ºC). Thus the temperature of chilled water is reduced to 7ºC. The chilled water obtained is sent into the air conditioner and this result in cool air. The water from the air conditioner obtained at 120C is sent again to the evaporator.

2.5 Heat Exchangers:

There are three heat exchangers in the TSVAS which are present between LTG-MTG, MTG-LTG and LTG-Condenser. The heat exchanger serves the purpose of pre-heating the LiBr and water solution before sending them to HTG from absorber. If heat exchangers are not used then it will require a large quantity of heat to be supplied to the HTG for increasing the temperature from 40ºC to 180ºC.

2.6 Thermal Storage:

The system has thermal storage for operating when there is not enough input from the solar field. The Air-conditioning system is connected with 13 AC units. Presently 6 units are operating. The thermal storage is available for both hot and cold. It has back-up for 30 minutes. If only one unit is operating then by the storage it can run for 13 hours. The material used in this is PCM (Phase changing material). It must be noted hear that, Hot thermal Storage PCM Melting Point is 200˚C and Cold thermal Storage PCM Freezing point is 9˚C.

2.7 Absorber:

The refrigerant vapour after flashing in the evaporator is sucked into the absorber by the absorbent. The vapour after absorbed by the absorbent becomes liquid by giving away the heat. Thus the concentration ratio of the LiBr and water again comes to 50/50. The heat rejected is removed by the same water from the cooling tower after passing through the condenser. And the LiBr-water is sent back to the HTG through the 3 regenerators mentioned before.

3. PERFORMANCE ANALYSIS:

3.1 Analysis of system using three stage vapour absorption technique:

A control volume is taken across each component i.e. the generator, absorber, evaporator, condenser and heat exchanger to analyze the working conditions of all components of the system. A steady flow analysis of the system is carried out with the following assumptions:

- System is under steady state
- Changes in potential and kinetic energies across each component are negligible
- No pressure drops due to friction
- Only pure refrigerant boils in the generator.

The analysis is carried out on the designed value of TSVAS and working fluid as refrigerant is water, thus the property of water / steam can determined by using standard steam stables.

Hot water temperature = 210˚C
Temperature of refrigerant vapour from HTG = 180˚C
Temperature of refrigerant vapour from MTG = 120˚C

Temperature of refrigerant vapour from LTG = 85˚C

Pressure at HTG = 4 bar, Pressure at MTG = 0.9 bar

Pressure at LTG = 0.1 bar, Pressure at Evaporator = 0.01 bar

Taking mixture of LiBr & H_2O as 10kg by mass

Initial Amount of absorbent and refrigerant in HTG

= 10kg mixture of (LiBr + H2O) = 5kg LiBr + H2O 5kg

= Water (50% LiBr + 50% H2O)

The final concentration level that has to be maintained

= 65% LiBr + 35% H2O

Total water that have to be evaporated from all the three generators

= 10 – (5/0.65) = 2.31 kg

The remaining concentrated solution sent to the absorber

= 7.69 kg.

The amount of water that to be evaporated from each generator = 2.31 / 3= 0.77 kg

Final Concentration ratio maintained in HTG

= 5 / (10 – 0.77) LiBr = 0.54 LiBr = 54% LiBr / 46% H2O

Final Concentration ratio maintained in MTG

= 5 / (10 – (2 x 0.77)) LiBr = 0.59 LiBr

= 59 % LiBr / 41 % H2O

Final Concentration ratio maintained in LTG

= 5 / (10 – (3 x 0.77)) LiBr = 0.65 LiBr

= 65% LiBr / 35 % H_2O

3.2 **Analysis of Heat Exchanger:**

To calculate the temperature of LiBr and water solution coming from the absorber to the generator, we have analyse all the three heat exchanger

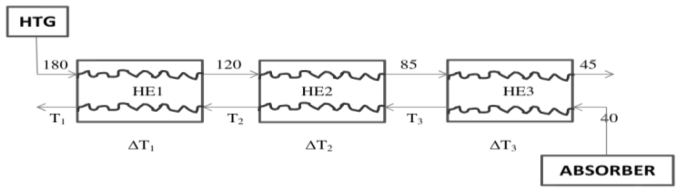

Figure-3, schematic diagram of heat exchanger

Applying energy balance at each heat exchanger, we get

Heat Exchanger 3:

We have, M_1 Cp ΔT = M_2 Cp ΔT

9.23(180-120) = 10 ΔT_3, ΔT_3 = 26.915

T_3=26.91+40=66.91˚C

Heat Exchanger 2:

8.46(120-85) = 10 ΔT_2, ΔT_2 = 29.61

T_2 = 66.915 + 29.61 =96.52˚C

Heat Exchanger1:

7.69(85-50) = 10 ΔT_1, ΔT_1 = 55.38

T_1 = 96.525 + 55.38 = 151.9˚C

3.3 Analysis of High Temperature Generator (HTG):

Sensible heat supplied = 10(180-151.9) =281 kcal =1180.2 KJ

Enthalpy of steam at 180°C= 2817.04KJ/kg, using steam table

Enthalpy of water at 180°C = 763.1 KJ/kg, using steam table

Latent Heat Supplied = (2817.04 - 763.1) x 0.77 kg

= 1581.53 KJ

Total Heat Energy supplied = 1180.2 + 1581.53

Net Energy Input to Generator (Q_g) = 2761.73 KJ

3.4 Analysis of Medium Temperature Generator (MTG):

Enthalpy of steam at 180°C = 2817 KJ /kg, using steam table

Enthalpy of water at 4 bar pressure = 604.7KJ/kg,

Heat rejected by condensation = (2817.04 - 604.7) x 0.77

= (2213 KJ) x 0.77 = 1704.01 KJ

Enthalpy of steam at 120°C = 2717 KJ /kg, using steam table
Enthalpy of water at 120°C = 503.7 KJ /kg, using steam table

Heat required for evaporation = (2717-503.7)x 0.77 =1704 KJ

3.5 Analysis of Lower Temperature Generator (LTG):

Enthalpy of steam at 120° C = 2717 KJ/kg, using steam table

Enthalpy of water at 0.9 bar pressure = 405.2 KJ/kg

Heat rejected by condensation by vapour from MTG

= (2717 - 405.2) x 0.77 = 2311.8 x 0.77 = 1780.086 KJ

Heat rejected by HTG tube = 0.77 x (597.7 - 402.2)

= 150.535KJ

Total heat rejected in LTG = 1930.021 KJ

Enthalpy of steam at 85°C = 2658.82 KJ/kg, using steam table Enthalpy of water at 85°C = 355.9 KJ /kg, using steam table

Heat required for Evaporation = (2658.82-355.9) x 0.77

= 2302.92 x 0.77 = 1773.24 KJ

3.6 Analysis of Condenser:

Enthalpy of steam at 85°C = 2658.82 KJ/kg, using steam table

Enthalpy of water at 45° C = 188.4 KJ/kg, using steam table

Heat given out while condensation of vapour from LTG

= 0.77 x (2658.82 - 188.4) = 1902.2234 KJ

Enthalpy of water at 96°C = 402.2 KJ/kg, using steam table

Heat given by condensed refrigerant from HTG & MTG

= 2 x 0.77 x (402.2 – 188.4) = 329.252 KJ

Total Heat Rejected = 1902.2234 + 329.252 = 2231.475 KJ

3.7 Analysis of Evaporator:

Enthalpy of steam at 0.01 bar= 2514.4KJ/kg,using steam table

Cooling effect produced = 2.31(2514.4-188.4)

Q_e = 5373.06 KJ

COP_{VARS} = (Net Heat Removed / Net Energy Input) = $\frac{\mathbf{Q_e}}{\mathbf{Q_g}}$

COP_{VARS} = (Cooling Effect Produced / Net Energy Input) = $\frac{Q_e}{Q_g}$

$$\mathbf{COP} = \frac{Q_e}{Q_g} = \frac{5373.06}{2761.73} = \mathbf{1.946}$$

COP = 1.946

Taking overall losses as 10 to 12%, then value of COP obtained from the theoretical analysis is 1.71 (COP = 1.71), which is approximately matching with operating value/ designed value of the system.

3.8 Some Practical problems with water-lithium bromide systems are:

- Crystallization
- Air leakage, and
- Pressure drops

To prevent crystallization the condenser pressure has to be maintained at certain level, irrespective of cooling water temperature. This can be done by regulating the flow rate of cooling water to the condenser. Additives are also added in practical systems to avoid crystallization. Since the entire system operates under vacuum, outside air leaks into the system. Hence an air purging system is used in practical systems. Normally a two-stage ejector type purging system is used to remove air from the system. Since the operating pressures are very small and specific volume of vapour is very high, pressure drops due to friction should be minimized. This is done by using twin- and single-drum arrangements in commercial systems.

4. CONCLUSION:

Utilization of this type system for air conditioning has significant importance as the demand of cooling is maximum, when the solar intensity is also maximum. Secondly it has no any negative impact on human health as well on the environment. Moreover, from the above analysis results, it clear that the performance (COP) of the a solar air conditioning system using three stage vapour abortion technique is increased by about 2.2 times (just double) that of the convention single stage vapour absorption system and it 50% more than that of double stage vapour absorption system. As the COPs obtained for a single stage system in range of 0.6 to 0.75 and for a double stage system it of the order of 1.2 to 1.38 as reported by many researchers and system producing companies. Again from the economy point of view, The payback of this system is dependent only on electricity rates, peak charges and the availability of solar radiations. It is assumed that the payback time will be significantly shorter in future as the fuel prices and electricity charges are increasing. Furthermore, the development and research in solar energy is going on, which will make solar energy cheaper.

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