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Research Article

Performance evaluation and COP calculation of Triple effect vapour Absorption machine working on Solar Thermal energy

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Abstract

The research paper deals with performance evaluation of a triple effect vapour absorption machine based on lithium bromide solution. The triple effect VAM at the National Institute of Solar Energy also has a provision of storage of heat and cool in PCM (phase change material) where excess heat from the solar field at peak hours is stored and the excess cooling effect generated at part load is stored in different PCM chambers when no radiation is available, especially at night time. The water in this mixture is the absorbent or refrigerant and Lithium Bromide is the absorber. The required heat source temperature is usually above 80°C for single-effect machines and the COP is in the range of 0.6 to 0.7. In triple effect systems, COP of 1.7 has been demonstrated at 210⁰C.

Keywords: *Vapour absorption machine, triple effect VAM, COP, performance, evaluation, Lithium Bromide, Thermodynamics, parabolic trough collectors, solar energy, Phase change material.*

Introduction

India lies in the sunny regions of the world. Most parts of India receive 4-7 kilowatt hours of solar radiation per square metre per day with 250-300 sunny days in a year. (Energy Sources: Solar, 2011) The highest annual radiation energy is received in western Rajasthan while the North-Eastern region of the country receives the lowest annual radiation.

Solar energy in the form of heat is required for many purposes in the domestic, agricultural, industrial and commercial sectors of the economy, like water heating, air heating, cooking, drying of agricultural and food products, water purification, detoxification of wastes, cooling/refrigeration, electrical power generation, etc. Solar thermal energy can meet many of these needs in a cost-effective and reliable manner. In principle, a solar thermal system absorbs incident solar energy, converts into heat and transfers it to a medium such as water or air for use in various applications. The use of solar can partially or fully replace the conventional fuels such as coal, oil and electricity. Solar thermal technology has a tremendous potential for saving conventional energy in India. Solar thermal technology depends upon 5 factors:

a) Direct Normal Radiation: The direct sun rays are only concentrated on to the receiver. Diffused radiation plays a role only in non-concentrated systems. Higher the DNI, higher will be the power output but unlike the photovoltaic systems, the energy conversion efficiency is not linearly related to radiation.

b) **Ambient Temperature**: The ambient or surrounding temperature affects the system greatly. They work on an optimal ambient temperature with maximum efficiency and it lowers on temperatures other than this.

c) **Latitude Effect**: As the seasonal change occur, the inclination of the place with respect to the sun changes, the cosine losses in the one-way tracking systems differ accordingly and cause performance change. These solar systems are fixed at latitude angle of the place. During summer, when the inclination of solar radiation is less, the cosine losses are losses and the radiation received on to the system is more and vice versa during winter season.

d) **Wind Speed**: The wind speed affects the systems in a way that they increase the convection losses occurring in the systems.

e) **Required temperature**: Higher the temperature required, higher are the losses and thus the efficiency of the system decreases.

Solar Thermal technologies can be divided into 2 main types, namely

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1. Non-concentrating collectors

In this technology, solar radiation falling on the collector is absorbed by it and converted into heat and this heat is transferred to water or air for different purposes. These are small systems comparatively and used for water heating, drying of products, etc. These are of two types:

a. Flat plate collector
b. Evacuated/-Non-evacuated tube collector (Heat pipes)
c. Solar chimney.

2. Concentrating collectors

Concentrating systems focus direct solar radiation through optical devices onto an area where a receiver is located. The radiation is transformed into heat and this heat is transferred to water, steam or any thermic oil. These systems are larger than non-concentrated systems and are used for mainly power generation. These systems can be sized for village power (10KW) or grid connected applications (up to 100MW). The different types of concentrating systems are:

a. *Parabolic Trough*
b. Dish concentrator (Stirling engine)
c. Heliostat (Central Tower Receiver)
d. CLFR (Compact Linear Fresnel Lenses).

These systems have their highest potential in the "sun belt" of the earth, which is between the 20th and 40th degree of latitude south and north.(Martin and Goswami, 2005) These systems can be combined with natural gas (gasifier engine systems) and the resulting hybrid power plants provide high-value power.

Materials and Methods

Vapour Absorption Machine (VAM) at National Institute of Solar Energy is a 'Triple Effect System' and uses Lithium Bromide-Water mixture. The water in this mixture is the absorbent or refrigerant and Lithium Bromide is the absorber. The required heat source temperature is usually above 80°C for single-effect machines and the COP is in the range of 0.6 to 0.7.(Spanish CSP Plant with Storage Produces Electricity for 24 Hours Straight) In triple effect systems, COP of 1.7 has been demonstrated at 210⁰C.

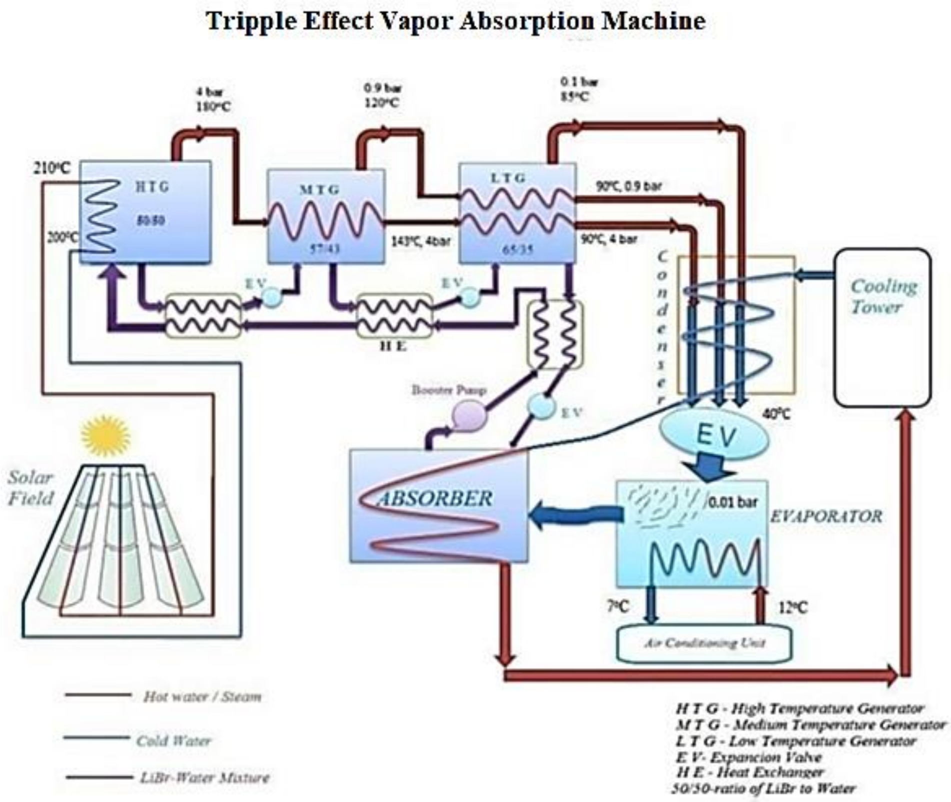

Fig 1: Process Flow Diagram of Triple Effect Vapour Absorption System

System Specifications

Heat source: Hot water from solar collectors
Heat Source: 48 no. Parabolic Trough Collectors,
Outlet Temperature: 210ºC,
Inlet: 200 ºC
Flow: 5.4 m3/hr
Hot water temperature: 210ºC
Cooling capacity: 100 kW
Chilled water Temperature: 12/7 ºC

Cooling water inlet Temperature: 32 ºC
Thermal storage: Hot – 30 mins, Chilled – 30 mins (PCM for short duration)

COP of cooling system: 1.7

The detailed process in the various components of the triple effect system is as follows:

Generator

The generator at the Solar Energy Centre is a 'triple effect' system, i.e. it has 3 chamber generators. This system has the LiBr-Water mixture. The thermic fluid from solar field delivers heat to the mixture at 210⁰C (design temperatures are mentioned here) and leaves the generator at 2000C in the first chamber which is maintained at 4 bar pressure. The heat from the thermic fluid is taken up by the mixture and water gets evaporated. The evaporation temperature of water is increased due to presence of LiBr and high pressure. Steam at 180⁰C leaves the first chamber and the LiBr-water mixture having lesser concentration than the first due to generation of steam, falls down and enters the second chamber due to pressure difference and also to get the mixture to the second generator's pressure condition, slow throttling is done. This is done with the help of a regenerator which delivers the heat to the same mixture at the end of the cycle. The steam from the first chamber passes through the second chamber of the triple effect system which has the LiBr mixture from the first chamber, which is maintained at 0.9 bar pressure and 1200C. Heat is exchanged in the second chamber and steam is obtained at 120⁰C and 0.9bar. Due to the loss of heat obtained from the steam from the first chamber condenses and we get water at 143⁰C and 4bar. The LiBr from this falls similar to the case before and the mixture is passed to the third chamber through the second regenerator which is maintained at 85⁰C and 0.1bar pressure. The water from the first chamber and the steam from the second chamber pass through this third chamber for heat transfer to obtain a) water at 4 bar pressure and approx. 90⁰C from the first pipe, b) water at 0.9bar pressure and approx. 900C from the second pipe and c) steam at 85⁰C and 0.1 bar pressure. LiBr mixture obtained from the 3rd chamber falls into the absorber. Heat input is only once in the first chamber and we obtain 3 outlets into the condenser, thus triple effect system.

This process cannot be done further to generate 4th outlet because then the first chamber of the generator has to be maintained at more high conditions and the mixture (higher concentration of LiBr) obtained after the 4th chamber is toxic. Also, the corrosion of the system parts (pipes) takes place. But the 4th effect might be achieved if another liquid is added with LiBr as absorber and water as the only absorbent. No substantial result has been obtained for such systems till date.

Condenser

All the three outlets from the generator go into the condenser where we obtain water at around 40⁰C temperature (depending upon the time of the year) but all at their respective pressures. The condensation is obtained by exchanging heat with water from a cooling tower.

Evaporator

The water from the three outlets of the condenser enters into the evaporator, which is maintained at 0.01 bar pressure. Water from the three pipes mix in this chamber and due to sudden drop in pressure in this chamber, flashing occurs and water gets vaporized. For this purpose, latent heat of vaporization is required which is taken from water in a pipe entering at 120C and chilled water at 70C is obtained. With this, vapours at very low pressure are sent into the absorber chamber.

The chilled water obtained is sent into the Air Conditioner and this results in cool air. The water from the air conditioner obtained at 120C is sent again to the evaporator

Absorber

Vapours after flashing in the evaporator are sucked into the Absorber chamber due to a back pressure built up in the chamber where it forms water droplets and these droplets get absorbed by LiBr and also heat is rejected for the condensation of water and forming the LiBr-Water mixture. This heat is removed by the same water from the cooling tower and the LiBr-water is sent to the Generator chamber through a booster pump to get it to the generator pressure and then through the 3 regenerators mentioned before into the first chamber at initial conditions and the cycle is completed.

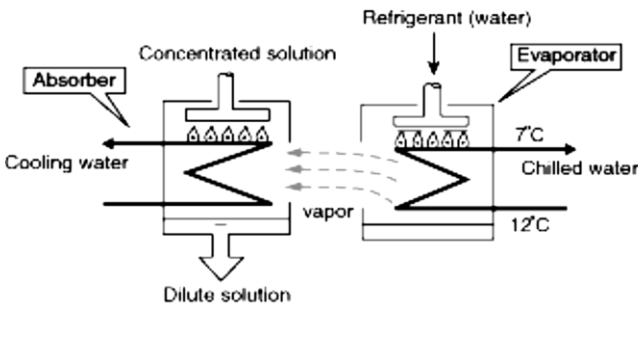

Fig.2 Absorbent-Absorber cycle (LiBr-Water cycle)

The triple effect VAM at the Solar Energy Centre also has a provision of storage of heat and cool in PCM (phase change material) where excess heat from the solar field at peak hours is stored and the excess cooling effect generated at part load is stored in different PCM chambers when no radiation is available, especially at night time.

This VAM is the most efficient in the World with Coefficient of Performance about 1.7

Theoretical Analysis

A triple effect system will produce steam thrice for a single input of heat into the VAM. Considering 1kg/hr of steam is produced from the first generator which in turn produces 'x' kg/hr of steam from the second generator and the heat from these two produces 'y' kg/hr of steam from the third generator. We can calculate these values by using energy balance equations and the enthalpy values from the steam tables at the various states.

Latent heat at 4 bars = H4bar = 2133.8 KJ/kg
Latent heat at 0.9bar = H0.9bar = 2266.24 KJ/kg
Latent heat at 0.1bar = H0.1bar = 2392.8 KJ/kg
Latent heat at 0.01bar = H0.01bar = 2484.9 KJ/kg
Let $H_{p,\ t,\ s}$ represent enthalpy at pressure 'p' bar, temperature 't' °C and 's'-state.
$H_{4,180,v}$ = 2817.12 KJ/kg $H_{4,143,l}$ = 604.73 KJ/kg
$H_{4,90,l}$ = 376.9 KJ/kg $H_{4,180,l}$ = 763.21 KJ/kg
$H_{0.9,120,v}$ = 2717.33 KJ/kg $H_{0.9,120,l}$ = 503.69 KJ/kg
$H_{0.9,90,l}$ = 376.9 KJ/kg $H_{0.1,85,v}$ = 2659.03 KJ/kg
$H_{0.1,45.8,v}$ = 2584.6 KJ/kg $H_{0.01,6.98,v}$ = 2514.2 KJ/kg

Now, in the second generator, steam having enthalpy 2817.12 KJ (at 1kg/hr) produces 'x' kg/sec steam by giving the required latent heat; therefore, balancing the enthalpies,
1*(H4, 180, v – H4, 143, l) = x*[H0.9, 120, v – H0.9, 120, l]
→ x = [2817.12 – 604.73] / [2717.33 – 503.69] = 0.99 kg/hr
Now, in the third generator, the two fluids from 1st and 2nd generator produce 'y' kg/sec steam by giving the required latent heat; therefore, balancing the enthalpies,
$1*(H_{4,143,l} - H_{4,90,l}) + 0.99*(H_{0.9,120,v} - H_{0.9,90,l}) = y*[H_{0.1,85,v} - H_{0.1,85,l})$
→ y = [(604.73 – 376.9) + 0.99*(2717.33 – 376.9)] / [2659.03 – 355.88] = 1.1 kg/hr

Now, the initial concentration in the first generator is 50/50 and the final concentration after generation of steam from the third generator is 65/35. So, after the third generator, we get 3.1kg/hr water/steam and the mixture going to the absorber is at 9.5 kg/hr. the total mixture from the absorber (at 40°C) is taken through the three heat exchangers, into the first generator at 12.6 kg/hr. assuming LiBr has specific heat equal to that of water = 1KCal/sec.

Balancing the mass and heat transfer in the regenerators, we get

3rd re-generator/heat exchanger

9.5kg/hr mixture is going from 85°C to 45°C and gives heat to 12.6kg/hr mixture.
9.5*(85 - 45) = 12.6*(t3 - 40)

Therefore, temperature after exchanging heat from the third generator = t_3 = 70.5°C.

2nd re-generator/heat exchanger

9.5+1.1(steam generated from 3rd is present in the mixture of the 2nd) kg/hr is going from 120°C to 85°C and gives heat to 12.6 kg/hr mixture.
10.6*(120 - 85) = 12.6*(t2 – 70.5)

Therefore, temperature after exchanging heat from the second generator = t_2 = 95.5°C.

1st re-generator/heat exchanger

9.5+1.1+0.99 (steam generated from 2nd is present in the mixture of the 1st) kg/hr is going from 180°C to 120°C and gives heat to 12.6 kg/hr mixture.
11.59*(180 - 120) = 12.6*(t1 – 95.5)

Therefore, temperature after exchanging heat from the first generator = t1 = 150.69°C.

The heat input from the solar field = heat for taking the mixture from 150.69°C to 180°C and converting water to steam at 180°C.

→ Q1 = [12.6*4.187*(180 – 150.69)] + [1*(2817.12 – 763.21)] = 3600.21 KJ/hr = 1KW

These three mix in the evaporator but before that, these are flashed slowly and then they enter into the evaporator which is maintained at 0.01bar pressure and evaporate at that point. Considering that the flashing process as an isentropic one.

Entropy before flashing = s = 0.5724 KJ/kg-K

The enthalpy after flashing can be calculated from this entropy of the steam/water mixture at 0.01bar and the dryness fraction, which can be calculated from the steam tables, i.e.

H_1 = 159.98 KJ/kg.

For evaporation, it takes heat from the water flowing through the AC as explained before. Therefore,

Heat taken from the water =

$(1+x+y)*(H_{0.01,6.98,v} - H_1)$ = (1+ 0.99 + 1.11)*(2514.2 – 159.98)
→ Q2 = 7298.08 KJ/hr = 2 KW

Coefficient of Performance (COP) = Q2/ Q1 = **2.02.**

The system was considered to follow ideal conditions but approximately 10% losses are occurred in the re-generators/heat exchangers and also the specific heat of LiBr was taken equal to that of water for simplicity of calculations but is higher than that. When these points are taken into consideration, the Coefficient of Performance goes to 1.7.

Fig.3 Actual Experimental setup of Triple effect vapour absorption machine at National Institute of Solar Energy

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