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Review

Thermal analysis of evacuated solar tube collectors

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A detailed design of the evacuated tube collectors is enumerated followed by the thermal network analysis of this collector. The temperature of each component is determined empirically. Numerical analysis is applied to find the coefficient of heat transfer across the air gap from absorber plate to the copper tubes. The performance characteristics of these collectors are analyzed and compared with commercially available brands to test their capability to power the generator of an absorption chiller. The generator of a typical 1 KW capacity refrigeration system is designed based on the hot water made available from outlet of evacuated tube collectors.

Key words: Evacuated tubes, heat transfer applications and absorption chiller.

INTRODUCTION

Various researches in the field of solar thermal conversion have deemed the prospect of using solar energy for space heating and cooling. It is a known fact that during the day, when the solar radiation is at its maximum and the ambient temperatures are soaring, the cooling requirement reaches its peak. Research is concentrated on the conventional compression cycle or the vapor absorption refrigeration cycle. With regard to the use of alternative source of energy, the vapor absorption system is a more viable option since it uses thermal heat to power the cycle. This energy could be sourced from the sun. As the cooling requirements are concurrent with the amount of solar radiation depending upon the time of the day, scientists and researchers find the idea of using solar thermal collectors viable. Although flat plate collectors are commonly in use but evacuated tube collectors are more appropriate for the space heating and cooling applications.

These collectors perform well in both direct and diffuse solar radiation and offer the advantage that they work efficiently with high absorber temperatures (Salah, 2009).

Evacuated tube collectors

Conventional flat plate collectors are suited for warmer climates and for the times when the intensity of the solar radiation is substantially high. Their benefits are however reduced when they are exposed to cold, cloudy and windy days. Furthermore, when exposed to weathering conditions, the tubes and the insulation has a tendency to deteriorate thereby causing loss of performance. Each evacuated tube consists of two glass tubes made from extremely strong borosilicate glass. The outer tube has very low reflectivity and very high transmisivity that radiation can pass through. The inner tube has a layer of selective coating that maximizes absorption of solar energy and minimizes the reflection, thereby locking the heat. The ends of the tubes connected to the copper header are fused together and a vacuum is created between them. This process is called as evacuation, as by definition, it means that the air is pumped out from the cavity. The vacuum is created to recreate the thermos flask effect as vacuum acts as an insulator and does not allow short wave radiation to escape through the glass tube. This traps the solar radiation much more effectively and hence higher temperatures can be achieved. This process is shown in Figure 1. It means that the evacuated tube collectors have a capacity to perform better than flat plate collectors in cold and cloudy climates. On the internal surface of the inner borosilicate glass tube there is a absorber plate which collects the radiation that passes through the glass layer. This absorber plate is mostly of aluminum or copper as both of these metals have a high heat reflectivity and transmitivity quotient. It is also painted black so as to allow it to absorb maximum amount of solar radiation.

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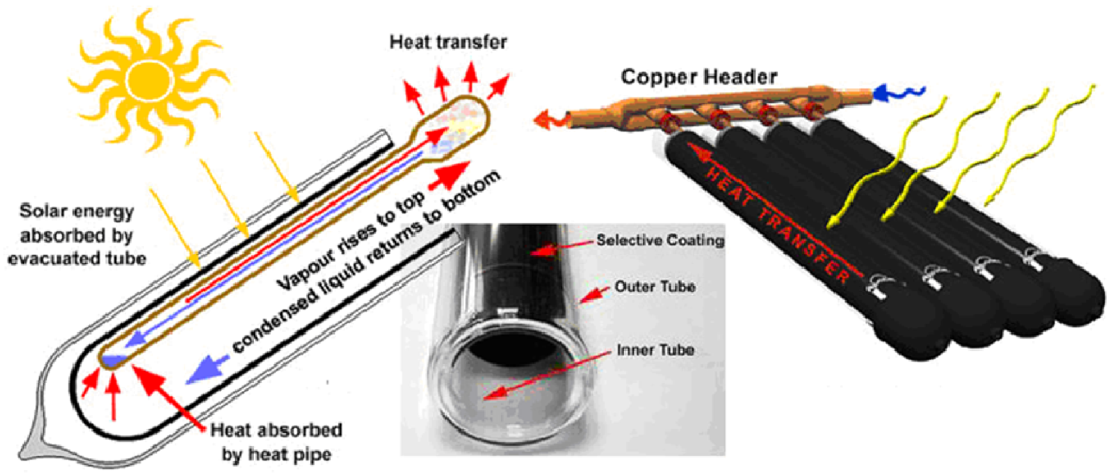

Figure 1. Design and working of evacuated (or vacuum) tubes pane.

Table 1. General parameters for design of evacuated tube collectors (Holman, 2005).

Parameter	Value
Glass tube diameter	65 mm
Glass thickness	1.6 mm
Collector length	1965 mm
Absorber plate material	Copper
Coating	Selective
Absorber area	0.1 m^2

Table 1 shows the typical dimensions of the vacuum tube collectors with type of used material. The glass tube diameter should be just enough to allow maximum amount of solar radiation to transmit through the collector system. The absorber tube is a blackened surface so it acts as a black body and ideally has $\alpha = \varepsilon \sim 1$ (Holman, 2009). Because the absorber area has to be maximized, the absorber plate is placed in direct contact with the inner glass tube. Evacuated tube collectors are used for a variety of applications such as: space heating and cooling, industrial and domestic hot water requirements. The design of evacuated tube collectors is complicated and is based on the thermos flask effect that is. heat loses from the low intensity radiation emitting from the interior tube are minimized. Various brands are available with similar designs and most manufacturers are based in Germany and in United States. Since Germany is a big market for solar energy conversion based products, their products are much more accomplished and have a better quality.

To enable the heat output of the evacuated tube collectors to power the generator of an absorption chiller, a pool type heat exchanger needs to be retrofitted to the generator section. This is done to facilitate optimum heat exchange and to maintain regulated flow.

Viability of use of evacuated tube collectors

A lot of research has been performed to find the viability of the use of evacuated tube collectors for applying them in single direct heat exchanger type absorption chiller. Various factors must be considered before designing a solar powered system.

Intensity of solar radiation

Measurements of intensity of solar radiation are important because of the increasing number of solar heating and cooling applications. Because the rate of receipt of solar radiation on a given surface on the ground depends on the orientation of the surface with reference to the sun it is important that we design the system is based on solar variables (NASA, 2007).

1. Performing the study of various products available in the market and finding which one is feasible for the particular application.
2. Finding out the heat transfer characteristics and solution of the thermal network of various components (Jean, 2005).
3. In order to model the evacuated tube collector, a number of simplifying assumptions have to be made (Jean, 2005).
4. These assumptions must be in accordance with actual values used in industry.

As most of the products are certified by various test labs in Europe and America, they conform to a certain test standard. The ANSI/ASHRAE test standard 93-2003 specifies the design of solar collectors and stipulated the

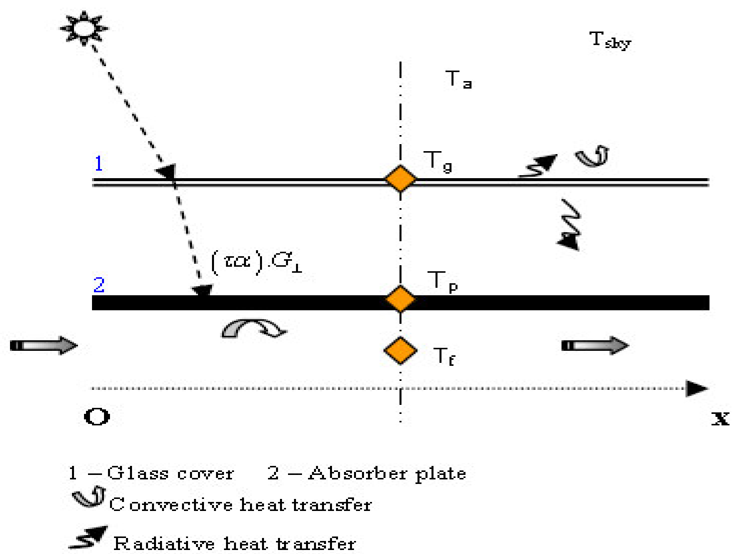

Figure 2. General description of the collector model (Jean, 2005).

Table 2. Properties of the outer borosilicate tube.

Property	Value
Transmitivity (τ)	0.92 (given)
Refractive index, n	1.474
Mean diameter	47 mm
Length	1500 mm

minimum criteria for a product to be made commercially available.

THERMAL ANALYSIS OF EVACUATED TUBE COLLECTORS

To create a thermal circuit so that heat transfer from the surface of the collector tube to the copper tubes can be explained. The amount of solar radiation incident on the face of the tube can be determined from the empirical relations. In effect this analysis is only suitable for a similar value of solar radiation.

General description and thermal network of collector tubes

The evacuated tube collectors have an outer and an inner casing of borosilicate glass 3.3. These tubes are sealed at each end and between them a vacuum is maintained to allow minimal heat loss due to radiation from the absorber plate. As solar radiation is incident on the outer layer of the borosilicate glass tube, a part of it is absorbed, part reflected back into the atmosphere and most of the radiation is transmitted to the next layer of glass tube. The properties of the outer borosilicate tube are given in Table 2. This arrangement is shown in Figure 2. Since,

$\tau = 0.92$
$\alpha = 1 - 0.92 - 0.04 = 0.04$

From the empirical relations, the insolation at Dubai's latitude and longitude incident on a horizontal collectors is measured to be approximately = 8.35 KWh/m^2 day. Figure 3 depicts a typical solar radiation curve over a clear day. The readings on the graph are been plotted every 15 min to obtain accuracy and correctness of the readings. The graph clearly explains the gradual rise and fall of the intensity levels of radiation. The area under the curve of this graph gives the value in KWh/m^2 day as radiation is only available from 7 AM to nearly 7 PM depending upon the season. The data calculated indicates a value of 8.35 KWh/m^2 day incident in Dubai, it represents the entire area under the curve of the Figure 3. To obtain the peak value of insolation, it is required that this value is divided with an approximate number of bright sunshine hours.

Assuming that May 15 is a clear day with no clouds and 8 h of bright sunshine, the radiation received/m^2 at every incident would be = 8.35/8 ~ 1050 KW /m^2. The further calculations are based on this value of incidence solar radiation flux.

$$G\,\alpha_{sun} = \alpha_{low\ temp}\,\sigma\,(T^4 - T^4_{surr})$$

Assuming the value of α_{sun} = 0.12 as given in Rai (2009), and the T_{surr}= 40°.

The temperature of the outer glass plate is calculated to

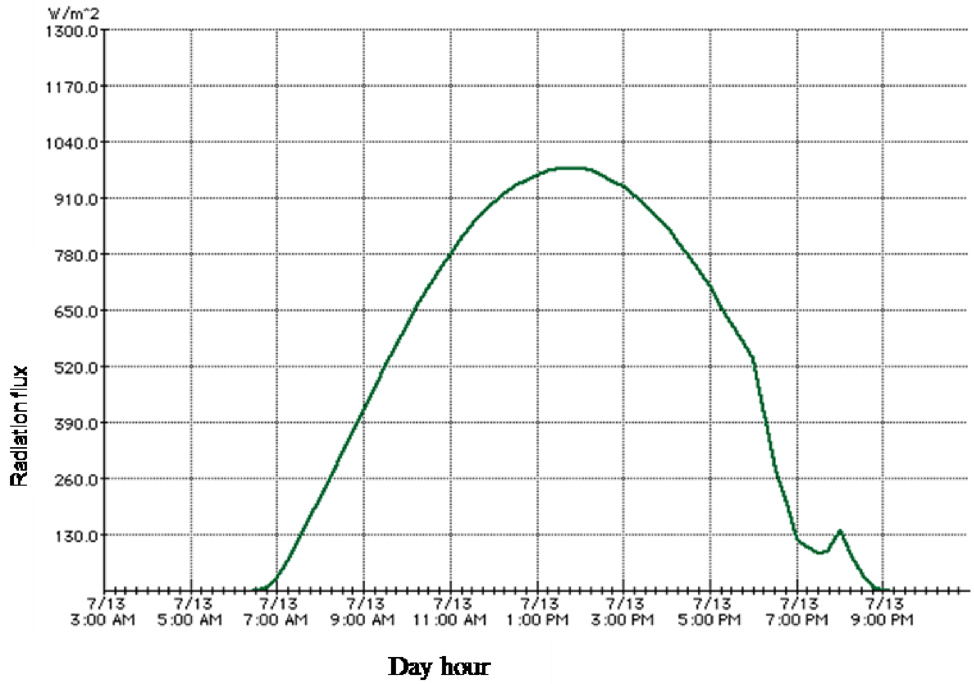

Figure 3. Daily solar radiation map.

be 232°.

It is further assume that the total incident energy available on the surface is;

G x Aperture Area.

Total incident energy = 1050 x 0.110685
= 116.219 W.

The temperature of the outer tube is determined and it is therefore required to calculate the temperature of the inner glass tube. As the two tubes are separated by a vacuum and we have assumed that no convection and only transmission takes place from the top layer.

$Energy_{trans}$ = τ x Energy Incident.
$Energy_{trans}$ = 0.92 x 116.219 W
= 106.92171 W

Using the aforementioned equation:

$106.92171 = 3.14 \times (0.037) \times 1.5 \times 0.04 \times 5.669 \times 10^{-8} \times (T^4 - 313^4{}_{surr})t = 180°$

At steady state, the inner borosilicate glass tube is maintained at a temperature of 180°C. This is shown in Figure 4. The absorber plate is in contact with the glass tube and at steady state, the temperature of the plate approximately equals the temperature of the inner glass tube. Since the aluminum absorber plate is a black body, its absorptivity and emmisivity are assumed to be 1 that is it absorbs the entire solar radiation incident on it and is capable of reflecting all radiation onto the Cu tube.

Heat transfer coefficient across the air gap

The heat available at the absorber tube is transferred to the copper tubes that carry the transfer fluid. This thermal exchange is both convection and a radiation problem. The amount of heat transfer through convection cannot be calculated unless the heat transfer coefficient of the medium is known. Figure 5 is a schematic diagram of a single copper tube running at the centre of the glass-tube absorber assembly, to arrive at an approximate value in estimation of the total transfer of heat, the area is adjusted in the final heat transfer equation.

Heat transmitted by the absorber place = 106.9271 W
Temperature of the plate = 180°

The diameter of the tube is assumed to be 10 mm. And the nature of the air gap is assumed to be vertical.

To calculate the heat transfer coefficient of the air gap, it is desired to perform a numerical analysis with the 1st iteration assuming the temperature of the copper tube to be 150°C and under ideal conditions when maximum heat is transferred from the absorber plate to the Copper tubes, the amount of heat transferred is the same as the amount of heat absorbed by the absorber tube.

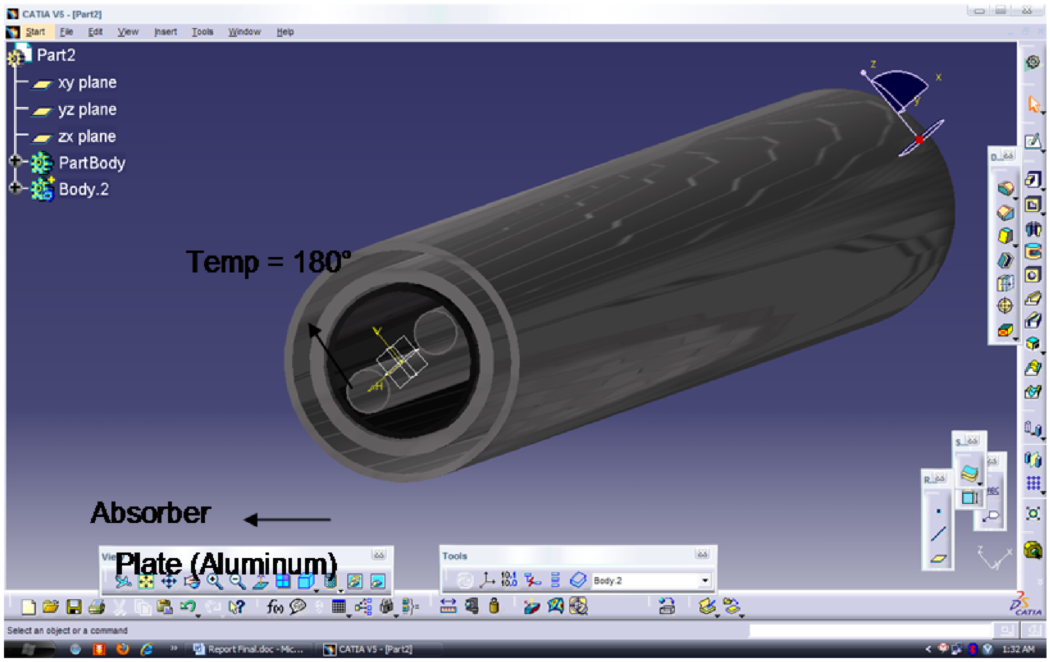

Figure 4. Model of the evacuated tube collector depicting the temperature of the absorber plate.

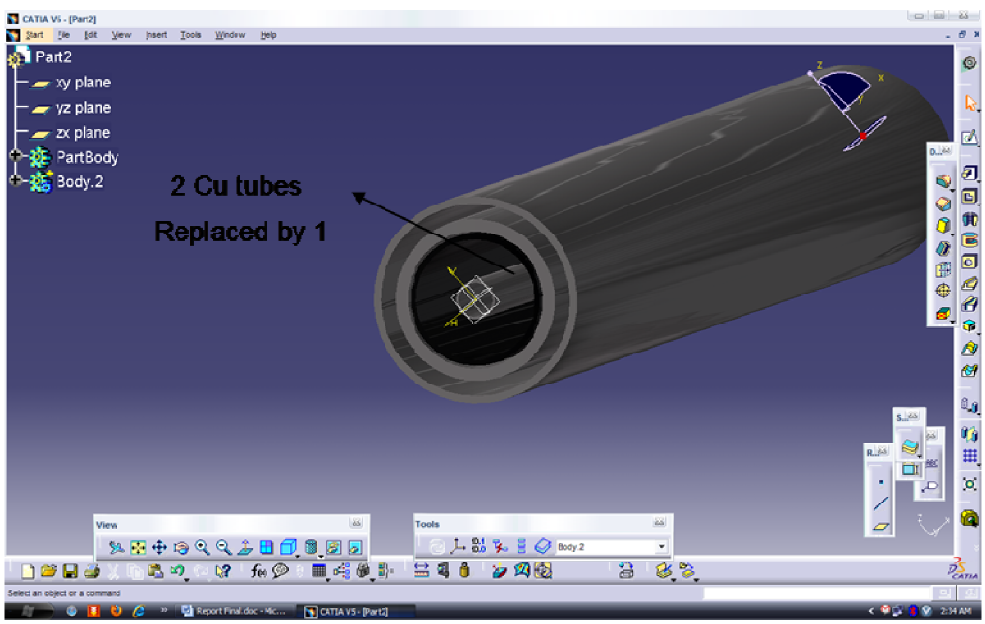

Figure 5. Depiction of the model of the evacuated tube collector with stated assumptions.

It can be noticed from Figure 6 that the heat transfer coefficient of the vertical air gap has refined itself to a particular value. At the start of the iteration the slope of the graph indicates a massive deviation from the actual value. As the number of iterations increases, the heat transfer coefficient holds to a constant value thereby indicating that the observed value of the variable is approaching its real value.

The refining of the value further suggests that the indicated value of heat transfer coefficient can be utilized to calculate the convective heat transfer between the absorber plate and the Copper tube. It can be noticed from graph in Figure 7 that the temperature of the central copper tube has refined itself to a particular value. At the

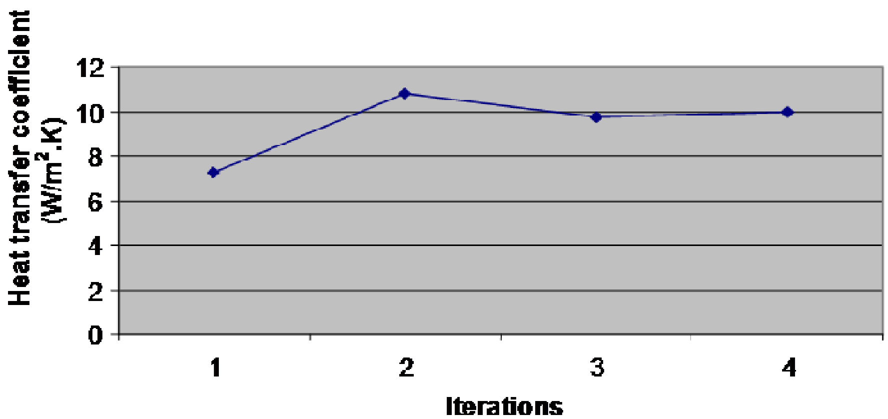

Figure 6. Numerical approximation of heat transfer coefficient with iteration

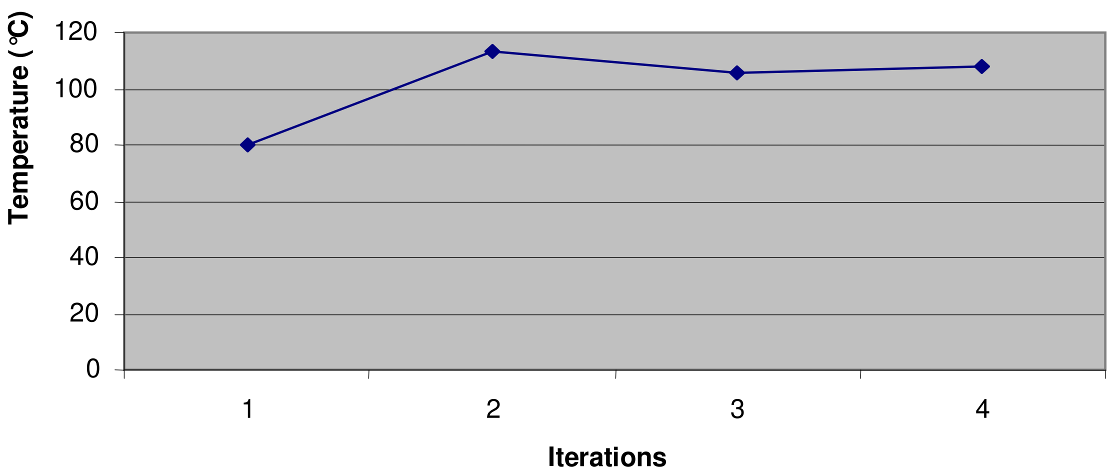

Figure 7. Numerical approximation of Cu tube temperature with iterations.

beginning of the iteration the slope of the graph illustrates a massive deviation from the actual value. With the increment in number of iterations, the slope of the graph decreases thus suggesting that the observed value of the variable is nearing its real value. The refining of the value further suggests that the indicated value of copper tube temperature can be utilized to calculate the convective heat transfer between the absorber plate and the Cu tube.

Calculation of the total heat transfer

The design of the evacuated tube collectors is such that a vertical gap exists between the absorber and the Cu tube; this facilitates convective heat transfer from the absorber plate and because they are maintained at different temperatures, heat transfer also takes place through radiation (NASA, 2007).

Total heat transfer:

$$Q_{total} = Q_{rad} + Q_{conv} = 54.71 + 24.60 \text{ W} = 79.31 \text{ W}$$

The mass flow rate of water into the collector array is approximately in the range of 15 to 30 LPH.

Assuming the output of the collector is fixed at 20 LPH:

This corresponds to a flow rate $= 5.55 \times 10^{-6}$ m^3/s
The cross sectional area of the Cu Tube $= 3.14 \times 10^{-4}$ m^2
Density of water $= 980$ kg/ m^3
Mass flow rate $= 5.439 \times 10^{-3}$ kg/s

Assuming there is no other heat loss and all the energy transferred from the absorber to the Cu tubes, we can calculate the outlet temperature of water.

$Q_{total} = m\ Cp\ (\Delta\ T)$.

At steady state we assume the inlet temperature of water

Table 3. Performance characteristics of commercially available solar collectors.

Description	Consolar (Tubo 12)	Viessman (SD2 20)	Ritter (CPC 12 OEM)
Number of tubes	12	20	12
Optical efficiency	0.62	0.82 #	0.66
1st order heat loss	0.395	1.62 #	0.82
2nd order heat loss	0.02	0.0068 #	0.0064
Aperture area	2.06	2.11	2.0
Angle correction K @ perpendicular	1.04	1.04	1.04
Other parameters			
Operating Pressure (max)	10 Bar	6 Bar	10 Bar
Stagnation Temperature	250°	282°	292°

Efficiency with respect to absorber area = 2.05 m².

to be 70℃. Most commercially available evacuated tube collectors allow 6 tubes to be connected in series.

$79.31 \times 6 = 5.439 \times 10^{-3} \times 4220 \times (T-70)$

$T = 90.732$℃

Hence with a series connection of 6 tubes, a temperature difference of 20.72℃ can be targeted and if the water inlet is considered to be 70℃ at steady state, an outlet temperature of 90.732℃ can be achieved.

Study of commercially available evacuated tube collectors

For the purpose of the study 3 German suppliers were identified for evacuated tube solar collectors. As efficiency of these collectors is a function of output temperature, desired output temperature was fixed at 120℃. The insolation value was obtained assuming optimum tilt of the module.

Test products:

1. Consolar Solare Energiesysteme GmbH- (Tubo 12)
2. VIESSMAN-Vitosol Range- (SD2 20)
3. Ritter Solar- (CPC 12 OEM)

Table 3 discusses the performance characteristics of commercially available solar collectors mentioned above. Efficiency is expressed as a function of incident radiation and temperature difference. To power the generator of an absorption air conditioner temperature required is in the range 90 to 120° at certain flow rate. at 10 bar = 179.88° and at 6 bar = 158.84°.

Therefore, when the maximum attainable temperature difference is taking average water inlet was 25℃ and Ambient temperature is assumed to be at 30° (160 + 25)/2 = 92.5. Temperature Difference, $\Delta T = 92.5 - 30 = 62.5°$. Temperature of about 110 - 120° can be attained in evacuated tube collectors. Temperature difference corresponding to $120^o = 42.5$℃

From graph in Figure 8 we observe efficiency corresponding to 42.5℃ temperature difference to be around 65%. Table 4 summarizes the overall efficiency and heat output of various collectors.

The available heat from the collector array is used to heat the refrigerant-absorbent solution in the generator of an absorption chiller. The design of the generator and the selection of the tubes play an important part in facilitating optimum heat transfer.

DESIGN OF THE GENERATOR OF AN ABSORPTION CHILLER

Single effect water-lithium bromide systems are ideal for air conditioning operations where the refrigerant flow normally does not exceed 10℃ under normal conditions. The generator of these systems can be powered easily with a low grade energy source such as hot water from evacuated tube collectors. The hot water heats up the refrigerant-absorbent mix in a pool boiling type heat exchanger. Water-Lithium Bromide solution enters the generator at a particular concentration and when heat is supplied, fraction of the water in the solution vaporizes leaving behind a strong solution of water and lithium bromide in the heat exchanger. The change in concentration of the solution affects its heat transfer coefficient. The heat transfer coefficient is found to increase as the heat flux increase. Average heat transfer coefficients were found to vary between 1600 and 7500 W/m2℃ (Kalogirou, 2001).

Design of the generator

The generator of a Water-Lithium Bromide absorption chiller is a pool type heat exchanger that is capable of extracting heat from low grade energy source such as hot water available from a solar water heater. The design of the generator is specific to the use of evacuated tube

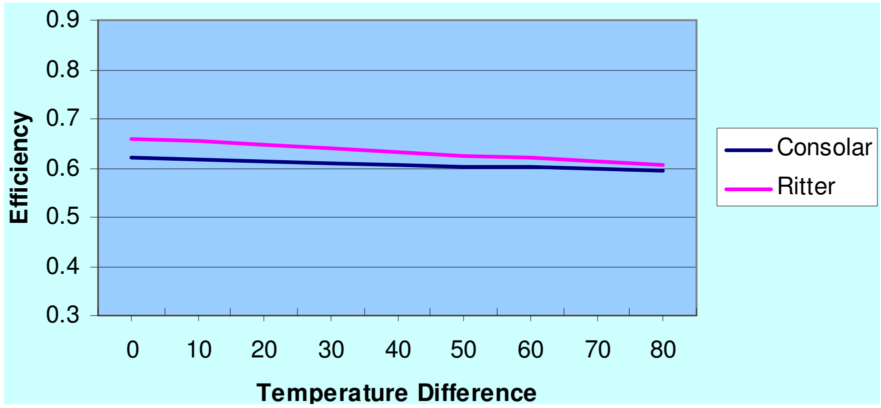

Figure 8. Efficiency as a function of the mean temperature difference at W/m^2.

Table 4. Overall efficiency and heat output of various collectors.

Description	Consolar (Tubo 12)	Viessman (SD2 20)	Ritter (CPC 12 OEM)
Overall efficiency @ dT= 42.5	0.60601	0.7626 #	0.630958
Heat output, Q_{out}	1498.05 W	1876.05 W	1514.30 W

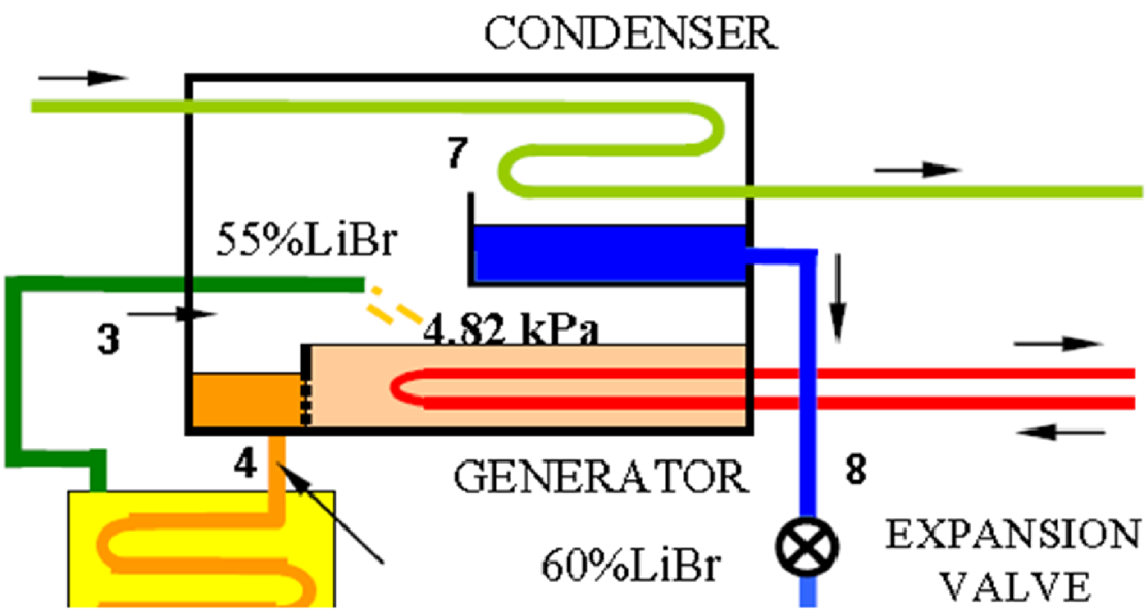

Figure 9. Typical conditions for an absorption chiller with 1KW Capacity (Duffie and Beckman, 1980).

collectors. Typical conditions for an absorption chiller with 1KW capacity are shown in Figure 9 and listed as follows (Kalogirou, 2001):

Generator pressure: 4.82 KPa
Generator solution Entering: 55% LiBr
Leaving: 60% LiBr
Generator water vapor mass flow rate: 0.000431 kg/s

With these typical values, the amount of heat transferred in the generator can be determined. As the generator is a pool type heater and the heat is utilized to raise the sensible heat of the water-Lithium Bromide Solution and to vaporize a part of the fluid. Lithium Bromide from the solution does not exert any vapor pressure on the liquid therefore; analyzer and dephlagmator are not required as ancillary units. Using the dimensions aforementioned, a

Table 5. Specifications of heat exchange tube in a pool type heat exchanger in the generator.

Particulars	Value
Material	Copper
Flow rate	1.85 x 10^{-5} m^3/s
Length	2.1673 m
Inner diameter	10 mm
Outer diameter	11 mm
Total capacity	1575 W

generator heat exchanger for an absorption refrigerator having the refrigerating effect of 1 KW can be designed. The specifications of this design are mentioned in Table 5.

CONCLUSION

The evacuated tube solar collectors provide a substantial difference in the temperature of the working fluid. The amount of heat transferred to the working fluid depends on the incident flux of solar radiation and on the aperture of the tubes. The heat transfer coefficient of the air gap in the tubes plays a major role in facilitating the heat transfer. Moreover, the report uses typical data for the design of a 1 KW absorption unit and analyse the design of the generator section using the heat available from evacuated tube collectors. The following conclusions could be drawn from the analysis.

1. The average influx of solar radiation in Dubai (Latitude 25°18'N, 55°20'E) was calculated and verified at 8.35 KWh/m^2.day. With 8 h of estimated sunlight 1050 W/m^2 is available for thermal conversion.
2. The temperature of the absorber plate is theoretically determined to be 180°C and the heat transfer to the Copper tube is suggested to be due to both convection and radiation.
3. Numerical analysis is used to calculate the heat transfer coefficient on the air gap: the value is calculated as 9.992 W/ m^2.K with the temperature of the copper plate as 107.62°C.
4. The total heat transfer from the array of 6 collector tubes in parallel was determined as 475.86 W commensurate with the performance of most commercially available collectors.
5. Approx 20 tubes are required to power the generator of an Absorption machine with 1 KW (0.285 TR) capacity.
6. The log mean temperature difference in the heat exchanger is calculated to be 17.65°C with the heat transfer coefficient 1192 W/ m^2.K. The generator must be a single pass pool type heat exchanger with 2.2 m long copper tube.

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