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LINEARIZED COMPARATIVE ANALYSIS OF STEEL AND ALUMINUM SOLAR FLAT PLATE COLLECTOR IN SOLID ABSORPTION REFRIGERATOR

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ABSTRACT

An analysis of design parametric effect on a flat plate collector of a solar refrigerator system shows that the emmissivity of the plate material gives the most significant effect on the refrigerator performance. A linearization process involving the least square method was used to ~~determine the~~ determine the steady state and transient components of some useful parameters in the performance operation of the refrigerator system for steel and aluminum plates and tubes. A comparative result obtained from the analysis shows that the Coefficient Of Performance (COP), Condensate (NH_3) yield and Useful Cooling (UC) were much higher for steel than aluminum plate and tubes due to the high thermal capacity and conductivity of steel which results in low emmissivity and low radiative heat losses. This implies that steel is a better material for the construction of flat plate collectors for a solar refrigerator system. It was also found that the COP, NH_3 yield and useful cooling signals followed a diurnal cycle of absorption and evaporation modes which peaked at 12noon, with the best working period beween 9 am and 3 pm (i.e. 3 hours to 9 hours) after sunrise.

INTRODUCTION

The American Society of Refrigerating Engineers (ASRE) defines refrigeration as the " science of producing and maintaining temperatures at below that of the surrounding atmosphere [1]. This rather implies the development of a temperature differential than the establishment of a temperature level. The temperature differential in a refrigerator system is usually established by electric power, generated either through hydro power plants or through burning of fossil fuel. Alternatively, such temperature differential can be created by using a renewable energy source such as wind or solar energy. Presently, the technology for utilizing solar energy for refrigeration is not well developed due to the relatively low density at which solar radiation is received at the earths surface, and the added need for storage. Consequently, the complete system for effective utilization of solar energy for refrigeration is quite expensive at the present. Future application prospects for solar powered refrigerators would therefore depend very much on research breakthroughs in the systems and materials that would yield optimum results.

THEORETICAL BACKGROUND

With respect to solar refrigeration, two major refrigeration cycles exist. Theses are:

Photovoltaic refrigeration cycle: This is a cycle that uses solar cells to convert solar energy into electric power, which is then used to create the temperature differential that runs the refrigeration system. This system comprises; solar cell arrays, series of batteries, voltage regulators and conventional cooling units [2].

Solar vapour absorption refrigeration cycle: This cycle is powered by solar heat collectors such as air or liquid flat plate collectors or concentrating collectors.

Solar vapour absorption is based on the principle that refrigerant combines chemically with suitable absorbents to release heat and cool down during absorption and absorb heat during evaporation. This type of cooling cycle is further split into liquid and solid absorption types [3], although solid absorption systems are more common, provides better cooling systems and are therefore considered in this work. Trombe and Foex, demonstrated the first solar powered intermittent operation NH_3-H_2O absorption refrigeration using a cylindrical parabolic reflector to concentrate and collect insolation [4]. Since then, other investigators have reported improved designs of solar absorption refrigerators [2,3,5-10]. Such design improvements includes

(i.) Integrating the collectors, boiler and solution reservoir into a single unit called collector / generator / absorber unit.

(ii.) The use of booster mirrors to enhance solar radiation harvesting; and

(iii.) The use of removable flat plate solar collector back insulation to facilitate solution cooling during absorption cycle.

Out of these improved designs, the integrated units offer the best option.

The parameters that determine the behavior of the collector unit for the integrated system are [7,8,9]:

(i.) Environmental variables such as solar intensity, ambient air temperature and wind speeds.

(ii.) Design variables such as dimensions (i.e. number of glazing and collector tube spacing) and tube / plate materials radiation characteristics (i.e. emissivity and conductivities of the materials used).

Although all environmental and design variables are important for the refrigeration system, the present work is restricted mainly to the analysis of the most important aspects of design variables which is the absorber plate and tube materials and their intrinsic emissive and conductive properties. In particular, the major parameters determining the performance of solar solid absorption refrigerators viz: coefficient of performance (COP), NH_3–yield and Useful Cooling (UC) would be studied with respect to the type of the collector materials used.

THEORECTICAL ANALYSIS

The choice of material for the collector plate and tubes is usually limited to steel and aluminum due to their thermal properties. The data in table 1 is a result for COP, NH_3 yield and Useful Cooling obtained by the use of steel and aluminum materials respectively in flat plate collectors reported in [8]. This serves good information for the analysis carried out in this work.

The method of solution is a mathematical (regression) equation for the data.

$$y_{ji}(t) = a_o + a_i x_j(t) \tag{1}$$

where $x_j(t) = \cos t$ such that

$$y_{ji}(t) = a_o + a_i \cos t \tag{2}$$

and $i = 1, 2, 3 \ldots n$

$j = 0, 1, 2, \ldots m$

For this information, we take that the steel and aluminum are represented by $y_{ji}(t)^*$ and $y_{ji}(t)^{**}$ parameters respectively such that the coefficient of performance (COP) can be represented as $y_{j1}(t)^*$ and $y_{j1}(t)^{**}$, while HN_3 yield can be represented $y_{j2}(t)^*$ and $y_{j2}(t)^{**}$, and useful cooling as

$y_{j3}(t)^*$ and $y_{j3}(t)^{**}$

In order to determine the steady state and the transient components of the data presented in table 1, a linearization process involving the least square method is carried out. The fitting of the linearized equation presented in equation (2) yields a set of constitutive equations in "a_o" and "a_1" as follows:

$$\begin{aligned} ma_o + \left(\Sigma x_j\right)a_1 &= \Sigma y_{ji} \\ \left(\Sigma x_j\right)a_o + \left(\Sigma x^2{}_j\right)a_1 &= \Sigma x_i y_{ji} \end{aligned} \tag{3}$$

These equations can be put in a concise matrix form as follows

$$a_o = \frac{\begin{bmatrix} \Sigma y_{ji} & \Sigma x_j \\ \Sigma x_i y_{ji} & \Sigma x^2{}_j \end{bmatrix}}{\begin{bmatrix} m & \Sigma x_j \\ \Sigma x_j & \Sigma x^2{}_j \end{bmatrix}} = \frac{\Sigma x^2{}_j \Sigma y_{ji} - \Sigma x_j \Sigma x_i y_{ji}}{m\Sigma x^2{}_j - \left(\Sigma x_j\right)^2} \tag{4}$$

and

$$a_1 = \frac{\begin{bmatrix} m & \Sigma x_j \\ \Sigma x_j & \Sigma x^2{}_j \end{bmatrix}}{\begin{bmatrix} m & \Sigma x_j \\ \Sigma x_j & \Sigma x^2{}_j \end{bmatrix}} = \frac{m\Sigma x_j \Sigma y_{ji} - \Sigma x_j \Sigma x_i y_{ji}}{m\Sigma x^2{}_j - \left(\Sigma x_j\right)^2} \qquad (5)$$

We can now substitute the values of a_0 and a_1 into the linearised equation which results in an equation of the form

$$y_{ji}(t) = a_o + a_1 \cos t \qquad (6)$$

The values of a_o and a_1 can now be computed for different choice of parameters and materials. The computed values of a_o, a_1 and the generic equations for $y_{ij}(t)$ are given in table 2.

RESULT AND DISCUSSION.

In this section, we present the various results of interest from the analytical solution of equations 4, 5 and 6.The result is finally developed as time (t) is measured in radian ranging from 0 to 2π for the steel and aluminum materials respectively. The values of $y_{ij}(t)$ for COP, NH_3 yield and Useful Cooling for Aluminum and steel are given in table 3. While figures 1-3 show the curve of $y_{ij}(t)$ for COP, NH_3 yield and Useful Cooling for time $t = 0$ to 2π, daily.

The tables and figures show that the values of the signal generated by the collector with steel material for each variable is significantly peaked at $t = \pi$. This behavior of the signals shows that if the collector is operated from 6 AM in the morning (set at $t = 0$), then by 9 AM (set at $t = \pi/3$), the amplitude of the generated signal of COP, NH_3 yield ands Useful Cooling for steel material was found to be 610, 3400 and 2100 respectively. This doubles to 1220, 6800 and 4200respectivly as the peak values for the collector with steel material at about 12 PM (set at $t = \pi$). Also the amplitude was seen to fall back to 610, 3400 and 2100 respectively at 3 PM (set at $t = 3\pi/2$). Then back to zero at 6 PM (set at $t = 2\pi$)

Thus the amplitude of the signals increase gradually with time of day from sunrise till they reach peak values at noon and gradually drop to their original values at sun set. This is attributed to the transient and intermittent nature of solar intensity received by flat collectors from sunrise to sun set. This behavior of the system from sunrise to sun set is known as the diurnal cycle of solar refrigerator, which comprises the generation (evaporation) mode and the cool down (absorption) mode.

Thus the coefficient of performance (COP), the Ammonia yield (NH_3 yield) and the Useful Cooling are all affected by time of day. Significantly, collectors are observed to work effectively between three hours and nine hours from sunrise (i.e. between 9 AM to 3 PM). From 3 PM to 9 AM (of the following day) collectors are found to be dormant.

Similarly, collectors with aluminum materials follow this same behavior, although their signals are very much reduced even at peak point. Infact the signal for Useful Cooling for aluminum is just along the time axis through out the day indicating that aluminum materials do not produce significant useful cooling at any time of the day.

This comparative analysis between steel and aluminum shows that collector with steel plates and tubes attained much more significant values of COP, NH_3 yield and Useful Cooling than collectors with aluminum tubes and plates. This shows that materials choice for flat plate collectors is significant in the operation of solar absorption refrigerators. This is due to the fact that as the tubes and plate materials of solar collectors absorb solar energy and heat starting from time $t = 0$ to $t = 2\pi$, the energy absorbed by the material will be sufficient to influence NH_3 yield, COP and Useful Cooling in the case of refrigerator with steel plates and tubes, where as that heat will be insufficient to affect these parameters in the case of refrigerator with aluminum plates and tubes.

This result follows from the physical properties (thermal capacity and conductivity) of steel and aluminum as they affect collector plate emmissivity, which as stated, is the most significant parameter in solid absorption refrigerators. Aluminum is more conductive and has higher thermal capacity than steel. The effect of these is a higher emmissivity for the aluminum plate; hence radiative heat loss from the plate is also high causing the mean plate absorbent temperature to be lowered. This will lead to a poor condensate (NH_3) yield; Consequently, the COP and Useful Cooling are also lowered. Therefore the collector operating at this higher plate emmissivity has poor performance.

On the other hand, steel materials with its lower thermal capacity will give lower thermal emmittance and reduced radiative loss. This causes the mean plate absorbent temperature to rise. This will eventually lead to increased condensate (NH_3) yield. Hence the COP and Useful Cooling are all increased, leading to an effective operation of the refrigerator for steel.

Also, since emmissivity increases with increase in temperature (heat), it follows that materials with low emmissivity will operate optimally between 9 AM and 3 PM (peak period of heat harvest for collectors) due to the favorable effect of low emissivity on radiative heat loss, COP NH_3 yield and Useful Cooling. Therefore steel offers a better collector material than aluminum due to their low thermal capacity, which affect their emmissivity.

CONCLUSION

A linearization process involving the least square method was used to determine the steady state and transient components of some useful parameters in the operation

of solar solid absorption refrigerators for steel and aluminum collector materials. The COP, NH_3 yield and Useful Cooling signals of the refrigeration system followed a diurnal cycle of absorption and evaporation modes which peaked at 12 noon. Steel was therefore found to give a better collector than aluminum due to its low thermal capacity and emmissivity.

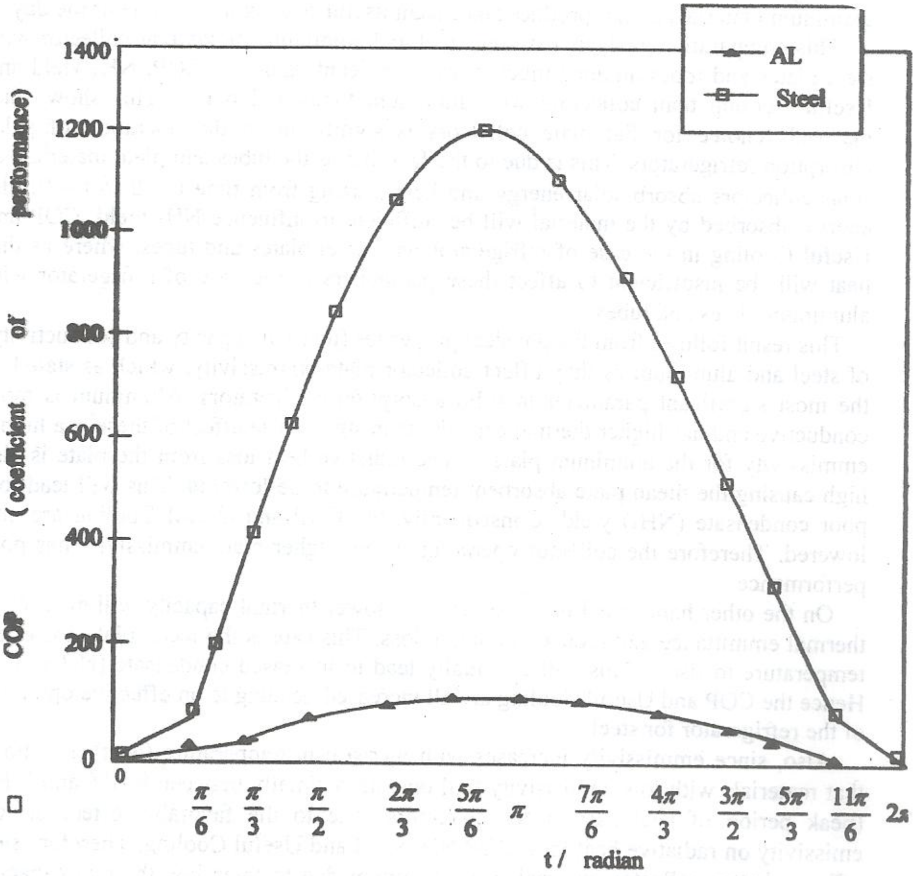

Fig 1: A graph of Yj1 (t) and Yj1(t)* (COP) against t taking the values of : t = 0 to 2π**

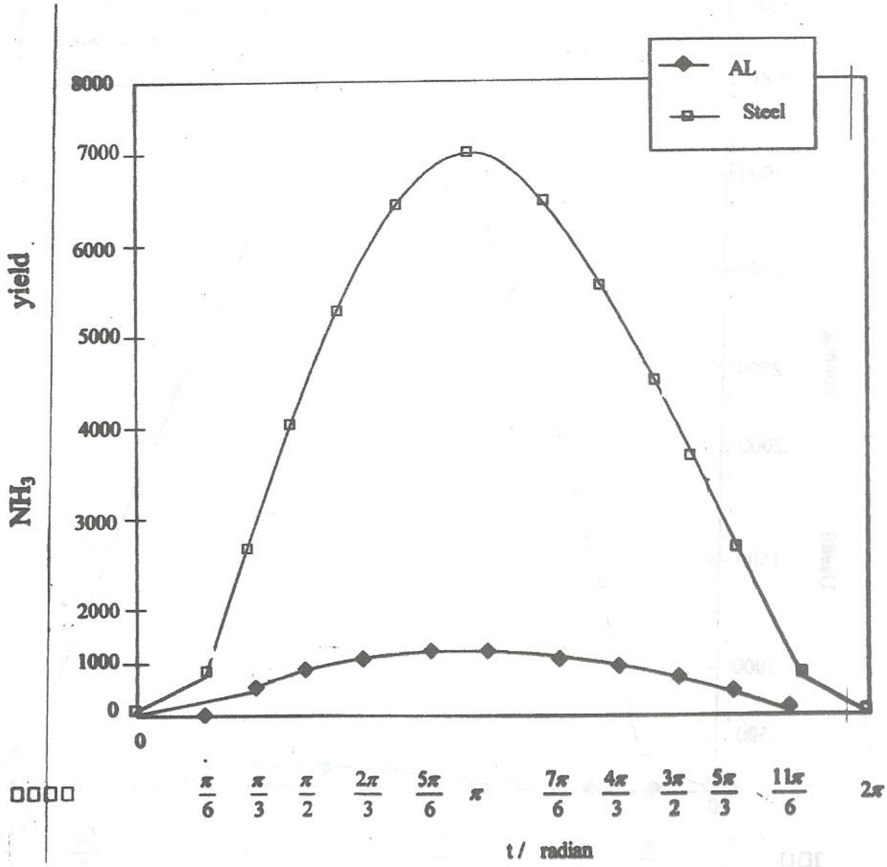

Fig 2: A graph of Yj2 (t)** and Yj2(t)* (NH$_3$ yield) against t taking the values of : t = 0 to 2π

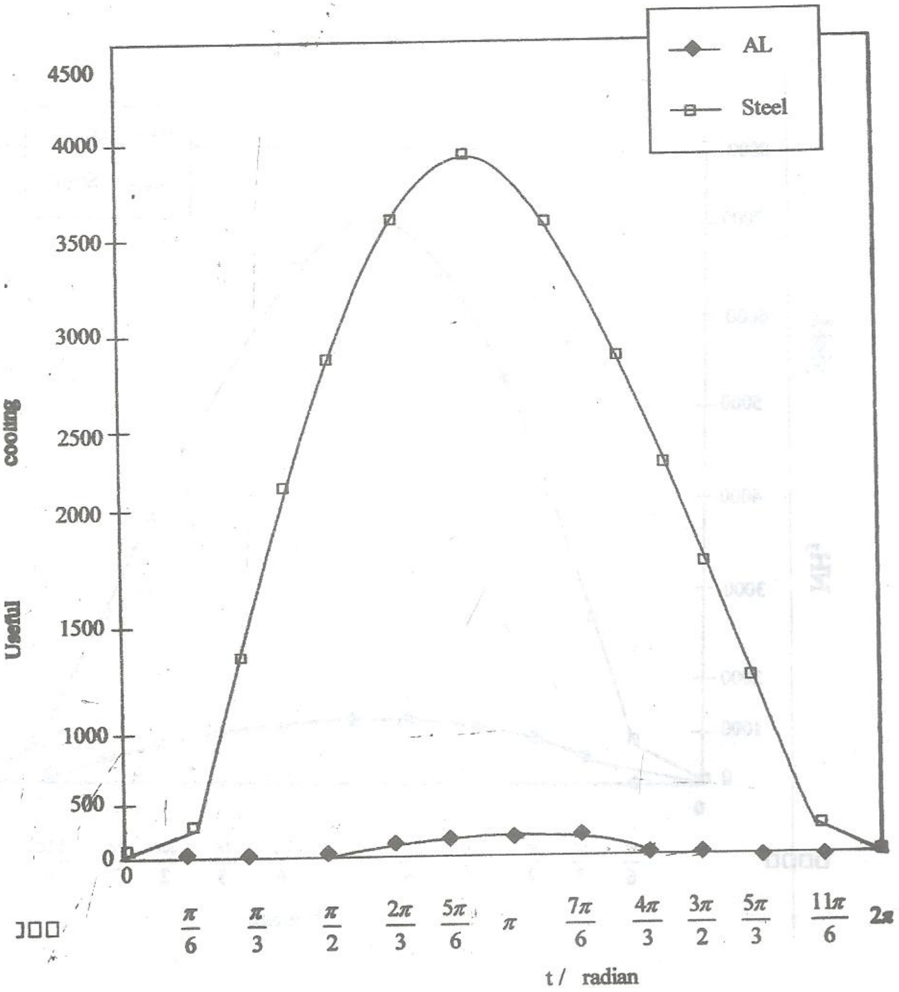

Fig 3: A graph of Y_{j3} (t)** and Y_{j3}(t)* (Useful Cooling) against t taking the values of : t =

Table 1. Raw data of COP, NH_3 yield, Useful Cooling Evaporation time obtained from [8]

	COP		NH_3 yield		Useful Cooling		Evaporation Time	
J	AL	Steel	AL	Steel	AL	Steel	AL	Steel
0	-5.7189	-4.2265	-35.7900	-24.6410	-33.0790	-17.7920	-21.4750	-5.1506
1	9.8337	6.4078	65.1580	36.2340	52.2580	23.0920	24.1310	7.3136
2	-4.3593	-2.7436	-27.1200	-13.5230	-21.7980	-8.4631	-9.9098	-2.1276
3	3.0241	3.4431	2.0330	22.0350	16.7250	13.907	11.5690	4.2669
4	-1.3780	-1.5442	-10.7590	-9.78930	-7.4870	-5.4962	-4.8261	-1.6891
5	-2.8045	-2.4483	-24.4790	-17.6850	-13.5250	-9.5242	0.2219	-3.8929
6	1.3733	1.1028	10.6190	7.4702	6.7296	4.0438	0.2151	1.4000
7	0.0680	0.0059	1.1138	-0.1421	1.0356	0.1685	0.2396	-0.4957
8	0.350	0.0312	1.1650	1.4098	0.6656	0.5064	0.4364	0.8296
9	-0.0836	-0.0417	-1.5090	-1.2445	-1.3234	-0.9187	-0.4492	-0.5309

Table 2: Computed values of a_o, a_1 and $[y_{ij}(t)]$ from raw data in table1 for aluminum and steel using equations 4, 5, and 6.

	COP $[Y_{i1}(t)]$		NH$_3$ yield $[Y_{i2}(t)]$		Useful cooling $[Y_{i3}(t)]$	
	Steel	AL	Steel	AL	Steel	AL
M	10	10	10	10	10	10
Σy_{i1}	- 0.0135	- 0.0102	- 0.1241	- 1.4318	- 0.4755	- 0.2014
Σx_j	9.9813	9.8045	9.9813	9.8045	9.9813	9.8045
Σx^2_j	9.96269549	9.62210147	9.96269549	9.62210147	9.96269549	9.968420527
$\Sigma x_j Y_{ji}$	- 0.05030253	-0.46438638	-0.08085412	-1.7950086	- 0.60156073	- 2.0587894
a_o	607.3730253 ≈ 610	48.96691451 ≈ - 50	3376.348273 ≈ 3400	338.1246044 ≈ 340	2093.647508 ≈ 2100	25.92690298 ≈ 26
a_1	-608.5123346 ≈ -610	-48.96691451 ≈ -50	-3382.66144 ≈ -3400	-344.7207144 ≈ -340	-2097.617604 ≈ -2100	-26.35854574 ≈ -26
Yji(t)	610 (1 - cost)	50 (1 - cost)	3400 (1-cost)	340(1 – cost)	2100(1- cost).	26 (1 - cost)

Table 3 : values of COP, NH_3 yields and Useful Cooling for Aluminum and Steel.

t / rad	COP		NH_3 yield	Useful Cooling		
	Steel	Al	Al	Steel	Al	Steel
0	0	0	0	0	0.0	0
$\frac{\pi}{6}$	15	61	34	340	2.6	210
$\frac{\pi}{3}$	25	305	170	1700	13.0	1050
$\frac{\pi}{2}$	50	610	340	3400	26.0	2100
$\frac{2\pi}{3}$	75	915	510	5100	39.0	3150
$\frac{5\pi}{6}$	95	1159	646	6460	49.4	3990
π	100	1220	680	6800	52.0	4200
$\frac{7\pi}{6}$	95	1159	646	6460	49.4	3990
$\frac{4\pi}{3}$	75	915	510	5100	39.0	3150
$\frac{3\pi}{2}$	50	610	340	3400	26.0	2100
$\frac{5\pi}{3}$	25	305	170	1700	13.0	1050
$\frac{11\pi}{6}$	15	61	34	340	2.6	210
2π	0	0	0	0	0.0	0

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