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A MATHEMATICAL MODEL FOR SOLAR ASSISTED AUTOMOBILE A/C BASED ON ABSORPTION REFRIGERATION SYSTEM

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ABSTRACT

Most conventional air-conditioning (AC) systems used in vehicle are driven by fossil fuel combustion, and therefore give raise emission of environmentally damaging pollutants. In addition, conventional cooling systems increase the load on the engine therefore increase the fuel consumption. In general vehicle is used, on average, about 249 hours annually or about 41 minutes per day, 365 days a year. Estimates of air-conditioning use range from 107 to 121 hours per year or 43% to 49% of vehicle usage. An air conditioner compressor can add up to 5-6 kW peak power draw on a vehicle's engine. This power draw is equivalent to a vehicle driving steady state down the road at 35 mph (56 km/h).

In this research a detailed thermodynamic analysis of water/lithium bromide absorption refrigeration cycle is performed, in specific operational conditions compatible with the nature of the weather in most areas of Saudi Arabia ($30 \le Ta \le 50, 5 \le Te \le 15$, $80 \le Tg \le 120$), and under cooling load compatible for large size vehicle(5 kW), and a mathematical model of solar assisted automobile A/C based on absorption refrigeration system was been deduced.

KEYWORDS: Air-Cooled Absorption System, Solar Radiation, Absorption, Water-Lithium Bromide, Vehicle Emission Gases, Saudi Arabia Transportation Road Sector

INTRODUCTION

The targets vary from country to country when talking about energy and its uses. Some countries suffer from scarcity and others do not exist at all, but all the countries involved in the issue of pollution caused by the burning of various fuels. Talk about the use of fossil energy in Saudi Arabia has its own meaning for several reasons, a simply applies the concept of burning very large quantities of oil for cooling, comparison with other countries for many different reasons, which will be reviewed later. The Kingdom of Saudi Arabia in the south-west of the continent of Asia, between latitudes 16 and 33 north and longitudes 34 and 56 east, and constitute the bulk of the Arabian Peninsula (80%) with an area of 2,149,690 km^2, and a population of nearly 29 million, including residents of different countries, in addition to the millions of visitors annually from different corners of the earth for the purpose of Hajj and Umrah. Saudi Arabia has a stable political and economic depends on oil wealth (has the largest reserves in the world), which forms the backbone of exports (90%), making it occupy a very advanced position among world economies in terms of GDP.

As a result of this situation the Kingdom witnessed a renaissance in construction, economic and rapidly reflected their results on the citizen in all walks of life and seemed effects are evident in the evolution of infrastructure, education, health and transport in recent years, for example but not limited to increased length of paved roads from 230 in 1955 to 52000 km in 2010 (21.5 % of total road) to cope with the increase in the percentage of ownership of individuals vehicles(individuals ownership vehicles Changed from one vehicle for every 48 persons in 1972 to the vehicle for 4 persons in 20 years), as the number of vehicles from 144,768 in 1972 to 2,069,479 in 1982 and to nearly ten millions in 2012 by Statistical issued by the General directorate of Traffic, subject to an increase of 700 000 to one million vehicles a year in the near future [5].

Use energy in Saudi Arabia, own its character. The comprehensive development that the government of Saudi Arabia seeks to achieve imposed increasing demand for energy at high rates (Figure 1) [4].

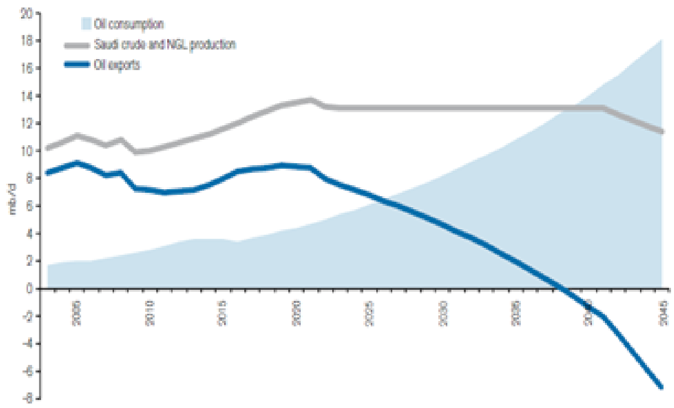


Figure 1: Saudi Arabia's Oil Balance on a Business – as – Usual Trajectory

Specialists in the field of energy and transport warn from excessive fuel consumption, which rose productions refineries in Saudi Arabia 7% at the beginning of 2011 (2.1 million barrels) to cover the needs of domestic consumption.[6,10] demanding to confront the increase in fuel consumption establishing public transport network and balancing fuel prices between income and consumption(Figure 2).

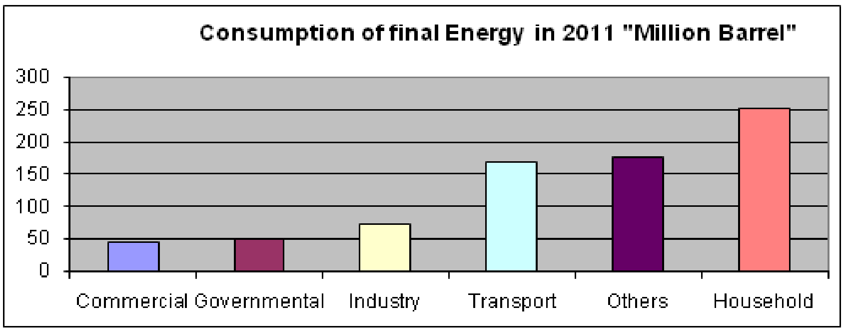


Figure 2: Consumption of Energy in 2011

Compared with industrialized countries Saudi Arabia is ranked fourth globally in fuel consumption after China and the United States and the Russian Federation (Figure 3).

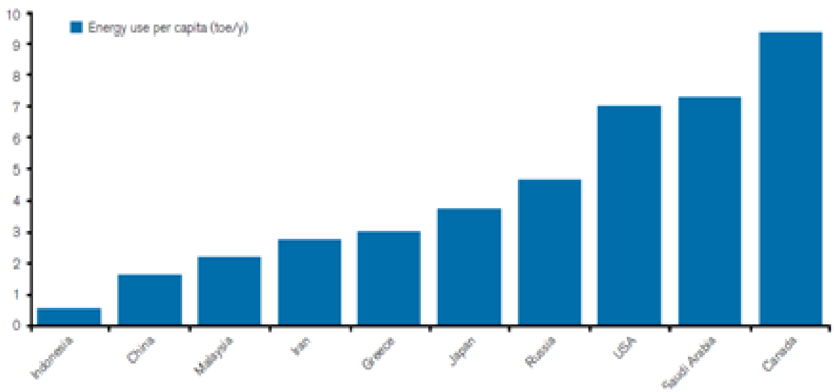


Figure 3: Energy Use by Countries, Ton of Oil Equivalent per Year [7]

Transport road sector is one the main consumer of primary and final energy in Saudi Arabia, with a share of around 22%, in 2011, of the final energy consumption in the form of gasoline 60%, and diesel fuel 40% (Figure 4).

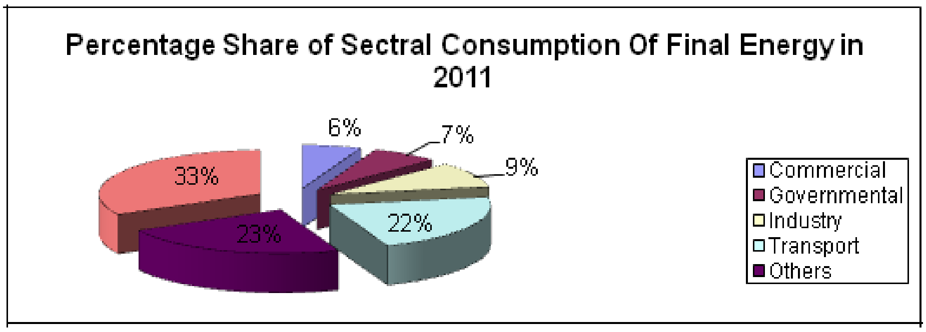


Figure 4: The Percentage Share of Sectoral Consumption of Final Energy in 2011

In addition to energy use, the associated greenhouse gas emissions and their potential effects on the global climate change are nowadays a worldwide concern. Saudi Arabia came in fifth place in the air pollution in the list of the World Health Organization, in the year 2006 Saudi Arabia contributed about 432739 kt (of CO_2 equivalent) of GHGs to the atmosphere (372.055 million metric tons).

The GHG emissions in Saudi Arabia considerably high (16.1 CO_2 metric tons per capita) compared with most industrial countries (Figure 5).

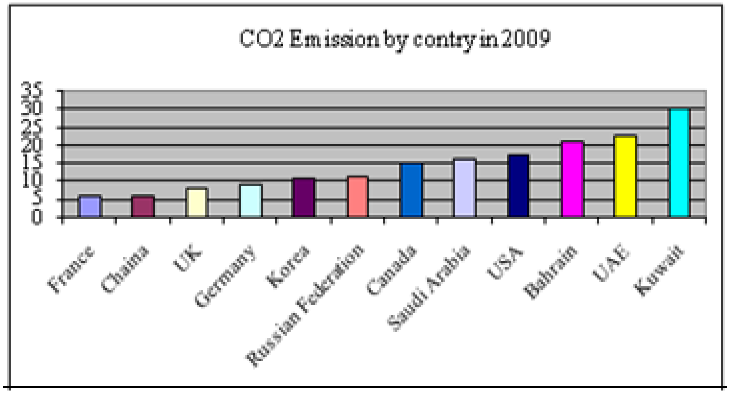


Figure 5:CO_2 Emission by Countries in 2009, Metric Tons per Capita

To find out the status of pollution in the road transport sector emissions were calculated from the amount of actual fuel consumption in 2011, using the amount of gases emitted during the combustion of gasoline and diesel. It turns out that pollution caused by the use of equivalent vehicles 7666.089 tons [8].

Saudi Arabia's annual energy consumption is growing at double the rate of GDP growth. With high population growth and planned industrial development, growth in power demand will remain high under current policy conditions. Oil products have particular demand growth potential given that vehicle ownership, currently at 230 vehicles per 1000 people, is only half the levels in Europe and Japan, and only 30% of that in the USA, and hence far from saturation.

Saudi Arabia, the largest oil exporter in the world aimed to reach a renewable energy generating capacity to 23.9 GW by 2020 and 54 GW by 2032, according to the road map that will make Saudi Arabia one of the largest producers of electricity from renewable sources in the world.

Saudi Arabia seeks for most renewable energy from solar energy at the first step .This trend is in line with the global energy statistics report for 2012 "The ability of solar installations in the world - which operates using photovoltaic technology amounted to about 69.4 GW in 2011"[1].

This requires further studies and research which is lacking in the field of alternative energy in Saudi Arabia in general. Especially important is the use of solar energy instead of electrical, oil or gas energy for cooling purposes, specifically for vehicle air conditioning.

METHODOLOGY

Absorption refrigeration system give a high efficiency and low operating cost, and also decrease the load on the engine, and the fuel consumption, and therefore the greenhouse gas emissions. The absorption cycle is a process by which refrigeration effect is produced through the use of two fluids and some quantity of heat input, rather than electrical input as in the more familiar vapor compression cycle. Both vapor compression and absorption refrigeration cycles accomplish the removal of heat through the evaporation of a refrigerant at a low pressure and the rejection of heat through the condensation of the refrigerant at a higher pressure.

Absorption machines are commercially available today in two basic configurations. For applications above zero Celsius (primarily air conditioning), the cycle uses lithium bromide (LiBr) as the absorbent and water as the refrigerant. For applications below zero Celsius, an ammonia/water cycle is employed with ammonia as the refrigerant and water as the absorbent [21]. Figure 6 shows Schematic diagram of the water–lithium bromide absorption refrigeration system (ARS) it consist of an absorber, a pump, a generator, a condenser, a evaporator and expansion valve. In this system the water used as a refrigerant and lithium bromide (LiBr) is used as an absorbent [9].\

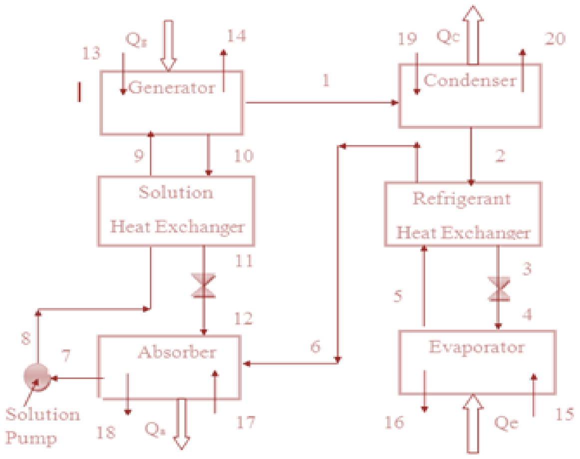
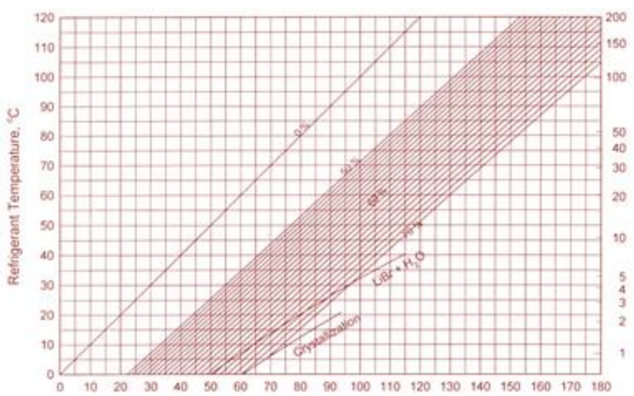
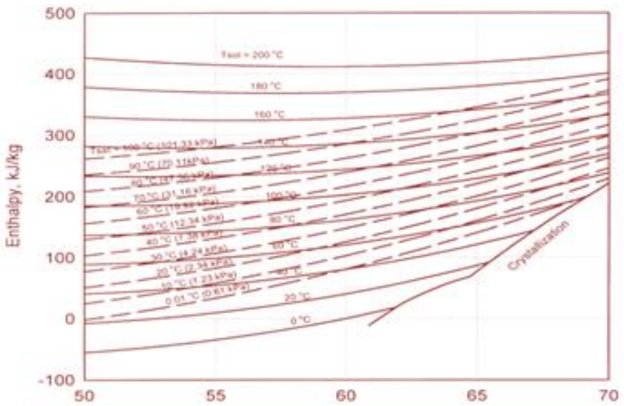


Figure 6: Schematic Diagram of the Water–Lithium Bromide Absorption Refrigeration System (ARS)

Thermodynamic properties (Figure 7) of LiBr given in the literature were with typical equations for an effective calculation of the design data [17] .The enthalpy of solution was calculated by the procedure of McNeely's [21].



Solution Temperature, °C
Figure 7: Duhring Diagram of the H2O + LiBr



Absorbent Concentration, wt %
Figure 8: Enthalpy-Concentration Diagram of the H2O + LiBr

The following equations were used for the regression [20]:

$$Q = \dot{m} * C_P * (T_{out} - T_{in}) \quad (1)$$

Where,

Q: Heat rate (W), $\dot{m}$: Mass flow rate (kg/s), C_P :specific heat at constant pressure(J/kg.°K),

T_{out}: Outlet temperature (°C.), T_{in}: Inlet temperature (°C).

$$\eta = \frac{\dot{m} * C_P * (T_{out} - T_{in})}{A_c * G} \quad (2)$$

Where,

η:Efficiency ,A_c : Surface area of collector(m^2),G : Irradiation(Wh/ m^2).

The same net power output can be written in terms of quantities representing the heat transfer mechanism, or the heat input minus the heat losses as:

$$Q = A_C * F_R * [G - U_L(T_m - T_a)] \quad (3)$$

Where,

F_R :is the collector heat removal factor and U_L is the overall heat loss coefficient.

T_m :is a mean temperature of the working fluid flowing inside the collector, generally taken as the average between the inlet and outlet temperatures of the collector.

Mass balance equations of the solution and lithium bromide at the generator can be written as follows [18]:

$$\dot{m}_{WS} = \dot{m}_{SS} - \dot{m}_R \quad (4)$$

$$\dot{m}_{WS} X_{WS} = \dot{m}_{SS} X_{SS} \quad (5)$$

Where,

$\dot{m}$: is the mass flow rate (kg s^{-1}), *X:* the lithium bromide concentration, WS: weak solution, SS: strong solution: refrigerant.

The circulation ratio (*f*) can be defined as the ratio of the mass flow rate of the solution through the pump to the mass flow rate of the working fluid. Also it can be expressed in terms of concentrations as follows:

$f = \dot{m}_{WS} / \dot{m}_R = X_{SS} / (X_{SS} - X_{WS})$ (6)

The measure of performance of refrigerators is expressed in terms of COP, defined as:

$COP = Q_e / (Q_g + W_p)$ (7)

The COP value is calculated as the ratio of refrigeration effect to the generator's heat.

Where,

Q: is the heat transfer rate (kW), W: is the pump power (kW), e: refer to the evaporator,

g: refer to the generator, P: refer to the pump.

According to[18] the equations for the first law of thermodynamics (energy balance) for components of the ARS(Absorption Refrigeration System) are expressed as follows:

$Q_a = \dot{m}_R [h_6 - (f-1) h_{12} - f h_7] = \dot{m}_a (h_{18} - h_{17})$ (8)

$Q_c = \dot{m}_R (h_1 - h_2) = \dot{m}_a (h_{20} - h_{19}),$ (9)

$Q_g = \dot{m}_R [h_1 + (f-1) h_{10} - f h_9 = \dot{m}_{wv} (h_{13} - h_{14}),$ (10)

$Q_e = \dot{m}_R (h_5 - h_4) = \dot{m}_a (h_{15} - h_{16})$ (11)

$W_p = \dot{m}_R f (h_8 - h_7) = \dot{m}_R f \upsilon_R (p_c - p_e) / \eta_p$ (12)

$Q_{SHE} = \dot{m}_R (f - 1) (h_{10} - h_{11})$ (13)

$Q_{RHE} = \dot{m}_R (h_2 - h_3) = \dot{m}_R (h_6 - h_5)$ (14)

Where,

h: is the specific enthalpy (kJ kg^{-1}), υ_R is the specific volume (m^3 kg^{-1}), P: is the pressure, η_p: is the efficiency of the pump, A:refer to the absorber, a to the air, c to the condenser, and WV to the water vapour

The second law of thermodynamics is sometimes called the law of entropy as it introduces the important property of the entropy. Entropy can be thought of as a measure of how close a system is to equilibrium; it can also be thought of as a measure of the disorder in the system.

The equations for the second law of thermodynamics (entropy generation) for each component of the ARS is expressed as follows:

$S_a = \dot{m}_R [f(S_7 - S_6) - (f-1) S_{12}] + \dot{m}_a (S_{18} - S_{17})$ (15)

$S_c = \dot{m}_R (s_2 - s_1) + \dot{m}_a (s_{20} - s_{19})$ (16)

$S_g = \dot{m}_R [s_1 - (f-1) s_{10} - f s_9] \dot{m}_{wv} (s_{14} - s_{13})$ (17)

$S_e = \dot{m}_R (s_5 - s_4) + \dot{m}_a (s_{16} - s_{15})$ (18)

$S_{SHE} = \dot{m}_R (f-1)(s_{11} - s_{10}) + \dot{m}_R f (s_9 - s_8)$ (19)

$S_{RHE} = \dot{m}_R (s_3 - s_2) + \dot{m}_R (s_6 - s_5)$ (20)

$S_P = \dot{m}_R f (s_8 - s_7)$ (21)

$S_{SEV} = \dot{m}_R (f-1)(s_{12} - s_{11})$ (22)

$S_{\mathrm{REV}} = \dot{m}_R\,(s_4\text{-}s_3)$ (23)

Where S is the entropy generation rate (kW K^{-1}), s the specific entropy (kJ kg^{-1} K^{-1}), SEV the solution expansion value and REV the refrigerant expansion value.

The total entropy generation of the absorption refrigeration cycle is the sum of entropy generation in each component, therefore:

$S_t = S_a + S_c + S_g + S_e + S_{SHE} + S_{\mathrm{RHE}} + S_{\mathrm{P}} + S_{\mathrm{SEV}} + S_{\mathrm{REV}}$ (24)

DISCUSSIONS AND RESULTS

The maximum load expected from a vehicle's air conditioner is equal to the energy required to drive the vehicle 35 miles per hour (56 km/h) at steady state conditions [14]. An automobile is used, on average, about 249 hours annually or about 41 minutes per day, 365 days a year. Estimates of air-conditioning use range from 107 to 121 hours per year or 43% to 49% of vehicle usage. Actual use varies considerably depending on such factors as climate, time of day, time of year, type of vehicle (including vehicle color), outdoor/indoor parking, occupant clothing, recent occupant activity levels, length of trip, vehicle speed, and personal preference [16].

To calculate the amount of fuel consumed to operate air – conditioning vehicle, ,must taking into consideration the nature of life in Saudi Arabia and social restrictions imposed by the conservative environment, the price of fuel and the distances between cities raise utilization rate vehicles for more than the above mentioned. Other factor that may increase the rate of use of the vehicle and accompanied by the use of cooling is that the utilization rate of the Saudi citizen public transport does not exceed 8%.

Apart from natural factors imposed by the heat most summer days of the year and the intensity of solar radiation for long hours during the day in most areas. The average temperature in most major Saudi cities (Riyadh, Dammam, Jeddah, Medina, and Mecca) is 30 – 50 degrees Celsius in the period between the beginnings of April to the end of September. This means that the average temperature in Saudi Arabia during the afternoon in the above mention months is 34 degrees Celsius.

Away from traffic congestion, there are other factors not included in the referred above. For example more often Saudi citizens leave the vehicle engine running while he completion some needs (shopping basic needs, delivery sons and wife to school and work, to do something that does not require a great time relatively. The cheap cost of fuel, and provide safety (because of strict laws on the act of theft -cutting off the hands of thieves), contributed to devote unacceptable this behavior when using the vehicle.

For these reasons we must adjust the vehicle operation hours to conform it with [16], where extra time of the vehicle operation hours must estimated.

To achieve this goal the Northern Border Region of Saudi Arabia, specifically its capital Arar has been chosen. The reasons of taking this city as a case study to calculate the vehicle additional operating hours because the following:

- It is relatively modern city (constructed in 1950).
- It does not suffer from the density or traffic congestion.
- There is reasonable number of vehicle (nearly 80000 vehicles).

The result shows that there is at least 49.08 hours annually of no justification vehicle use, and could have been saved.

Saudi Arabia appears to be the second sunniest place on Earth, only over-shadowed by Chile's Atacama Desert which has a DNI of up to 9.77 kWh per square meter per day [2].

Solar cooling could be a useful technology in area of the world where there is a demand for cooling, high insolation levels, high pollution levels, no firm electricity supply to power conventional systems, and in those countries where there are no Fossil energy.

Found a lot of research and studies that are interested and calls for the use of solar energy as an alternative to fossil energy in different applications: to provide homes with hot water and electricity, street lighting, water desalination ...... etc, and most importantly in this regard to applications running absorption cooling systems.

Concerning the work principle, equipment and results of calculation of such systems there exist many publications [3,11,12,13,14,15,16,17,18,19,21], but this Field still need more attention, in the entire world, , especially if we talking about the use of these systems for cooling vehicles.

In order to find an alternative way to cool the vehicle we examine the possibility of vehicle air- conditioning based on lithium bromide–water absorption refrigeration system drive through heat from solar thermal collectors.

The air conditioning was assumed to be used for the same 6 months as the baseline scenario. The average solar irradiance in Saudi Arabia, during these months (from April to September is 5393.43W/m2).

Absorption refrigeration system give a high efficiency and low operating cost, and also decrease the load on the engine, and the fuel consumption, and therefore the greenhouse gas emissions.

For this purpose depending on first and second thermodynamic laws, a detailed thermodynamic analysis of the water/lithium bromide absorption refrigeration cycle is performed, in specific operational conditions compatible with the nature of the weather (ambient temperature of the air) in most areas of Saudi Arabia ($30 \leq T_{amb} \leq 50$), and under cooling load compatible large size vehicle 1.43 ton (5 kW).

Using a special program coefficient of performance of the system (COP) was calculated at variable values to the temperature of the generator and condenser compatible with the conditions for vehicle air conditioning, taking into account the ambient temperature and the crystallization temperature of the solution. The thermodynamic design data considered in this study covers the following operating range:

Evaporator temperature, $T_e = 15^oC$,

Condenser temperature, $30 \leq T_c \leq 50^oC$,

Absorber temperature , $30 \leq T_a \leq 50^oC$

Generator temperature, $60^oC \leq T_g \leq$ crystallization limit,

Cooling load, Qe=5 kW,

Exchanger effectiveness, $\varepsilon_{SHE} = \varepsilon_{RHE} = 0.50$,

The cycle of higher COP gives higher cooling capacity with the same heat input. The crystallization temperature is one of criteria for a safe cycle operation and the concentration difference represents the cooling capacity of the absorption cycle.

All the results were plotted according to the temperature of the generator, and to the condenser temperature. A mathematical model which expressed the relationship between these variables also was found.

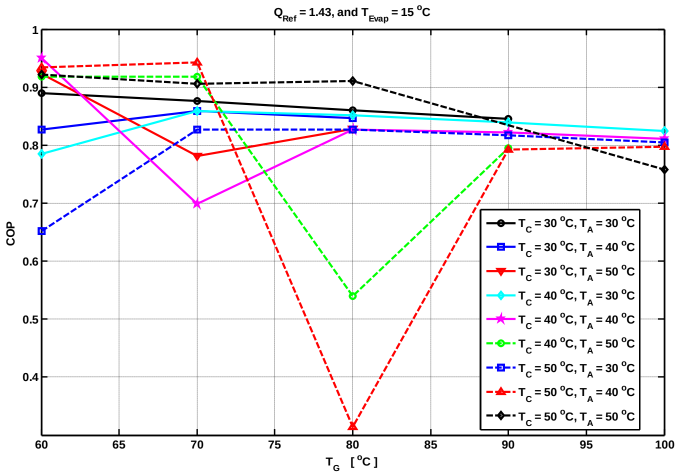


Figure 9: The Relationship between the Coefficient of Performance and Heat Generator, at T_e=15°C

Figures 9, shows that the optimum values of the coefficient of performance when Tc=50 and Ta=40 °C, with a generator temperature ranging from 60 to 70 °C. The thermodynamic design data considered covers the these operating conditions are listed in Table 1.

Table 1: Thermodynamic Design Data at T_e = 15 °C, Q_{ref} =1.43 Ton (5 kW)

T_g, °C	T_c , °C	T_a , °C	Q_g, KW	Q_a,kW	Q_c, KW	COP
60	40	40	5.291735	5.11676	5.2042	0.9504
60	50	40	5.381607	5.20737	5.2034	0.9345
60	50	50	5.453528	5.27929	5.2034	0.9222
70	40	40	7.200743	6.98475	5.2452	0.6984
70	50	40	5.337417	5.12143	5.2452	0.9423
70	50	50	5.551058	5.33507	5.2452	0.906
80	40	40	6.080391	5.82338	5.2862	0.8271
80	50	40	16.01493	15.7572	5.2869	0.314
80	50	50	5.525838	5.2681	5.2869	0.9101

At Tg equal to 80 °C, the coefficient of performance suffers from a sharp decline which will stabilize the system. Also it should be noted that design data at generator temperature equal to 90 are not listed in table due to the lithium bromide begins to turn into crystals. Taking this into consideration, the performance of the system will be better at Tc = Ta = 50 °C, with a generator temperature up to 70 degrees Celsius (Figure 10).

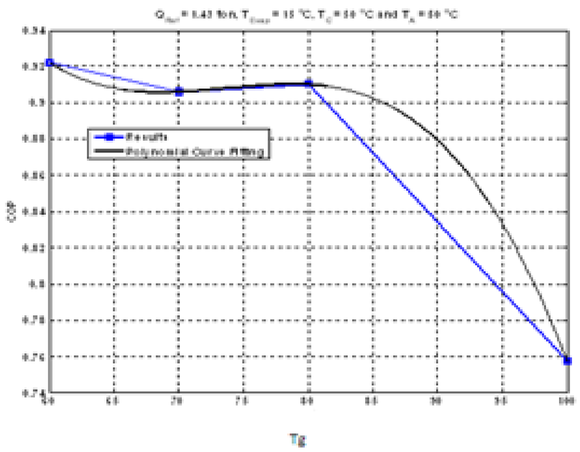


Figure 10: The Relationship between the Coefficient of Performance and Heat Generator, at Tc=Ta=50 °C

It is found that the relationship between the coefficient of performance and the generator temperature when Tc = Ta = 50 ° C is governed by the following equation:

$$\mathbf{COP = -9.2333e\text{-}6\ T_G^3 + 0.002\ T_G^2 - 0.1496\ T_G + 4.5481}$$

Figure 11shows the relationship between the coefficient of performance and condenser temperature at a generator temperature of 70, and different temperatures of absorption system.

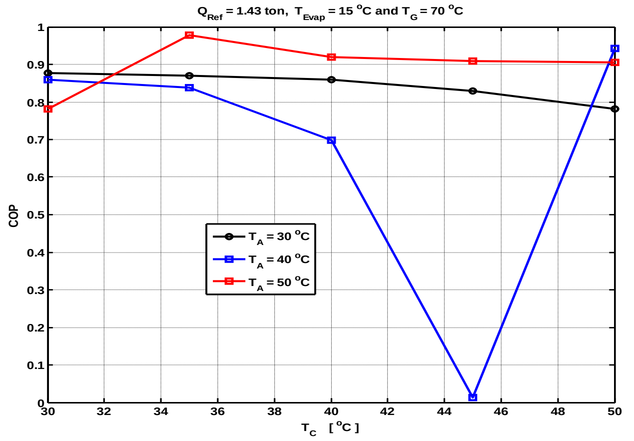


Figure 11: The Relationship between the Coefficient of Performance and the Condenser Temperature

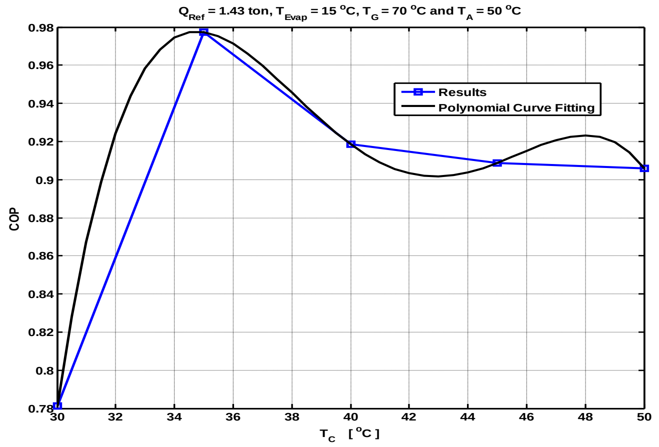


Figure 12: The Relationship between the Coefficient of Performance and the Condenser Temperature, When Generator Temperature Equal 70°c, and Absorption Temperature Equal 50 °c

The mathematical model of relationship between the coefficient of performance and the condenser temperature, when the generator heat equal 70°C,and absorption temperature equal 50 °C is given by the equation:

$$\mathbf{COP = -2.3073e\text{-}5\ T_c^4 + 0.0039\ T_c^3 - 0.2409\ T_c^2 + 6.6110\ T_c - 66.4080}$$

CONCLUSIONS

- Emission gases from the combustion of gasoline and diesel in the Saudi road transport sector in 2011 was 7666.089 tons.
- The Saudi citizen use the vehicle 48.08 hours per year more than the global average rate (global average rate about 249 hours per year), and thus the total number that Saudi citizen use the vehicle about 297 hours per year, of which about 156.08-170.08 hours to air-conditioning the vehicle (63-68% of the total use of the vehicle).This mean an increase in the rate of fuel consumption equivalent to 115 million barrels per year, which equal 15.1% of the total fuel consumption (nearly double that consumed in the United States of America).

- Due to the international attempt to find alternative energies, thermal energy, where its available can very well substitute the classic method used somehow to operate the air conditioning system of the vehicle (vapour compression system).
- In the use of absorption refrigeration cycle for vehicle air-conditioning, the coefficient of performance reached 92% under conditions appropriate to the nature of the weather (Tc = Ta = 50 ^{o}C),and the conditions required for air-conditioning large-size vehicle (Te = 15, Qref = 5 kw).
- The most important feature of using solar assisted automobile A/C based on absorption refrigeration system is the possibility of operating the vehicle A/C without running the Vehicle engine.

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