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Utilizing Exhaust Gases Thermal Energy in an Absorption Refrigeration System

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Abstract

The research includes a theoretical study to verify the possibility of operating an absorption refrigeration system that uses (lithium bromide - water) and works by utilizing the wasted energy with the gases of an internal combustion engine under various operating conditions for both the engine and the refrigeration system. The experimental results obtained from the operation of a four-cylinder, four-stroke, laboratory engine were used to simulate the absorption refrigeration system and study the effect of some operational factors of the engine and the refrigeration system on the system's performance coefficient, using the engineering equations solver (EES) program. The study showed the possibility of utilizing the thermal energy wasted with the exhaust gases of the engine to operate an absorption refrigeration system in certain conditions, especially at high loads. The thermal energy wasted with the exhaust gases was ranged between 4.599 and 20.27 kW at an engine speeds of (1250 and 2500 rpm), respectively, and the highest cooling capacity obtained was 5.401 kW when the flow rate of the strong solution was 0.35 l/min at engine rotational speed 2500 rpm, and the highest value of the performance coefficient was (0.8543), which was recorded when the temperature of each of the evaporator, condenser and absorber was (12, 35 and 35 ˚C).

Introduction

The absorption refrigeration system represents an economical and environmental option as an alternative to the traditional compression refrigeration systems. Absorption refrigeration systems operate with heat that can be obtained by recovering part of the waste heat in industrial processes and various thermal systems, or through direct exploitation of solar energy or thermal energy available in Earth core or others, and scientific research continues to verify the possibility of operating such systems using thermal energy associated with exhaust gases or cooling water for internal combustion engines to reduce environmental pollution and protect the ozone layer from corrosion as a result of the leakage of gases containing chlorofluorocarbons into the atmosphere that are used in vapour compression system. The energy used in the operation of vehicles represents about 35% of the energy generated by the combustion of fuel in the engine, and the rest of energy is Wasted in the form of heat with engine cooling water through the radiator and with exhaust gases and by radiation [1,2]. A study by Mathapati et al., [3] conducted a feasibility of using the available energy in the exhaust gases of an internal combustion engine to operate an absorption system that uses (lithium bromide - water) to condition the air in a regular passenger car. The mathematical modeling of the system was carried out using the EES program, and the effects on the performance coefficient with the change in the various parameters were studied. The researchers showed that the amount of heat of 2 kilowatts is sufficient to provide air conditioning in the car. They also showed that the performance coefficient increases with the increase in the generator temperature and evaporator temperature, but it decreases with the increase in the temperature of the condenser and the absorber. There is also an optimum value for the generator temperature, which when exceeded, the performance coefficient decreases, and the coefficient of performance increases with the increase in the rate of mass flow of water. Longo et al., [4] studied the recovery of wasted heat from the internal combustion engine to operate an absorption system that works with a solution of (lithium bromide - water) using the waste heat available in cooling water system once and the thermal energy wasted with the exhaust gases again, and integrating them in one cycle with an evaporator and a combined absorber. The results showed that the performance of the two sessions are similar. As using engine cooling water, the solution temperature in absorber was about 30 ˚C and the evaporator temperature 7 ˚C, and when using exhaust gas, the solution temperature in absorber was 35 ˚C and the evaporator temperature was 3˚C , the coefficient of performance is almost one. Sorawit et al., [5] made a study on an absorption refrigeration system that operates with exhaust gases from an engine as a source of energy. Experiments were conducted with different engine speeds, variable expansion valve opening, refrigerant temperatures at the condenser exit were 25 ˚C, 30 ˚C and 35 ˚C, and strong solution flow rates were 0.35 l/min and 0.7 l/min. Their results showed that the system can operate at 1200-1400 rpm engine speed, and the cooling load and performance coefficient increase with the increase in speed. And that the highest performance coefficient was 0.275 at 1400 rpm, the opening ratio of expansion valve was (72.7%) at the generator exit and (4.55%) at the condenser exit, the water temperature was (25˚C) at the exit of condenser, and the rate of flow of the lithium bromide-water solution was 0.7 l/min. Also, the decrease in the temperature of the coolant at the exit of condenser led to an increase in both cooling capacity and coefficient of performance. Osta-Omar and Micallef [6] developed a model for thermodynamic analysis of an absorption cooling system working with (lithium bromide - water). The temperatures of the system components, cooling capacity, and mass ratio of solution, were specified as input data. The model estimates the properties of all state points in the refrigeration cycle, rate of heat in each part of the system, flow rates of mass, and system performance coefficient. The results found that increasing the generator temperature and decreasing the absorber temperature leads to an increase in the performance coefficient of the system.

Laboratory device

Figure (1) shows the laboratory device used to obtain real data to use it in simulating an absorption system that works with a solution of (water - lithium bromide). This device consists of a four-cylinders, four-stroke internal combustion engine running on gasoline, also contains 10 kW alternating generator which is connected to the base of electrical loads of 30 bar halogen heater, and its full ignition means that the load is 100%, when ignite 20 bar halogen heater means that the load is 66%, and ignite 10 bar halogen heater means that the load is 33% .

Figure (1) The test rig.

engine speeds from 1250 to 2500 rpm and the temperatures of exhaust gases are recorded, ambient temperature, fuel consumption rate, and mass flow rate of exhaust gases in order to calculate the amount of energy produced by burning the fuel and the amount of heat wasted with the exhaust gases.

Energy balance in Internal combustion engines

Internal combustion engines emit a large amount of thermal energy as a result of fuel combustion to the external environment through engine cooling water and exhaust gases, as well as heat transmitted by radiation and can be represented by the following equation:

$$Q_f = Q_L + Q_{wr} + Q_{exh} + Q_{un} \quad \text{... (1)}$$

The thermal energy produced by the combustion of the fuel can be calculated using the following relationship:

$$Q_f = \dot{m}_f * CV * \eta_{comb.} \quad \text{... (2)}$$

To calculate the thermal energy Wasted with the exhaust gases, the following equation can be used [7];

$$Q_{exh} = \dot{m}_{exh} * Cp_{exh} * (T_{exh} - T_{amb}) \quad \text{... (3)}$$

The flow rate of mass of the exhaust gases leaving the internal combustion engine can be calculated from the mass balance of the engine cylinder as and according to the following equation:

$$\dot{m}_{exh} = \dot{m}_{air} + \dot{m}_{fuel} \quad \text{... (4)}$$

The specific heat of the exhaust gases Cp_{exh} is a function of the fuel components, the (air / fuel) ratio and the temperature of the exhaust gases. Greene [8] suggested a mathematical relationship to calculate it depending on the temperature of the exhaust gases, which is:

$$Cp_{exh} = 0.988 + 0.230 * 10^{-3} * T_{exh} + 0.050 * 10^{-6} * {T_{exh}}^2 \qquad ... (5)$$

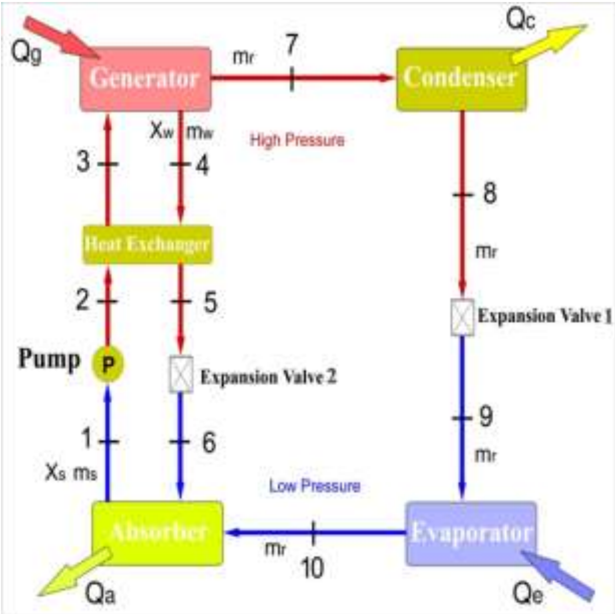

Figure (2) Simple absorption system.

Absorption refrigeration system

The single-effect absorption system consists of main parts, which are the steam generator, condenser, evaporator, absorber, heat exchanger and two expansion valves, as illustrated in Figure (2) and depend in their design on the energy balance, mass balance and heat transfer equations, and each part will be simulated, to calculate the system performance coefficient.

The mathematical analysis of the absorption system are based on following assumptions**:**

1- The system is stable.
2- The pressure in the evaporator is the vapour pressure of the refrigerant at saturation temperature and is equal to the pressure of the absorber.
3- The pressure in the condenser is the vapour pressure of refrigerant at saturation temperature and is equal to the pressure of the steam generator.
4- The refrigerant at the exit of evaporator is saturated vapour.
5- The refrigerant at the exit of condenser is a saturated liquid.
6- The refrigerant mass flow rate generated in generator is equal to that sucked into the absorber.
7- Neglecting the pressure drop in the pipes.
8- Neglecting the heat exchange between the system with the surrounding environment.
9- Atmospheric air is used in the heat exchange process in both the condenser and absorber.
10- The expansion process in the expansion valve is adiabatic.
11- The generator temperature is equal to the temperature of both refrigerant and weak solution leaving the generator.
12- Effectiveness of the heat exchanger between the steam generator and the absorber (0.75).
13- The efficiency of the steam generator used is 40% [9].
14- The Strong solution flow rate is 0.35 l/min [5].

Refrigeration System Analysis:

The mass and energy balance equations for the absorber are as follows:

$$\dot{m}_r + \dot{m}_w = \dot{m}_s \qquad ...(5)$$

$$\dot{m}_r X_r + \dot{m}_w X_w = \dot{m}_s X_s \qquad ...(6)$$

Since the vapour leaving the evaporator is pure water, so;

$$\dot{m}_s X_s = \dot{m}_w X_w \quad \text{... (7)}$$

$$Q_a = \dot{m}_r h_{10} + \dot{m}_w h_6 - \dot{m}_s h_1 \quad (8)$$

For generator, The balance equations of mass and energy are ;

$$\dot{m}_w + \dot{m}_r - \dot{m}_s = 0 \quad \text{...(9)}$$

And,

$$Q_g = \dot{m}_r h_7 + \dot{m}_w h_4 - \dot{m}_s h_3 \quad \text{...(10)}$$

The heat rejected from the condenser is;

$$Q_c = \dot{m}_r (h_7 - h_8) \quad \text{... (11)}$$

And the heat absorbed by the refrigerant in evaporator is;

$$Q_e = RE = \dot{m}_r (h_{10} - h_9) \quad \text{... (12)}$$

The energy balance equations in heat exchanger is;

$$\dot{m}_s (h_3 - h_2) = \dot{m}_w (h_4 - h_5) \quad \text{... (13)}$$

and the effectiveness;

$$\varepsilon_{ex} = \frac{T_3 - T_2}{T_4 - T_2} \quad \text{... (14)}$$

For the expansion valve (1) and (2);

$$h_9 = h_8 \quad \text{... (15)}$$

$$h_5 = h_6 \quad \text{... (16)}$$

To calculate the Required work to operate the solution pump, the following equation can be used [10]:

$$W_P = \frac{\dot{m}_s * (P_c - P_e)}{\rho_{sol} * \eta_{pump}} \quad \text{... (17)}$$

And the coefficient of performance is ;

$$COP = \frac{RE}{Q_g + W_P} \quad \text{... (18)}$$

Thermal properties of Refrigeration solutions:

The thermal properties of solutions such as pressure, temperature, concentration, enthalpy and density depend on each other and are necessary for the mathematical modeling of absorption cooling systems. The thermal properties of each of the refrigerant (water) and the absorbent material (lithium bromide) must be calculated for use in the simulation of the system. as follows:

A- The refrigerant (water):

To calculate the specific enthalpy of water leaving the condenser at a temperature (T_c), the following relationship can be used [11]:

$$h_8 = 4.19(T_c - 273.15) \quad \text{... (19)}$$

The relations used to calculate the specific enthalpy of the saturated steam leaving the generator in the case of saturated steam, and the saturated steam coming out of the evaporator, they are [11]:

$$h_7 = 2.326\left[(0.004932T_g - 2.2493008)\frac{P_c}{6894.76} + (0.80895T_g + 854.2151086)\right] \quad \text{... (20)}$$

$$h_{10} = 2.326[(0.004932T_e - 2.2493008)\frac{P_e}{6894.76} + (0.80895T_e + 854.2151086)] \quad \text{...(21)}$$

The pressure of the refrigerant in the condenser at the condenser temperature and the pressure in the evaporator, can be represented by the relationships below [12]:

$$P_c = 10^{\left(10.04999 - \frac{1603.541}{T_c} - \frac{104095.51}{T_c^2} - 3\right)} \quad \text{... (22)}$$

$$P_e = 10^{\left(10.04999 - \frac{1603.541}{T_e} - \frac{104095.51}{T_e^2} - 3\right)} \quad \text{... (23)}$$

B - The solution (water - lithium bromide):

The concentration of solution leaving the absorber and the concentration of the solution leaving the generator can be calculated based on the temperatures of each of the absorber, evaporator, generator and condenser from the following two relationships [12]:

$$X_1 = X_2 = X_3 = X_s = \frac{49.04 + 1.125T_a - T_e}{134.65 + 0.47T_a} \quad (24)$$

$$X_4 = X_5 = X_6 = X_w = \frac{49.04 + 1.125T_g - T_c}{134.65 + 0.47T_g} \quad \text{... (25)}$$

The specific enthalpies of the strong solution at the exit of absorber, and the weak solution leave the generator can be estimated by the following relationships [13]:

$$h_1 = \sum_{i=0}^{4} A_n X_s^n + T_a \sum_{i=0}^{4} B_n X_s^n + T_a^2 \sum_{i=0}^{4} C_n X_s^n \quad h_4 = \sum_{i=0}^{4} A_n X_w^n + T_g \sum_{i=0}^{4} B_n X_w^n + \quad ...(26)$$

$$T_g^2 \sum_{i=0}^{4} C_n X_w^n \quad ...(27)$$

And Table (1) includes the values of the constants for equations (26) and (27) [13].

Table (1) values of the constants for equations.

i	Ai	Bi	Ci
0	−2024.33	18.2829	−0.037008214
1	163.309	−1.1691757	0.0028877666
2	−4.88161	0.03248041	−0.000081313015
3	0.06302948	−0.0004034184	0.00000099116628
4	−0.0002913705	0.0000018520569	−0.000000004441207

And the density of the strong solution can be estimated by the following relationship[14]:

$$\rho_{sol} = 1145.36 + 470.84X_s + 1374.79X_s^2 - T_a(0.333393 + 0.571749X_s) \quad ... (33)$$

RESULTS AND CONCLUSIONS:

The amount of heat energy resulting from burning the fuel under loaded and unloaded with various engine speed is shown in Figure (3). It can be noted that as the speed of engine increase, the amount of heat energy increases. This is due to the increasing of rpm revolution per minutes which caused by increasing the number of combustion process, and therefore the amount of heating energy will increase.

Figure (4) shows the variation of the amount of heat energy available in the exhaust gases with engine speed. It can be seen that the amount of heat energy increase as the engine speed is increased. the percentage increase in the amount of heat energy associated with the exhaust gases, when the engine loaded by 100% load, ranged between 15.23% at an engine speed of 1250 rpm and 33.15% at an engine speed of 2500 rpm. The highest value of energy reached 20.27 kW at an engine speed of 2500 rpm and load 100%.

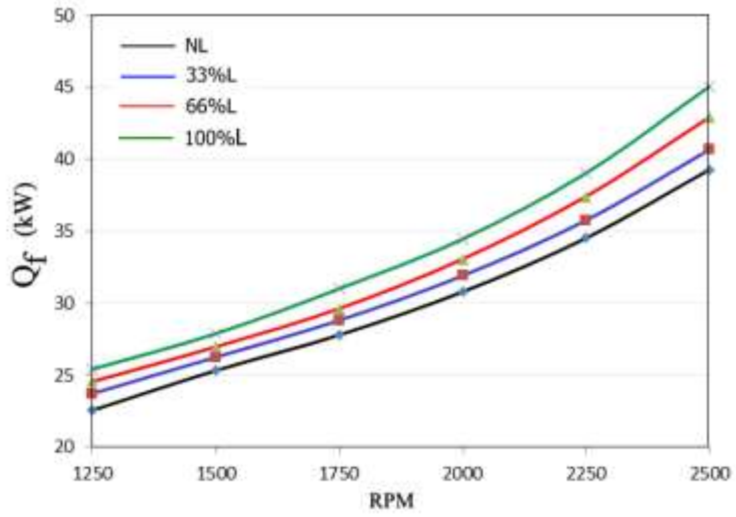

Figure (3) variation of heat energy generated by the combustion of the fuel with engine speed.

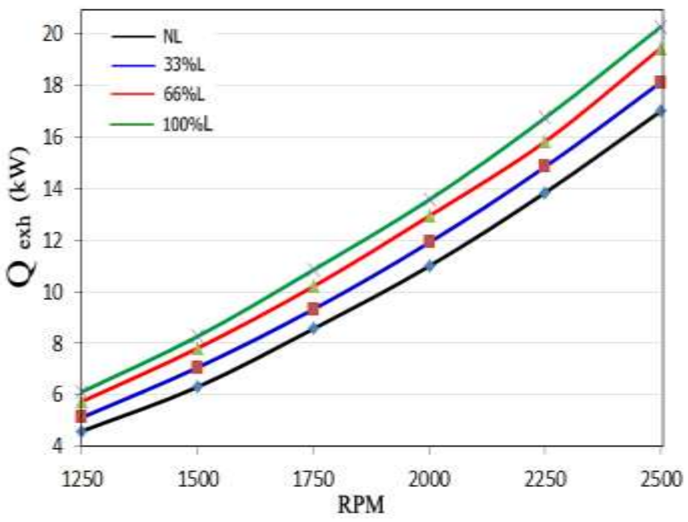

Figure (4) variation of the thermal energy wasted in the exhaust gases with the engine speed.

The variation of the exhaust gases temperature with engine speed at different engine load illustrated in Figure (5). The figure indicates that the exhaust gas temperature is directly proportional to the engine speed for all engine load conditions. The highest exhaust gas temperature obtained is 416.7 °C at an engine speed of 2500 rpm.

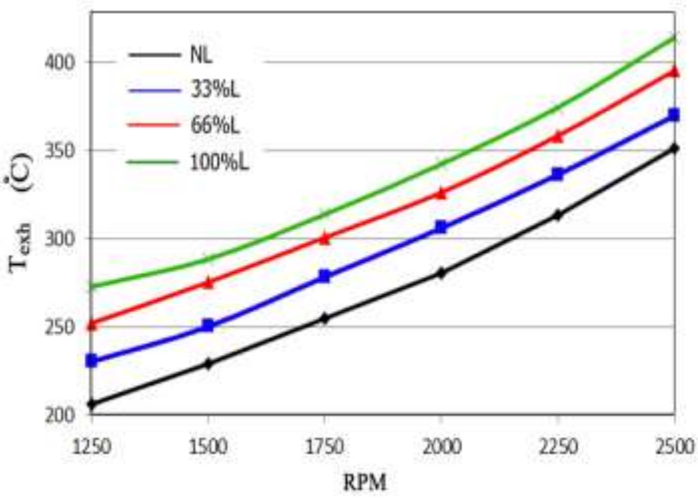

Figure (5) Exhaust temperature versus engine speed.

Figure (6) shows the variations of the refrigerant mass flow rate and system refrigerating capacity with the engine speed at different engine loaded conditions, different condenser temperture, and the evaporator temperture is 12 ˚C. it can be noted that there is an icrease in the refrigerant mass flow rate due to an increase in engine speed and caused by increasing the refrigerating capacity for all cases of engine loaded. Also, it can be seen that, it is able to obtain a refrigerating capacity contiously when the condenser temperture is 35 ˚C, as shown in figure (6A). The refrigerating capacity is 5.401 kW at an engine speed of 2500 rpm and 100% load. While it can not be able to get a refrigerating effect when the condensr tempertures is 40 ˚C or 45 ˚C, at all engine speed as illustrated in figure (6B) and (6C).

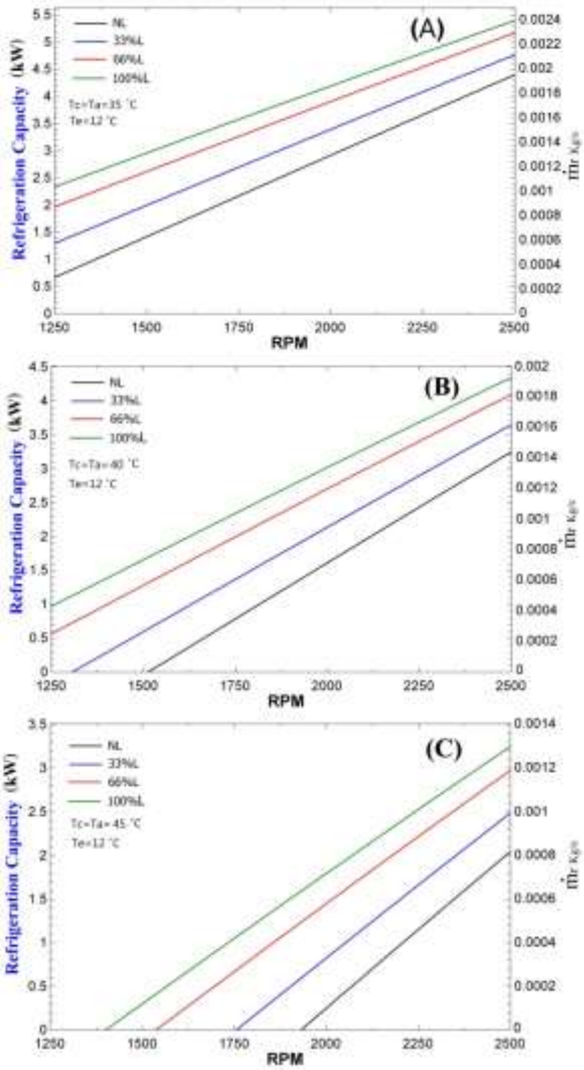

Figure (6): variation of refrigeration capacity of the absorption system with engine speed.

The variation of the performance coefficient with the engine speed , at different evaporator temperture is illustrated in figure (7). The figure shows that the performance coefficient is stable, under a various engine speed, when the evaporator temperture is 12 ˚C . Also, it can be noticed that as the evaporator temperture is increases, the performance coefficient was increased. This mean that the system performance suffers with an increase in the evaporator temperture.

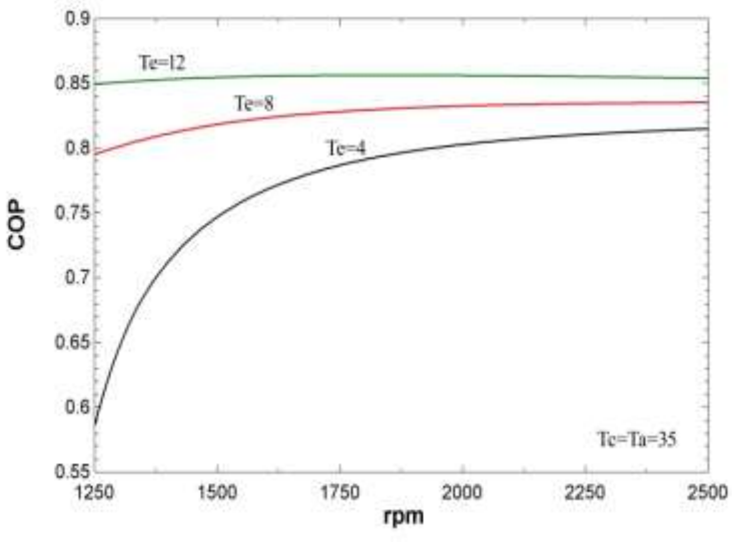

Figure (7): COP versus engine speed.

Conclusion

1. The amount of heat dissipated by the exhaust gases and the exhaust temperature are increased with an increase in an engine speed and engine load.
2. The refrigerating capacity and the performance coefficient are increased by increasing the engine speed for all loading and no loading conditions.
3. The system performance coefficient is increased with an increase in evaporator temperature.
4. It can be possible to operate an absorption refrigeration system by utilizing a thermal energy attendant with the exhaust gases, at relatively high evaporator temperature, high engine speed, and high engine load.

Nomenclature

COP	Coefficient of performance	---	Subscripts		
Cp	Specific heat	kJ / kg . K	A	Absorber	---
CV	Caloric value		C	Condenser	---
H	Enthalpy	kJ / kg	E	Evaporator	---
L	Loading	---	Ex	Heat exchanger	---
ṁ	Mass flow rate	kg / s	exh	Exhaust	---
NL	No Loading	---	F	Fuel	---
P	Pressure	kPa	G	Generator	---
Q	Heat energy	kW	R	Refrigerant	---
SCR	Solution circulation ratio	---	S	Strong solution	---
Wp	Work of Pump	kW	Un	Uncounted energy	---
X	lithium bromide concentration	---	W	Weak solution	---
Greek letters			water	Water engine cooling	---
η	Efficiency	----	$\sum$	Sum of	---
$\boldsymbol{\rho}$	Density	kg/m^3			
ε	Effectiveness of the heat exchanger	---			

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