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A Preliminary Study on Designing and Testing of an Absorption Refrigeration Cycle Powered by Exhaust Gas of Combustion Engine

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Abstract: In order to recover the waste heat from the exhaust gas of a combustion engine an adsorption refrigeration cycle is proposed. This is a preliminary study on design and testing of a prototype of absorption refrigeration cycle powered by an internal combustion engine. The heat source of the cycle is a compression ignition engine which generates 122.36 W of heat in generator of the cycle. The pairs of absorbent and refrigerant are water and ammonia. Here the generator is made of a shell and tube heat exchanger with number of tube and its length are 20 and 0.69 m, respectively. In the experiments the exhaust gas with a mass flow rate of 0.00016 kg/sec, enters the generator at 110°C and leaves it at 72°C. Here, the solution is heated from 30-90°C. In the evaporator, the lowest temperature can be reached is 17.9°C and COP of the system is 0.45. The main conclusion can be drawn here is that the proposed system can be used to recycle the waste heat and produced cooling. However, the COP is still low.

Key words: Absorption refrigeration cycle, exhaust gas, produced cooling, COP, system, solution

INTRODUCTION

The vapor compression refrigeration system is currently the most widely refrigeration system used to cool the room or building because the system is more convenient in terms of installation. But for the present, where the cost of electricity continues to increase, the vapor compression refrigeration system will release expensive cost for compressor component that requires the electricity (Hilali and Soylemz, 2015; Jotova *et al*., 2014). Besides the use of compound refrigerant hydrocarbon-fluorine resulting in the emergence of the greenhouse effect is the depletion of the ozone layer in the stratosphere. In an absorption refrigeration system energy consumption expenditures can be reduced because it does not use a compressor and easier maintenance costs (Besagni *et al*., 2016; Ouadha and El-Gotni, 2013). Absorption refrigeration cycle is a refrigeration process which utilizes two types of fluid. Both vapor compression refrigeration cycle and absorption refrigeration cycle through evaporation refrigerant at low temperatures and heat release when condensation at higher pressures. In both types of cycles there are differences in the way to create the pressure difference and the driving cycles of refrigerant. The vapor compression cycle use mechanical compressor power to suppress refrigerant, so high pressure. At the absorption cycle, the absorbent used to run the circulation. In the study absorption refrigeration cycle is used ammonia which acts as a working fluid cooling.

MATERIALS AND METHODS

Absorption cycle is a thermodynamic cycle which can be used as the refrigeration cycle and is driven by the energy in the form of heat (Dehua, 2016). Ferdinand Carre, a French national, found the absorption system and obtained a patent from the US government in 1860 (Hong *et al*., 2016). One of the features of this cycle is the heat that is used to run the cycle can be a source of heat where temperatures <200°C (She *et al*., 2015; Shi *et al*., 2016). To know the working principle of a simple absorption cycle, the diagram is divided into two cycles, the first is the cycle when the refrigerant is separated from absorbent, indicated by point 1-2-3-4. The second is the cycle in which absorbent and refrigerant dissolved or bound. In the picture shown at the point of 5-6-7-8. Description of the working principle of a simple absorption cycle starts from the point of 1-2-3-4. In the first cycle, the refrigerant evaporated from the evaporator at point 1. The steam will go into the second cycle in and out at point 2 on the condition of dry steam or superheat and high pressure.

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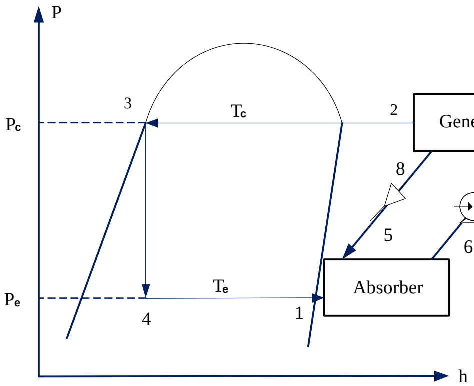

Fig. 1: The P-h diagram of a simple absorption cycle (Cengel, 2008)

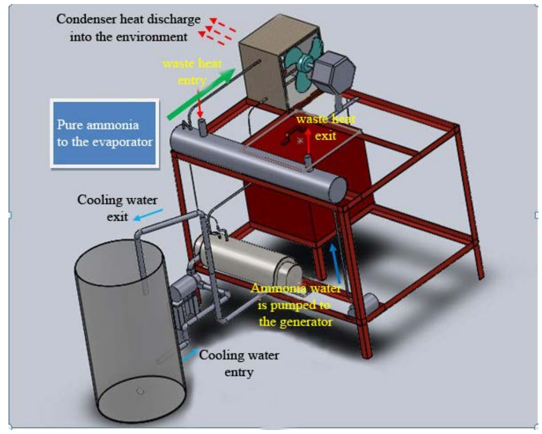

Fig. 2: Scheme of experiment

From point 2, refrigerant vapor enters the condenser. In the condenser, heat released into the environment. The process of heat loss is occurring isobaric and eventually turns into a refrigerant liquid at point 3. Then refrigerant flowing from point 3-4. In this process occurs adiabatic pressure reduction by the expansion valve. When the pressure drops the temperature will go down and some of the liquid will turn into vapor at point 4. Furthermore, from point 4-1. The refrigerant will perform the functions of refrigeration in the evaporator and eventually evaporates and the cycle will be repeated.

In the second cycle, after completion of the first cycle, refrigerant vapor out of the first entry point to the absorber and out through point 6. In the absorber, a vapor bonding process occurs by the solution coming from point 5 is the solution concentration is weak. This chemical bonding process will remove the amount of heat into the environment. Then a solution of point 6 becomes stronger concentration solution will be pumped to the point 7 to the generator by a pump. The solution from the point of entry into the generator 7, here the solution will be heated, causing the release of refrigerant and absorbent. The refrigerant will be out of point 2 while absorbent or solution of weak concentration out of point 8. From the point 8 weak solution concentration will be reduced pressure by an expansion valve and out towards point 5. The P-h diagram of a simple absorption cycle shown in Fig. 1.

As noted to create a cycle of absorption can occur, so that, the pressure ratio at the generator or absorber or condenser and evaporator must be set high enough. The pairs of absorbent and refrigerant are water and ammonia. In this study, the heat used in the generator taken from the exhaust gas of a diesel engine with the temperature range of 110°C. The experimental procedure can be described as follows:

- Make vacuum the absorption refrigerator cycle by using a vacuum pump
- Turn on the refrigerator and the heating process is done 10-15 min until the generator temperature reaches 110°C
- Insert the tube into the water solution of ammonia as much as 5 L.
- Turn on the pump, condenser fan and evaporator fan
- Open the valve on the absorber, so that, the ammonia-water solution into the absorber
- Open the valve before entering the condenser with the provisions of the desired pressure has been reached
- Measure the temperature of components by using a digital thermometer
- Measure the working pressure using a pressure gauge
- Measure the length of time from entry refrigerant until achieved the lowest temperature The schematic of experimental systems as shown in Fig. 2

RESULTS AND DISCUSSION

The absorption thermodynamic cycle can be seen in Fig. 3. The initial stage begins with determining the temperature of the evaporator, condenser, generator and absorber which the evaporator temperature 0°C, the condenser temperature 35°C, the generator temperature 90°C, the absorber temperature 30°C. From the component temperature can be calculated the value of the pressure, enthalpy and entropy. This was calculated from the tables of thermophysical properties of refrigerants and the results are shown in Table 1.

The load on the evaporator is set at 50 W on this research. Table 1 can be calculated from the mass flow rate in the evaporator.

Mass flow rate = $Q_{generator}/(h_1\text{-}h_4)$

Mass flow rate = (0.05 kW)/(1461.81-366,58kJ/kg)

Mass flow rate = 4.56483×10-5 kg/sec

By knowing the mass flow rate in the evaporator, the load value on the condenser can be calculated as follows:

The condenser load = $m\times(h^3\text{-}h^2)$ =

4.56×10^{-5} kg/s×(1615- 366.58kJ/kg) = 0.057 kW

The next stage is to determine the concentration of ammonia-water solution. By using the graph of concentration of ammonia-water, at a pressure of 13.51 bar and a temperature of 90°C obtained ammonia-water solution concentration of 0.533 and the type of concentration is strong. At a pressure of 4.29 bar and a temperature of 35°C is obtained ammonia-water solution concentration of 0.4 and the type of concentration is weak. By knowing the concentrations of ammonia-water solution, so that, the enthalpy at points 5, 6, 7 and 8 can be obtained (Table 2).

From the law of conservation of mass, then the values of the mass flow rate refrigerant in the generator can be calculated from the equation:

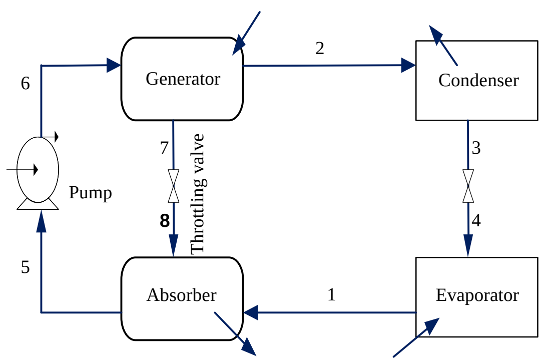

Fig. 3: Absorption thermodynamic cycle

Table 1: The values of enthalpy and entropy

Points	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)
1	4,294	1461,81	5,610
2	13,510	366,58	
3	13,510	1615,07	5,619
4	4,294	366,48	1,568

Table 2: The values of enthalpy and concentration

Points	Temperature	Concentration	Enthalpy (kJ/kg)
5	30	0.40	-100
6	30	0.40	-100
7	90	0.53	175
8	90	0.53	175

$$\dot{m}_6.X_6 = \dot{m}_7.X_7+\dot{m}_1$$

$$\dot{m}_7 = \dot{m}_6\text{-}\dot{m}_1$$

$$\dot{m}_6.X_6 = (\dot{m}_6\text{-}\dot{m}_1).X7+\dot{m}_1$$

$$0{,}533\ \dot{m}_6 = (\dot{m}_6\text{-}4{,}56483.10^{-5})0{,}4+4{,}56483.10^{-5}$$

$$\dot{m}_6 = 2{,}05932\times10^{-4}$$

$$\dot{m}_7 = 1{,}60284\times10^{-4}$$

According to the law of conservation of energy, the amount of energy contained in the absorber is:

$$Q_a = \dot{m}_8.h_8+\dot{m}_1.h_1\text{-}\dot{m}_5.h_5$$

$$Q_a = 0{,}1153 \text{ kW}$$

The amount of energy contained in the generator is:

$$Q_g = \dot{m}_2.h_2+\dot{m}_7.h_7\text{-}\dot{m}_6.h_6$$

$$Q_g = 0{,}1224 \text{ kW}$$

The design of evaporators begins by determining the cooling capacity of the evaporator. The cooling capacity is set at 50 W. The fluid to be cooled is air at a temperature of 32°C inside the cooler with dimension 50×50 cm. The refrigerant used is ammonia. In this study, the temperature of the air to be cooled is expected to achieve a temperature of 0°C. With the temperature of evaporation is 0°C and the temperature of condensation is 35°C, so, the mass flow rate in the evaporator:

$$\dot{m} = \frac{Q_e}{h_1\text{-}h_4}$$

$$\dot{m} = \frac{0.05\text{kW}}{1461{,}81\frac{\text{kJ}}{\text{kg}} - 366.58\text{kJ/kg}}$$

The dimension of the evaporator is shown in Table 3. The heat transfer parameter in the evaporator can be seen in Table 4.

Table 3: The dimension of the evaporator

Designs	Dimension (mm)
Inner diameter of tube	8.7
Outer diameter of tube	9.5
Distance of tube pitch	50
Number of tube	5

Table 4: The heat transfer parameter in the evaporator

	Values	
Items	Air	Refrigerant
Re	2186.96	43.473
Nu	21.16	
H	59.37 W/m²K	247.9 W/m²K
U	51.325 W/m°C	
LMTD	16.301°C	
A	0.0597 m²	
L	0.4 m	

Table 5: The heat transfer parameter in the condenser

	Values	
Items	External flow	Internal flow
Re	2508.28	743.04
Nu	23.34	
H	85.76 W/m^{2}K	2452.11 W/m^{2}K
U	80.70 W/m°C	
LMTD	22.11	
A	0.0319 m^2	
L	1.452 m	

Table 6: The dimension of absorber

Design	Dimension (mm)
Inner diameter of tube	128.1
Outer diameter of tube	141.3
Number of tube	1
Inner diameter of shell	154
Outer diameter of shell	128.1

Where Re is Reynold number, Nu is nusselt number, H is the convection heat transfer, U is the overall heat transfer, LMTD is a logarithmic mean temperature difference, A is cross area of evaporator and L is the length of the evaporator.

The condenser using air as a fluid heat sink. The input water temperature in the tube is 28°C and the output water temperature is 28.44°C. Whereas the input ammonia-water temperature in the shell is 39.5°C and the output temperature is 30°C. The dimensions of condenser used consisted of an inner diameter of tube is 6.82 mm, outer diameter of tube is 10.28 mm, distance of tube pitch is 50 mm, the number of pipes is 5 and the intake air velocity is 5 m/sec. The heat transfer parameter in the condenser can be seen in Table 5.

The absorber designed is a heat exchanger with shell and tube type. Ammonia is flowing on the inside with inlet temperature 90°C and the exit temperature is 35°C. While the air is flowing on the outside with inlet temperature 30°C and the exit temperature is 31°C. The amount of heat that can be removed by the cooling water is:

$$Q = m \cdot C_p . \Delta T$$

$$Q = 0.0025 \frac{kg}{sec} \cdot 4178.31 \text{ kJ/kgK} \cdot (302,44K\text{-}301) = 115 \text{ W}$$

The dimensions of absorber used can be seen in Table 6. The heat transfer parameter in the absorber can be seen in Table 7.

The type of heat exchanger of generator used is shell and tube. In the tube is flowing exhaust gas with input temperature of 110°C and the output temperature of 72.87°C. Whereas, in the shell is flowing ammonia-water with input temperature of 30°C and the output temperature of 90°C. To determine the energy produced by the exhaust gases of combustion engine can be calculated using the equation:

$$Q = m \cdot C_p . \Delta T$$

$$Q = 0.0036 \frac{kg}{sec} \cdot 915.62 \text{kJ/kgK} \cdot (110\text{-}72.87)$$

$$Q = 122.365 \text{ W}$$

In this study is determined the dimensions of shell and tube as shown in Table 8. By calculating the parameters of heat transfer, so that can be obtained the length of the generator which needed. From the experimental results obtained the lowest air temperature that can be achieved is 17.9°C (Table 9).

Table 7: The heat transfer parameter in the absorber

	Values	
Items	Shell	Tube
Re	3.76	8689.48
Nu	4.86	65,84
H	136.90 W/m^{2}K	460.06 W/m^{2}K
U	8.54 W/m°C	
LMTD	5.71	
A	0.26 m^2	
L	0.61 m	

Table 8: The dimension of the generator

Design	Dimension (mm)
Inner diameter of tube	110
Outer diameter of tube	130
Distance of tube pitch	230
Buffle distance	70
Number of tube	20
Inner diameter of shell	150
Outer diameter of shell	165

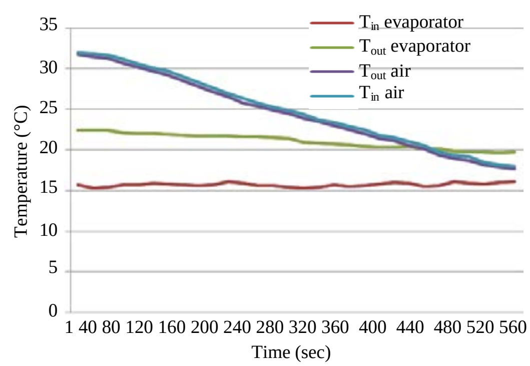

Fig. 4: Evaporator and air temperature during experiments

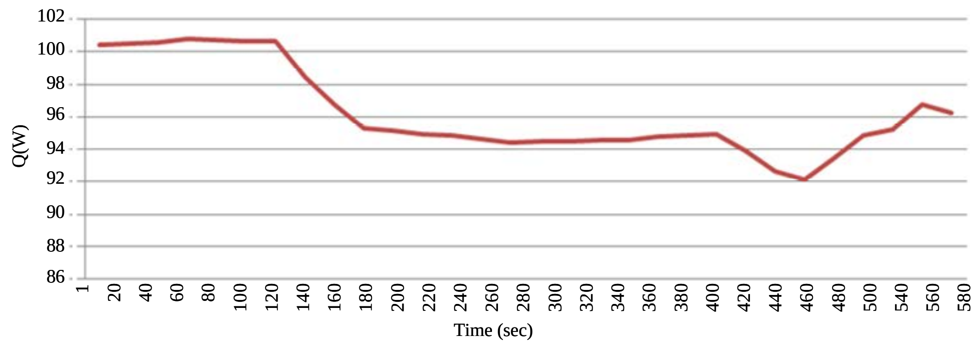

Fig. 5: The heat transfer rate of the generator during experiments

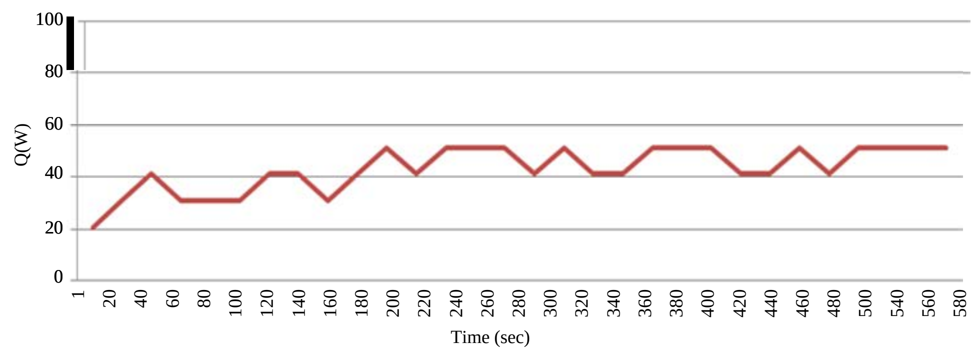

Fig. 6: The heat transfer rate of the evaporator during experiments

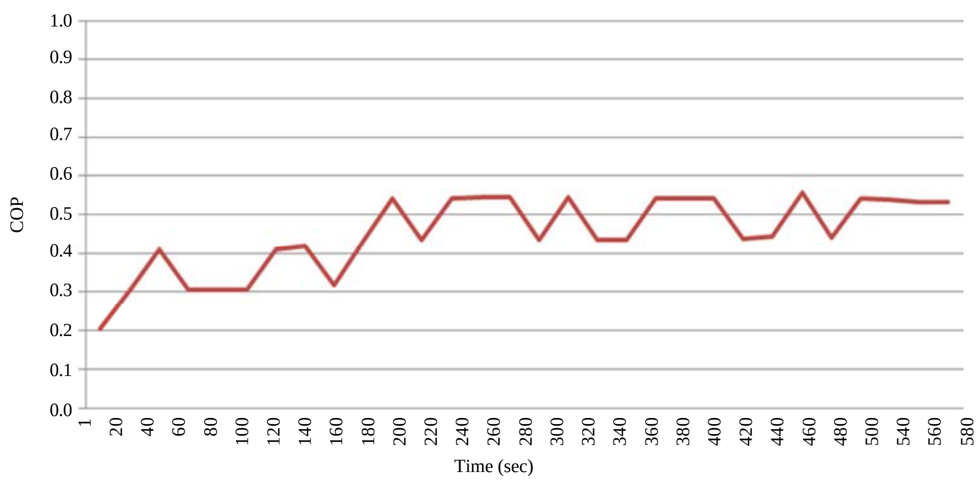

Fig. 7: The values of COP during experiments

From the testing data obtained the heat transfer rate in the generator as shown in Fig 5. The maximum heat transfer rate obtained 100.9 W. The heat transfer rate of the evaporator is obtained as shown in Fig. 6.

The maximum heat transfer rate in the evaporator is obtained 53.8 W. From the test results obtained the heat transfer rate on the generator and the evaporator, so that, the value of COP can be calculated.

The values of COP during experiments is shown in Fig. 7. It appears that the COP values which obtained between 0.2-0.6 and the average value obtained is 0.45. There are several parameters that affect the performance of the absorption refrigeration system. One of them is the isolation of the components of the refrigerator are still less than optimal, so that, there is infiltration of outside air into the evaporator, thus, affecting the absorption process.

Table 9: The heat transfer parameter in the generator

	Values	
Items	Shell	Tube
Re	1872.53	2.35
Nu	20.55	
h	8.93 W/m^{2}K	193.28 W/m^{2}K
U	8.54 W/m°C	
LMTD	29.99	
A	0.477 m^2	
L	0.691 m	

Another thing that affects the performance of the absorption refrigerator is the ability of absorbent to absorb ammonia. This condition can be caused by a vacuum process is not yet optimal, so that, there are unwanted gases that interfere the absorption process in the refrigerator. That is because the refrigerant absorbed by adsorbent is less than without the presence of unwanted gases. The unwanted gases absorbed earlier than the refrigerant, making more absorbent micropores available for unwanted gases than refrigerant during the process.

CONCLUSION

The preliminary study of the performance of absorption refrigeration driven by exhaust gas of a diesel engine with water-ammonia as working pair has been studied. Experimental data results shown that the COP average is 0.45. The minimum temperature that can be achieved in this research is 17.9°C. It is clear that the proposed system can be used to recycle the waste heat and produced cooling eventhough the COP is low. For further research required some modifications to the components of absorption system, so that, the value of COP can be improved.

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