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New Design For a 2 kW Capacity Cooling System Powered by Exhaust Gases of a Diesel Engine

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ABSTRACT

The major goal of this project is to design an automobile air conditioning system equipped with a 2 kW electric compressor that works by recovering waste heat from exhaust gases. In other words, we have converted the energy of the exhaust gases from exhaust manifold into electrical energy by linking the engine exhaust with the gas turbine to generate torque that is transmitted to the dynamo and thus generates a continuous electric current. The experimentation was done for a four-cylinder Kia carnival diesel engine. At speed engine 1600 rpm, the results showed that the engine efficiency improved through a decrease factor in several variables such as the rate of fuel consumption, the temperature of the exhaust gases, and the amount of heat released from the engine about 4.4%, 10.1% and 18%, respectively. The performance coefficient of the proposed cooling system, on the other hand, increased by 3.7%, according to the findings. We were able to develop a solution to the energy wasting concerns of the air conditioning system in a vehicle that uses the vapor compression cycle based on these findings.

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1. INTRODUCTION

In the current era, more emphasis is placed on energy conservation. Refrigeration and air conditioning is one of the growing engineering fields, and the current system is hampering the environment because they suffer from various environmental problems such as depletion of the ozone layer and global warming impact due to the emission of harmful gases for example HFCs, CFCs and CO2. To fulfill the growing global need for energy, however, the rate of depletion of nonrenewable energy sources must be slowed while alternative renewable energy sources are developed. This can be accomplished by improving traditional power plants' overall thermal efficiency. The most popular method is exhaust heat recycling. The majority of the technologies available today recover waste heat as thermal energy, which is subsequently transformed into electricity in a traditional steam power plant. The direct conversion of the energy of the exhaust gases released from fuel combustion into electricity is another option that has gotten little attention thus far.

A drawback of a traditional automotive internal combustion engine (ICE) is that only about a third of the energy spent during operation is transformed into useable mechanical energy. The remaining two-thirds of total energy in water-cooled engines is squandered in the cooling systems and exhaust gases, resulting in an increase in entropy and substantial environmental pollution [1]. As a result, there is a desire to convert the vehicle’s waste heat into productive work output. The internal combustion engines of automobiles that run on diesel oil contain 45 MJ/kg of low heating value (LHV). In theory, energy from burning diesel oil in compression engines wastes about 27 MJ/kg of energy in the exhaust gas (see Figure 1).
Most of the traditional air conditioning systems used to cool the cabin or to transport goods that depend on pressure of vapor [2-3]. These systems derive their energy from the engine, so they have a major role in reducing the engine's performance. Therefore, there has been an urgent necessity since three decades ago in order to increase the performance of the engine without reducing the performance of the cooling system. This is done by finding alternative energy to operate the cooling system without affecting the performance of the internal combustion engine. One of the most important sources of energy lost from combustion engines are exhaust gases.

Johnson [4] experimented for a typical 3-liter engine with a maximum power of 115 kW and calculated the total waste heat dissipation from the engine, which ranged from 20 kW to 400 kW over a typical operating range of the engine. In comparison to the 0.8-3.9 kW cooling capacity given by ordinary passenger car systems, the average engine power available from dissipate heat for a typical and representation drive cycle was calculated to be approximately 23 kW. Another disadvantage of the VCR system in automobiles is that the compressor uses too much engine power, decreasing the vehicle's overall efficiency. The absorption cycle has been proven to be the best alternative because the leaking of CFCs from these air conditioners has a negative impact on the environment. Keating earned a patent in 1954 for his invention of the absorption refrigeration system for mobile applications. Large trucks, boats, and railcars can all benefit from this technology [5]. The absorption cooling system uses environmentally friendly refrigerating fluids, such as lithium bromide and water or ammonia and water. A turbine-powered absorption machine was patented by McNamara[6] in 1972. Three liquid ammonia and helium systems were employed in this system.

In the past years, numerous studies and research have been conducted on the design of the absorption refrigeration cycle (VAR) in automobiles as an alternative to the vapor compression refrigeration cycle (VCR) because the last machine uses compounds that are harmful to the environment as well as more costly from an economic point of view. It also produces noise, wastes energy as heat and increasing fuel consumption. Since the 1960s, various investigations were performed on the use of the thermal energy created by the exhaust gases from engine, which is squandered to the environment. According to studies, a third of the fuel combustion energy is transformed into productive work in a car engine and the rest of the combustion energy is lost as heat in the radiator or as exhaust gases through the manifold (Greene and Lucas, [1]). In a small automobile engine, Wang, [7] conducted his experiments on the engine type Nissan 1400 and concluded that it is possible to extract 15 kW of heat energy from the exhaust stream which is enough to keep an absorption system running. Sohail and Tiwari [8] used the exhaust gases from a 4-cylinder diesel engine to heat the solution inside the generator to conditioned the automobiles cabin. Lithium bromide and water were one sort of working material employed in the system, while ammonia and water were the other. According to the researchers, the ammonia and water cooling system requires an additional heat source in addition to the exhaust energy while the LiBr–H2O cooling system has a crystallization problem. Ghassemi [9] pioneered the application of ammonia water absorption cooling in automobiles. The system performance coefficient decreased by approximately (COP = 0.29). Salim [10] used the ICE waste heat cooling system obtainable in the ICE and simulated a lithium bromide single-stage water absorption cycle for automobiles that removes heat from the engine's exhaust fumes. This system may be used for both water-cooled and air-cooled systems, and it employs ABSIM to calculate the results. Shah Alam [11] tested absorption cooling systems with one-ton capacity driven by a 4-cylinder, 4-stroke vehicle engine and used three types of working fluids in his tested. Ramanathan et al. [12] used steady state model to simulated the absorption refrigeration cycle. The LiBr–H2O solution was employed as a working mixture in comparison to usual refrigerants used in refrigeration applications due to its good thermodynamic and transport properties.

Through previous studies. It is clear to us that the vapor compression cycle is the most successful air conditioning and refrigeration cycle, despite the problems of energy waste and environmental pollution. Through this design, the problem of energy wastage was solved and environmental pollution was.

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reduced to some extent by reducing fuel consumption. The major purpose of this project is to utilize the energy of exhaust gases from ICE to generate electricity and cool the vehicle's cabin. As a result of this project design has been several advantages, the first of which is to reduce fuel consumption and thus reducing exhaust gas emissions to the environment, and the second to enhance the engine thermal efficiency by removing the load resulting from the cooling system and finally, to increase the COP of the cooling system.

2. EXPERIMENTAL TEST RIG

The experimental setup of the proposed system is established in the laboratory building of the Department of Air Conditioning and Refrigeration Techniques Engineering at Al-Mustaqbal University Collage and developed to invest the energy of exhaust gases to operate the cooling system in the automobile. The experimental rig is consisted of three basic components, namely the car cabin, the cooling system, and the engine and its accessories. These components come together to form the proposed system. A picture of the test rig with associated hardware and main components is shown in Figure (2).

![Figure 2. A photograph of the test rig (a) front view and (b) back view.](image)

2.2 MATERIALS AND METHODS

2.2.1. Description of the Experimental Section and Components:

This study's experimental engine is a Kia Carnival with attachments that runs on four-stroke turbocharged diesel fuel. The engine also has an intercooler that reduces the temperature of the air entering the engine from the compressor. The choosing a diesel engine compared to a gasoline engine are for several reasons, among which is that diesel fuel has a higher density, which gives it about 15% more power. Furthermore, the temperature of a diesel engine's exhaust gases is larger compared with a gasoline engine. The rest of the specifications are illustrated in Table No. (1).

<table>
<thead>
<tr>
<th>Table No. (1): Engine Specifications [26]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of engine</strong></td>
</tr>
<tr>
<td>Max. speed</td>
</tr>
<tr>
<td>Max. power</td>
</tr>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Engine cooling</td>
</tr>
<tr>
<td>Max. Torque</td>
</tr>
<tr>
<td>Capacity</td>
</tr>
<tr>
<td>No. of cylinder</td>
</tr>
<tr>
<td>No. of valves</td>
</tr>
<tr>
<td>Diameter cylinder</td>
</tr>
<tr>
<td>Stroke length</td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>Mean effective pressure</td>
</tr>
<tr>
<td>Turbocharger</td>
</tr>
<tr>
<td>Compressor of turbocharger</td>
</tr>
</tbody>
</table>

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2.2.2 Experimental Data Reduction:

In order to compute performance parameters such as cooling effect, power consumption, and heat rejection, coefficient of performance, and other aspects, the thermodynamic properties of the refrigerant must be determined at specific points along the cooling cycle. The enthalphy of the refrigerant at the intake and outlet of each component is used to determine the experimental results. The average measured temperature and pressure of refrigerant at each state point are used to determine enthalphy values. A turbine flow meter is located in the liquid line between the condenser and the capillary tube which measures the mass flow rate of refrigerant directly. The suggested cycle’s energy equations are reduced to data as follows:

The heat absorbed by the evaporator (\(Q_{\text{evap}}\)) is calculated from the following equation:

\[ Q_{\text{evap}} = m_{\text{ref}}(h_{11} - h_{10}) \]  

(1)

Where \(h_{10}\) and \(h_{11}\) represent the enthalpy at the inlet and outlet of the evaporator and \(m_{\text{ref}}\) denotes the refrigerant mass flow rate. The work done by the compressor (\(W_{\text{comp}}\)) is:

\[ W_{\text{comp}} = m_{\text{ref}}(h_{5} - h_{12}) \]  

(2)

Where \(h_{11}\), \(h_{5}\) represent the enthalpy at the inlet and outlet of the compressor. The heat released by the condenser (\(Q_{\text{con}}\)) is calculated from the following equation:

\[ Q_{\text{con}} = m_{\text{ref}}(h_{7} - h_{6}) \]  

(3)

Where \(h_{6}\) and \(h_{7}\) signify the enthalpy at the condenser’s inlet and outlet. The expansion device’s process is an isenthalpic process (\(h_{5} = h_{6}\)). The first law of thermodynamics is applied to flow processes to calculate the internal work of gas turbine (\(W_{\tau}\)) as follows:

Energy Input - Energy Output = Increased Energy in the System

\[ Q_{\text{r}} - W_{\tau} = m_{\text{ex}} c_{p, \text{ex}} (T_{4} - T_{3}) \]  

(4)

Where \(T_{a}, T_{1}\) represent the temperatures of the exhaust gases at the inlet and outlet of the gas turbine, respectively. And \(m_{ex}, c_{p, \text{ex}}\) represent the flow mass and the adiabatic heat capacity of the exhaust gases, respectively. We calculate wasted heat from the engine, assuming that 30% of the engine’s power is removed from the outside, as follows:

\[ Q_{\text{r}} = 0.3 m_{\text{fuel}} L. C. V \]  

(5)

Where \(m_{\text{fuel}}\) represents the average running mass of diesel fuel and L.C.V is the diesel low calorific value of diesel fuel which is equal to 45.83 MJ/kg. Substituting eq. (6) into Eq. (5), we get the power of the gas turbine:

\[ W_{\tau} = 0.3 m_{\text{fuel}} L. C. V - m_{\text{ex}} c_{p, \text{ex}} (T_{4} - T_{3}) \]  

(6)

Than the actual cycle efficiency becomes:

\[ \eta_{\text{cycle}} = 1 - \frac{m_{\text{ex}} c_{p, \text{ex}} (T_{4} - T_{3})}{0.3 m_{\text{fuel}} L. C. V} \]  

(7)

The energy required to operate the dynamo can also be calculated from the law of energy conservation, where the electric compressor power is equal to the energy generated by the dynamo:

\[ W_{\text{dynamo}} = W_{\text{comp}} = V.I \cos \theta \]  

(8)

Where \(V\) is voltage (volt), \(I\) is electric current (Amp.) and \(\cos \theta\) is power factor which is taken as 0.98 in the calculation.

The performance coefficient (COP) of the cooling system in the car can be determined from the ratio of the amount of heat absorbed in the evaporator to the capacity of the compressor, as follows:

\[ \text{COP} = \frac{Q_{\text{evap}}}{W_{\text{comp}}} = \frac{m_{\text{ref}}(h_{11} - h_{10})}{V.L.\cos \theta} \]  

(9)

The heat rejection ratio (H.R.R) of cooling system is the ratio of amount of heat rejection at the condenser to the amount of heat absorbed at the evaporator.

\[ \text{H.R.R} = \frac{Q_{\text{con}}}{Q_{\text{evap}}} = \frac{h_{7} - h_{6}}{h_{11} - h_{10}} \]  

(10)
2.3.3 Practical Steps for Tests and Working Conditions:

The testing of the system was performed under Iraqi climate. The tests were carried out after connecting the engine with the cooling system and placing measuring devices and equipment at specific points. The refrigeration system was charged with refrigerant R134A based on Iraqi blog for cooling at Hilla city.

Two essential conditions must be satisfied for automobile cooling systems:

a) Providing a cooling effect of 2 kW at design conditions.

b) Allowing the vehicle to pass a standard test that manufacturers can use as a benchmark. The following are the steps in standard testing:

1) When the air is fully recirculated (400m3/h) without external feed, the temperature of the cabin should drop to approximately 25°C in around 10 minutes with the cooling system functioning.

2) During the standard test, around 6 kW of cooling effect is required, which is 4 kW more than the design parameters.

In order to better understand the proposed system with all measurement devices, a diagram of the proposed test rig has been developed as shown in Figure (3).

![Diagram of the test rig](image)

Figure (3): A schematic diagram of the test rig.

3. RESULTS AND DISCUSSION

Exhaust gases from a 4-cylinder diesel internal combustion engine equipped with a turbocharger were used to generate enough electricity to drive a 2kW air-conditioning system of the vapor-compression cycle. This is done by expanding the exhaust gases inside turbine to generate torque that drives the dynamo. As for the diesel engine, increased engine speed increases consumption of fuel, the quantity of heat released from the engine, and the temperature of exhaust gases coming out of the engine, as is known in advance. Experiments on the proposed system indicated an improvement in the rate of fuel consumption, as indicated in Figure (7) with compared to the usual system (direct coupling of the cooling system and the engine). When the engine speed is increased, the temperature of the exhaust gases and the amount of heat generated from the engine both rise, as illustrated in Figures 8 and 9, respectively. In the same figures, we also note that the temperature of the exhaust gases and the amount of heat released from the engine are lower for the proposed system, and this shows a reduction in waste energy if compared with the usual system. The influence of diesel engine speed on CO2 emissions is depicted in Figure 10.

The table (3) shows the exhaust gas emission test with an average engine speed between 900 and 2200 rpm for the proposed system and the usual system. It was noted that the emission of exhaust gases for the proposed system is lower by certain percentages than the usual system.

<table>
<thead>
<tr>
<th>Emission</th>
<th>Proposed system</th>
<th>Usual system</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (%)</td>
<td>0.7</td>
<td>1.77</td>
</tr>
<tr>
<td>CO₂ (%)</td>
<td>0.6</td>
<td>1</td>
</tr>
</tbody>
</table>

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| HC (%) | 1.2 | 2.52 |

On the other hand, the results obtained from practical experiments showed that the cooling load increases gradually with time (see figure (11)) and also an increase in the coefficient of performance with increment of the engine speed (see figure (12)). From the results, it was found that the coefficient of performance improved for the proposed system more than the usual system. The heat rejection ratio with operation time for proposed and usual systems is depicted in figure (13). Figure (14) shows the P-H diagram of new cooling system.

Based on these findings, solutions have been found to the problem of energy loss resulting from burning diesel fuel in internal combustion engines and using it to operate the air conditioning system in the automobile that works with the vapor compression cycle.

Figure (7): Diesel engine speed versus the fuel ma
Flow rate

Figure (8): Diesel engine speed versus the exhaust gas temperature

Figure (9): Diesel engine speed versus the heat rejection from engine.

Figure (10): Diesel engine speed versus the CO₂ Emission.

Figure (11): Cooling effect with time

Figure (12): Diesel engine speed as function for C
4. CONCLUSION

In this study, we exploit the energy of the exhaust gas of diesel engine that was previously wasted to generate enough electrical work to operate the cooling system by converting the kinetic energy of the exhaust gas into electrical energy. This was done by connecting the exhaust of the Kia Carnival engine with the gas turbine on the one hand and connecting the gas turbine with the dynamo on the other side, meaning we converted the kinetic energy into electrical work. The traditional air cooling system has also been operated through the electrical work produced by the dynamo after it is connected to an electric compressor. An inverter is used to change the phase of the current from DC to AC. The exhaust gas recycling process has been utilized as follows:

1. Generating electrical energy and using it for different purposes
2. Improving the thermal efficiency of the engine by reducing the load on the engine
3. Decreasing the fuel economy of a diesel engine to about 4.4%, and thus leads to the possibility of reducing emissions of harmful gases to the environment such as carbon monoxide, carbon dioxide, nitrogen oxides and others.
4. Improving the performance coefficient of the proposed cooling about 3.7% if compared to the traditional cooling system.
5. The characteristics of the engine is examined under variable engine speed (960-2800) rpm where the BTE is decreased by 9.67% and the BSFC is increased by 10.7%.
6. Dramatic reduction in the emissions of NOx and PM is recorded 15.7% as the engine speed is changed from 960 to 2800 rpm.

5. ECONOMIC CONSIDERATION

The proposed system's most appealing features are fuel savings, energy recovery, and energy conservation. Because it works on waste energy, the proposed system is practically free of additional fuel costs. Assuming a diesel heating value of 135.5 MJ/gal, we may approximately estimate the amount of fuel spent by a 1/2 ton cooling unit powered by a one horsepower diesel engine at 35% thermal efficiency. The diesel consumption for 8h/day, five days/week, and 50 weeks/year is estimated to be 5420 gals/year. At present diesel price of 0.33$/gallon. The annual saving will be about 1804 $.

6. ACKNOWLEDGMENTS

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7. REFERENCES

New Design For a 2 kW Capacity Cooling System Powered (Qusay Rasheed Al-Amir)


