EXPERIMENTAL ANALYSES OF TRIPLE FLUID VAPOUR ABSORPTION REFRIGERATION SYSTEM DRIVEN BY ELECTRICAL ENERGY AND ENGINE WASTE HEAT

by

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In this study, performance analysis of absorption refrigeration cycle has been carried out under variable power sources namely electrical and thermal energy sources. The triple fluid vapour absorption system was used in this work. The temperatures at each point in the cycle such as generator, absorber, evaporator and condenser have been measured. The coefficient of performance of the system was calculated and then compared. The results showed that when the cycle driven by electricity, the coefficient of performance varied from 0.28-1.6 along the test time and the generator temperature changed from 66 °C to 106 °C. When thermal energy used to generate power, the coefficient of performance varied between 0.16 and 0.6 under the generator temperature of 98 °C and 150 °C. It was observed that the waste heat energy from engine exhaust can be used efficiently and can replace the conventional power source to drive the absorption refrigeration unit.

Key words: *waste heat, generator, vapour absorption refrigeration, coefficient of performance, triple fluid, exhaust gas*

Introduction

The diversity of energy sources is one of the major motivations for technological development. The rising demand for energy involves the search for new sources of energy or new processes to save more. Internal combustion engines (ICE), mostly based on fossil fuels, are one of the most mature and widespread thermal engines. One of the challenges of these engines is to reduce their emissions of GHG and to raise their efficiency. Indeed, only one third of the energy supplied to the ICE is converted into mechanical work, the rest is lost through the cooling and exhaust systems.

Khaled [1] investigated the feasibility of using waste energy to operate the vapour absorption refrigeration (VAR) system. The obtained results showed that the COP values directly proportional with increasing generator and evaporator temperatures but decrease with increasing condenser and absorber temperatures. Sowjanya [2] used Pro/Engineer for the design of condenser and evaporator and used ANSYS for the analysis. The result showed that the thermal flux is more for aluminum alloy 204 than copper for both condenser and evaporator. Mathapati *et al.* [3] have used EES software for analyzing the effect of generator temperature, evaporator temperature, condenser temperature and absorber tempera-

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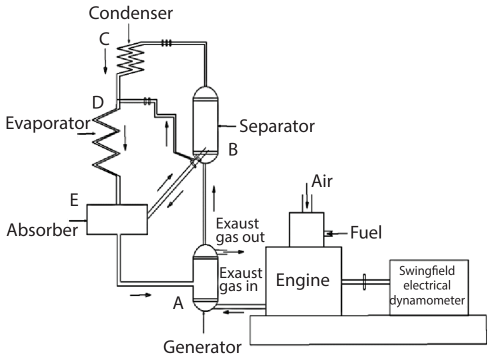
ture on system COP. They showed that the COP of system increases with increase in generator and evaporator temperatures but it reduces with increase in condenser and absorber temperatures. Yadav and Bharat [4] acknowledged that the heat required in generator can be saved up to 33% by using hot exhaust gases as an energy source. Obtaining more cooling effect even in the lower engine speeds and loads if a generator is designed with a minimum pressure drop, but a maximum heat transfer efficiency was suggested by Hilali and Soylemez [5]. Study of the possibility and potentiality of using the ICE exhaust gas as energy source for an absorption refrigeration system was carried out by Manzela *et al.* [6]. They concluded that a dedicated absorption refrigeration system can be able to take benefit of the availability of exhaust gas power and provide the cooling capacity required for automotive air conditioning. Vicatos *et al.* [7] developed and tested a prototype absorption system and concluded that automobile air-conditioning by utilizing the waste energy of exhaust gases is feasible, although they reported very low COP of the system.

A combined sensible and latent heat storage system was designed, fabricated and tested by Pandiarajan *et al.* [8] using phase change material capsules (10-15%) for thermal energy fuel power combined storage system. The exhaust gas of a Diesel engine carries a lot of heat and this energy can be recovered efficiently using heat recovery and if this energy can be recovered, the efficiency of the engine will be increased [9] significantly. Wilson *et al.* [10] presented a custom designed triangular finned shell and tube heat exchanger and NEPCM based thermal energy storage tank of capacity 23,913 kJ were fabricated and tested by integrating them with a Diesel engine of capacity 7.4 kW. It is observed from the experimental results that the heat extraction rate is 4.04 kW in full load condition of the engine. Talom and Beyene [11] conducted experiment on 2.8 L V6 ICE and the exhaust gas from it was used to run a 3 tonnes absorption chiller. They proved that the concept is feasible, and could significantly enhance system performance depending on part load of the engine. Ramanathan and Gunasekaran [12] simulated an automotive air conditioning system based on absorption refrigeration cycle. They found that the system performance varies with varying operating temperatures of the desorber. Also they reported that the heat transfer rates of the system components are interrelated with each other and being significantly influenced by the operating temperature of the system and the heat exchanger performance. The amount of wasted heat from different parts of a 12 liter compression ignition engine and potential for waste heat recovery were investigated by Tahani *et al.* [13]. Two configurations were introduced for simultaneous heat recovery from exhaust gases and coolant. The best performance was obtained when R123 was applied as the working fluid. Also, it was observed that in the case of R134a as the working fluid in both configurations, the preheat configuration had better results. Rahaman *et al.* [14] have designed and fabricated a simple vapor absorption system to analyze the performance. The system was tested with heat input from an electric heating element of 500 watts capacity for a pressure of 32.5 mbar. The results showed that COP of the system increases minutely with generator temperature, but the exergy efficiency of the system dropped with the increase in generator temperature. Wang and Wu [15] conducted a study on combined cooling heating and power system using waste heat from engine exhaust. They reported that for a 16 kW ICE, the cooling output could reach 34.4 kW with COP of 0.96.

Experimental set-up of Diesel engine integrated with triple fluid VAR system

The need of a pump is eliminated in a triple fluid refrigeration system and the system is run entirely by heat. It uses a third fluid to regulate the partial pressure of the refrigerant and therefore, its saturation temperature. The decrease in refrigerant's saturation temperature to create cooling is achieved by a low partial pressure. The system remains at constant total pressure and avoids the use of expansion valves.

Schematic diagram of a three fluid absorption refrigeration system that uses ammonia and hydrogen is shown in fig. 1.



Figre 1. Experimental set-up

At point *A*, the application of heat vapourizes the strong NH_3-water solution up into the bubble pump. At *B*, the solution and gas pass into the separator where the water vapour condenses to liquid and passes through a separate series of tubes back to the absorber. Now, superheated ammonia vapor rises to the condenser, leaving a small amount of weak NH_3-water solution pooled in the separator. At *C* the NH_3 is traveling through the condenser, releasing heat to the surroundings and condensing back to liquid state. The liquid ammonia meets with hydrogen and enters the evaporator at point *D* to cause the ammonia to evaporate by lowering the saturation temperature of the liquid ammonia. This expansion lowers the temperature of the hydrogen-ammonia mixture allowing it to absorb heat from the refrigerator compartment providing cooling. At *E* the hydrogen-ammonia mixture exits the evaporator into the absorber in a gaseous state. In the absorber the gaseous ammonia and hydrogen meet with liquid water.

The ammonia is less dense than hydrogen, causing it to sink and consequently accumulate under the hydrogen. This increases its partial pressure and induces a phase change back to liquid. As ammonia is soluble in water, ammonia and water are capable of forming a solutiongether. Hydrogen is incapable of mixing and continues to circulate back to the top of the evaporator as a pure gaseous substance. The solution of ammonia and water exits the absorber and travels to the generator thus completing a cycle of operation.

The VAR can be operated in two different ways:

– Conventional VAR system uses electricity or liquid/gaseous fuel to generate required amount of heat to separate refrigerant from refrigerant – absorbent solution. Using electricity or fuel will result in use of high grade energy and valuable fuel.
– Obtaining the heat energy required in the *Generator* of VAR system from engine exhaust (waste heat) is a wise idea which saves a significant amount of high grade energy or fuel.

The present work aims at analysing the feasibility of utilising the heat energy of exhaust gases in the generator of VAR system. A thorough investigation is made on quality of exhaust gas at different speeds and loads in a stationary compression ignition engine.

Engine specifications:

Type	: Single cylinder four stroke Diesel Engine
Brake power	: 4.4 kW
Speed	: 1500 rpm
Bore	: 80 mm
Stroke	: 110 mm
Compression ratio	: 17.5:1

The test rig consists of a single cylinder Diesel engine fitted with Swingfiled Electrical dynamometer, air-flow measuring device and temperature and fuel measuring devices. The exhaust gas from the engine is sent to the generator of VAR refrigeration system. Provisions are made to measure exhaust gas temperature at inlet and outlet of Generator. The load applied to the engine is by means of Swingfiled dynamometer.

Suitability analysis

The exhaust gas-flow rate increase with the engine load as the air consumption and fuel consumption increase. Increase in engine load also causes an increase in exhaust gas temperature, and consequently the exhaust gas heat capacity. As far as the performance of the VAR system is concerned, with higher engine power, the greater cooling capacity of the VAR system can be achieved. This is entirely what would be expected in the VAR system, *i. e.*, the cooling capacity is to be directly proportional to the heat input to the generator.

As the power output increases, the heat recovered from exhaust gases also increases, releasing a greater quantity of ammonia from the solution in the generator with a subsequent increase in the cooling effect. Since the greater cooling effect is achieved with increased heat transfer, no matter whether the heat input is from natural gas or from the exhaust gases of the ICE.

Considering a cabin dimension of 2.5 m × 1.5 m × 1.5 m, the cooling load can be estimated as follows.

Assuming an average wall temperature of 40 °C and cabin temperature of 23 °C, the heat transfer rate can be estimated:

$$Q = UA\Delta T \tag{1}$$

The heat to be transferred from the cabin is estimated approximately as 1.95 kW assuming a overall heat transfer coefficient value of 5 W/m^{2}K [16].

Considering 4 occupants in the cabin, the capacity of the system is assumed to be 0.75 ton of refrigeration (required capacity).

Heat to be given to the solution of the generator is estimated considering the system works between pressure limits of 7 to 14 bar. The heat liberated by the exhaust gases (no load condition) are estimated as 0.88 kW assuming it equals to the heat absorbed by the strong solution in the generator making the refrigerant vapour separated.

Heat carried away by the exhaust gases at part load conditions is estimated as 2.75 kW:

$$Q_{\text{exh}} = \dot{m}_{\text{exh}} C_{p,\text{exh}} T_{\text{exh}} \tag{2}$$

where

$$\dot{m}_{\text{exh}} = \dot{m}_f + \dot{m}_a \tag{3}$$

A simple method of calculating the mass-flow rate of exhaust gases from displacement volume neglecting the mass of fuel:

$$\dot{m}_{\text{exh}} = \dot{m}_a = \frac{V_{\text{disp}} N}{120} \tag{4}$$

The four stroke engine is used for the present work. The number of working stroke per second is $N/2$. In order to make $\dot{m}_{\text{exh}}$ in kg/s, the speed N (revolution per minute) is divided by 60. Finally the equation becomes:

$$\frac{V_{\text{disp}}(N/2)}{60} = \frac{V_{\text{disp}} N}{120}$$

Actually about 25-35% of total energy available is shared as brake power and about 15-25% is lost to the exhaust gases. Hence it is known that the energy lost via exhaust is around 60-75% relative to that of the brake power.

Considering a scenario where energy lost via exhaust gas is 20% relative to brake power, the energy available in the exhaust gases is estimated to be around 0.88 kW.

The minimum amount of heat that the exhaust gases must possess was found earlier as 0.43 kW [16] to operate VAR system in a car and the amount of heat energy required for the separation of refrigerant from the solution in the generator as 0.43 kW. However the wonderful nature of this system is such that even this conservative Q_{exh} value is in excess of the minimum energy required to cool the given volume.

Results and discussion

The triple fluid VAR system was used to test and compare the suitability of different sources of energy and their impact on working conditions at the absorption refrigeration process. So it has been used two types of energy sources: electrical energy (coil) and thermal energy (waste heat in the engine exhaust).

The variation of temperature changes in the generator has been represented in fig. 2.

It is observed that the generator temperature increases with the increase of time. After 15 minutes of operation, the temperature increases for the source of thermal energy at 75% engine load to the value of 98 °C and during the same time the temperature ranged around 66 °C for the electrical source. After the time interval, the generator temperature was found to be 150 °C using thermal energy at 75% engine load whereas it was 106 °C with electrical energy. Comparing the both sources, higher generator temperature is obtained in the thermal energy based VAR system than that of electrical energy based system.

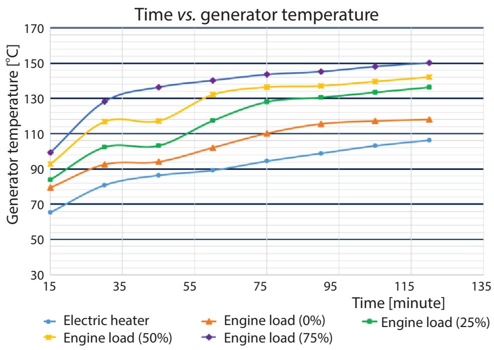


Figure 2. Variation of generator temperature with time at different engine loads

The variation of temperature in the evaporator is represented in fig. 3.

It is observed that with increase in time, the evaporator temperature decreases with both the sources. The temperature practically decreases linearly, when electrical energy is used to run the system and reached a value of 15.6 °C and 12 °C with the use of thermal energy at 75% engine load to run the absorption refrigeration system. It is clearly observed that lower evaporator temperature can be obtained in the thermal energy based VAR system than that of electrical energy based system because of good amount of energy content of exhaust gases.

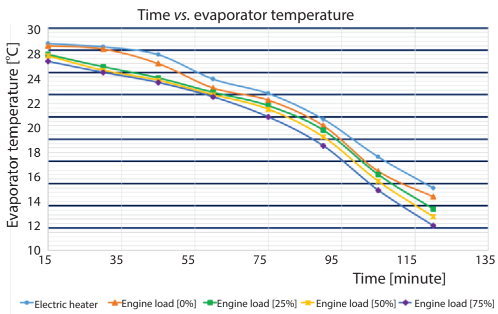


Figure 3. Variation of evaporator temperature with time at different engine loads

Figure 4 shows the variation of temperature in the condenser with time. It can be observed that the condenser temperature increases with time. After 15 minutes of operation of the system, the temperature increases for the source of thermal energy at 75 % engine load to the value of 40 °C with the maximum value of 53.5 °C whereas it is ranged around 30 °C with the maximum value of 47 °C with the electrical source.

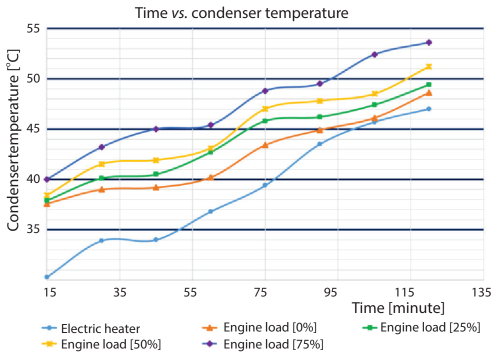


Figure 4. Variation of condenser temperature with time at different engine loads

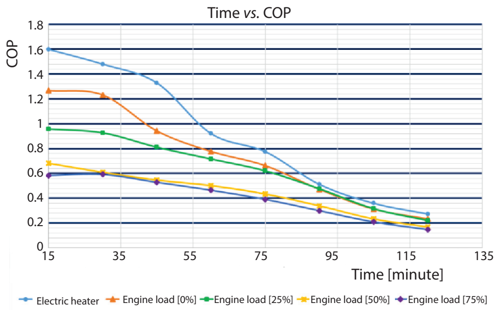


Figure 5. Variation of COP with time at different engine loads

Figure 5 shows the comparison of COP of the electrical based and thermal energy based systems. COP is calculated:

$$COP = \left[\frac{T_e}{T_a - T_e}\right]\left[\frac{T_g - T_a}{T_g}\right] \tag{5}$$

It can be seen in that the COP which is calculated only on the basis of the measured temperatures at various points in the system such as temperature in the generator, temperature in the absorber, temperature in the evaporator and temperature in the condenser and the value is found to be 0.28 for electrical energy source and 0.16 for thermal energy source (75% load).

Differences in thermal performance between the novel and traditional absorption system:

– The COP in the novel system is less than the COP of the conventional system. But the conventional system uses high grade mechanical energy (electrical energy) as input whereas the novel system uses waste heat and hence the benefit of the novel system is justifiable.
– The suggested system will start working effectively only after few minutes of operation since the exhaust gas temperature will be low during cold start.

Conclusions

A triple fluid VAR system powered by two different power sources (electrical energy and engine exhaust) has been investigated in this work. The experiment was conducted for 120 minutes. Based on the results of the investigations performed in this study, the concluding remarks are

- The heat energy of the waste exhaust can contribute effectively to operate the generator of the VAR system. But, the COP value is lower than that of electrical system. However the required cooling load can be achieved with the thermal system.
- The results indicate that a triple fluid VAR system can be run using waste heat available in the engine exhaust. This concept can be extended to automotive air conditioning having high heat energy potential of waste exhaust from automotive engines.

Nomenclature

A – area, [m^2]
$C_{p,\mathrm{exh}}$ – specific heat of exhaust gas at constant pressure, [kJkg^{-1}K^{-1}]
$\dot{m}_a$ – mass flow rate of air, [kgs^{-1}]
$\dot{m}_{\mathrm{exh}}$ – mass flow rate of exhaust gases, [kgs^{-1}]
$\dot{m}_f$ – mass flow rate of fuel, [kgs^{-1}]
N – speed, [pm]
Q_{exh} – heat given out by the exhaust gases, [kW]
T_{exh} – temperature of exhaust gas, [°C]
T_{a} – absorber temperature, [°C]
T_{e} – evaporator temperature, [°C]
T_g – generator temperature, [°C]
ΔT – (= wall temperature – cabin temperature), [°C]
U – overall heat transfer co-efficient, [Wm^{-2}K^{-1}]

V_{disp} – displacement volume of cylinder, [m^3]

Acronyms

COP – coefficient of performance, [–]
ICE – internal combustion engines
VAR – vapour absorption refrigeration

References

[1] Khaled, S. A., Performance and Evaluation of Aqua Ammonia Auto Air Conditioner System using Exhaust Waste Energy, *Energy Procedia*, *6* (2011), Dec., pp. 467-476
[2] Sowjanya, S. L., Thermal Analysis of a Car Air Conditioning System Based on an Absorption Refrigeration Cycle Using Energy from Exhaust Gas of an Internal Combustion engine, *Advanced Engineering and Applied Sciences*, *3* (2013), 4, pp. 47-53
[3] Mathapati, S. S., *et al.*, A Study on Automobile Air-Conditioning Based on Absorption Refrigeration System Using Exhaust Heat of a Vehicle, *International Journal of Engineering Research and General Science*, *2* (2014), 4, pp. 80-86
[4] Yadav, J. P., Bharat, R. S., Experimental Set-up of Air Conditioning System in Automobile Using Exhaust Energy, *A Journal of Physical Sciences, Engineering and Technology*, *5* (2010-2014), Special ed.-1, pp. 71-80
[5] Hilali, I., Soylemez, M. S., An Application of Engine Exhaust Gas Driven Cooling System in Automobile Air-Conditioning System, *Journal of Thermal Science and Technology*, *35* (2015), 1, pp. 27-34
[6] Manzela, A. A., *et al.*, Using Engine Exhaust Gas as Energy Source for an Absorption Refrigeration System, *Applied Energy*, *87* (2010), 4, pp. 1141-1148
[7] Vicatos, G., *et al.*, A Car Air-Conditioning System Based on an Absorption Refrigeration Cycle Using Energy from Exhaust gas of an Internal Combustion Engine, *Journal of Energy in Southern Africa, 19* (2008), 4, pp. 6-11
[8] Pandiarajan, V., *et al.*, Experimental Investigation on Heat Recovery from Diesel Engine Exhaust Using Finned Shell and Tube Heat Exchanger and Thermal Storage System, *Applied Energy*, *88* (2011), 1, pp. 77-87
[9] He, M., *et al.*, A Combined Thermodynamic Cycle Used for Waste Heat Recovery of Internal Combustion Engine, *Energy*, *36* (2011), 12, pp. 6821-6829
[10] Wilson M. R. J., *et al.*, Waste Heat Recovery from Diesel Engine Using Custom Designed Heat Exchanger and Thermal Storage System with Nanoenhanced Phase Change Material, *Thermal Science*, *21* (2017), 1B, pp. 715-727
[11] Talom, H. L., Beyene., A., Heat Recovery from Automotive Engine, *Applied Thermal Engineering, 29* (2009), 2-3, pp. 439-444
[12] Ramanathan, A., Gunasekaran, P., Simulation of Absorption Refrigeration System for Automobile Application, *Thermal Science*, *12* (2008). 3, pp. 5-13
[13] Tahani, M., *et al.*, A Comprehensive Study on Waste Heat Recovery from Internal Combustion Engines Using Organic Rankine Cycle, *Thermal Science*, *17* (2013). 2, pp. 611-624
[14] Rahaman, M. A. U., *et al.*, Design and Fabrication of Vapour Absorption Refrigeration System (Libr-H_2O), *International Journal of Modern Engineering Research*, *4* (2014), 9, pp.13-18
[15] Wang, J., Wu, J., Investigation of a Mixed Effect Absorption Chiller Powered by Jacket Water and Exhaust Gas Waste Heat of Internal Combustion Engine, *International Journal of Refrigeration, 50* (2015), Feb., pp. 193-206
[16] Venkatesan, J., *et al.*, Performance Improvement in Automotive Engines Using Vapour Absorption Refrigeration System for Air Conditioning, SAE Technical paper, 2005-01-3466, 2005

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