EXPERIMENTAL ANALYSIS OF ABSORPTION REFRIGERATION SYSTEM DRIVEN BY WASTE HEAT OF DIESEL ENGINE EXHAUST

by

Mukul KUMAR* **and Randip Kumar DAS***
Department of Mechanical Engineering, Indian School of Mines, Dhanbad, India

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This work presents an experimental study of an ammonia-water absorption refrigeration system using the exhaust of an internal combustion engine as energy source. The exhaust gas energy availability, the performance of the absorption refrigeration system and the engine performance are evaluated. A commercial turbocharged Diesel engine has been tested in a bench test dynamometer, with the absorption refrigeration system adapted to the exhaust system. The maximum COP obtained from the refrigeration system is 0.136 and it has been shown that heat energy available with exhaust gas is capable of producing sufficient cooling capacity for air conditioning the vehicle without requiring any energy input from the engine.

Key words: *absorption refrigeration, Diesel engine, COP, efficiency, refrigeration effect, waste heat*

Introduction

Energy efficiency and environment preservation are two driving force to develop more efficient systems from energy and exergy standpoints. On one hand, it is necessary to develop devices which are more energy efficient and are capable of utilizing waste energy and on the other hand it is of utmost importance that the new inventions should be environment-friendly. An absorption refrigeration system can be operated with low grade energy sources and also helps in continuing substitution of chlorinated fluorocarbons (CFC) by alternative refrigerants to protect the ozone layer [1].

Exhaust gases from internal combustion engines are potential energy sources for absorption refrigeration systems, since about one third of the energy availability in the combustion process is wasted through the exhaust gas. Thus it is possible to run the air conditioning unit of a vehicle utilizing the heat energy associated with the exhaust gases from the engine, which drives the vehicle. Thus, there will be a net reduction in fuel consumption and emissions and improvement in the overall efficiency of the system.

Other important factors are the continuous strive for improvement of performance of internal combustion engines. Inlet air cooling and charge air intercooling are one of the prominent methods for improving engine performance without changing engine design parameters. A lower air temperature increases the charge density thereby increasing the volumetric efficiency and power output of the engine. It also increases the efficiency and decreases fuel consumption of the engine by decreasing the maximum and exhaust gas temperatures.

* Corresponding author, e-mail: mukul_2577@yahoo.co.in

This work has as an objective to study the feasibility and potentiality of using the internal combustion engine exhaust gas as energy source for an absorption refrigeration system. For this purpose, a commercial automotive engine has been tested in a bench test dynamometer, with the absorption refrigeration system adapted to the exhaust system. The performance of the refrigeration unit has been tested for different operating conditions and presented here. Also the influences of inlet air pre-cooling and charge air inter-cooling on the performance of the engine have been reported. The chilled water produced by the refrigeration system can be used in a mobile vehicle for precooling and/or for intercooling the charge air, which in effect, improves engine performance. This is an additional impetus for an exhaust gas-driven refrigeration system. Normally, energy content of the exhaust gas from an engine of a medium or a heavy-duty vehicle is capable of producing much higher cooling effect than what is required for cooling a vehicle cabin. Hence, the additional amount of cooling can be utilized for better engine performance.

Literature review

The utilization of solar and waste heat technologies for engineering applications, have several benefits. These include reduction in electrical demand during peak utility hours, reduction in operational costs, and low environmental impact due to the use of CFC-free refrigerants [2]. These advantages have led to a renewed interest in this technology for a variety of applications. It could be operable in remote locations, during disaster relief situations, or anywhere a Diesel engine or solar energy is in operation. In all instances, the implementation of a waste heat recovery system would reduce the electrical demand for space conditioning [3, 4].

There are many refrigeration and air conditioning applications that can be covered by thermal driven cooling systems. This has recently expanded to a series of new technologies available or in a stage of development that can be an option in the near future. Absorption, adsorption, desiccant systems, ejector-compressor systems are being developed for coupling with thermal heat sources, such as waste heat in cogeneration systems as well as RES such as solar, geothermal and biomass. The search for new systems is directed towards higher efficiency systems such as double effect or even triple effect systems and on the other hand, towards the development of systems that can operate at even lower operating temperatures than systems available ten years ago. A recent area of study is small capacity systems for air conditioning for small size commercial or domestic applications. Industrial refrigeration as well as refrigeration for small size applications such as ice making and food storage in less developed areas of the world are some of the applications that require more development [5].

Manzela *et al.* [6] studied the feasibility and potentiality of using the internal combustion engine exhaust gas as energy source for an absorption refrigeration system. They concluded that a dedicated absorption refrigeration system may be able to take advantage of the exhaust gas power availability and provide the cooling capacity required for automotive air conditioning.

Vicatos *et al*. [7] developed and tested a prototype absorption system and concluded that vehicle air conditioning by utilizing the waste energy of exhaust gases was feasible, although they reported very low COP of the system.

Koehler *et al*. [8] developed and tested a prototype of an absorption refrigeration system using heat from the exhaust gas for truck refrigeration. They reported a low coefficient of performance, but the results indicated the system as an interesting alternative for long distance driving on flat roads.

Meunier [9] observed that sorption systems are ideal for car air conditioning from the perspective of global warming despite a low COP. The author also pointed out the technical areas that need improvement for practical application of the system, namely, improvement of efficiency and heat transfer intensification to reduce the size and weight of the units.

Jiangzhou *et al*. [10] presented an adsorption system driven by the engine exhaust gas waste heat used for air conditioning of a locomotive driver cabin. The mean refrigeration power obtained from the prototype system was 5 kW. The authors claimed the system to be simple in structure, reliable in operation, and convenient to control, meeting the demands for air conditioning of the driver cabin.

Qin *et al*. [11] developed an exhaust gas-driven air conditioning system working on a new hydride pair. They reported that with growth of the heat source temperature, the cooling power and the COP of the system increased while the minimum refrigeration temperature decreased.

Huangfu *et al*. [12] designed and developed an experimental prototype of an integrated thermal management controller (ITMC) for internal combustion engine based co-generation system. They verified the working principle of the ITMC and reported that the developed prototype can effectively control the temperature under variable working conditions.

Li and Wu [13] developed and constructed a novel micro combined cooling heating and power (CCHP) system, based on a two-bed silica gel-water adsorption chiller. The authors recommended the use of a cold accumulator for higher performance and system security.

A waste heat powered absorption cycle cooling system has been developed by Tao Cao *et al*. [14] for shipboard application. The authors have reported a COP of 0.6 and 62% reduction in fuel consumption and CO_2 emission.

Mustafa [15] investigated the effects of three different heat inputs, 62, 80, and 115 W, supplied to a generator to study the energy performance of the diffusion absorption refrigeration (DAR) system. The highest and the lowest energy performances were reported for DAR-62 W system as 0.36 and for DAR-115 W system as 0.30, respectively.

Wang and Wu [16] conducted a study on CCHP system using waste heat from exhaust gas. They reported that for a 16 kW internal combustion engine, the cooling output could reach 34.4 kW with COP of 0.96 and exergy efficiency of 0.186. Authors concluded that compared to double-effect or single-effect air conditioning system, the CCHP system could make better use of different forms of waste heat.

Experimental set-up

The aim of this study is to investigate the utilization of exhaust gases from an internal combustion engine to drive an absorption refrigeration system for refrigeration purposes under various operating conditions. The schematic diagram of the experimental set-up consisting of a commercial turbocharged Diesel engine coupled with dynamometer and the absorption refrigeration unit is shown in fig. 1. The engine set-up comprises four major components, namely: a turbocharger (a compressor and a turbine coupled together), an inter-cooler, a charge air pre-cooler, and the Diesel engine unit. The specifications of the Diesel engine unit is shown in tab. 1.

The thermal energy in the exhaust gases is transferred to the generator of the refrigerator unit through water which is circulated through gas heat exchanger and the generator. Heat is supplied to the generator partly by this hot water and partly by electric heater, however the generator is shell and tube heat exchanger. The purpose of adding electric heater is to maintain the necessary required temperature of the generator. Maximum generator temperature is controlled by an auto-cutout switch.

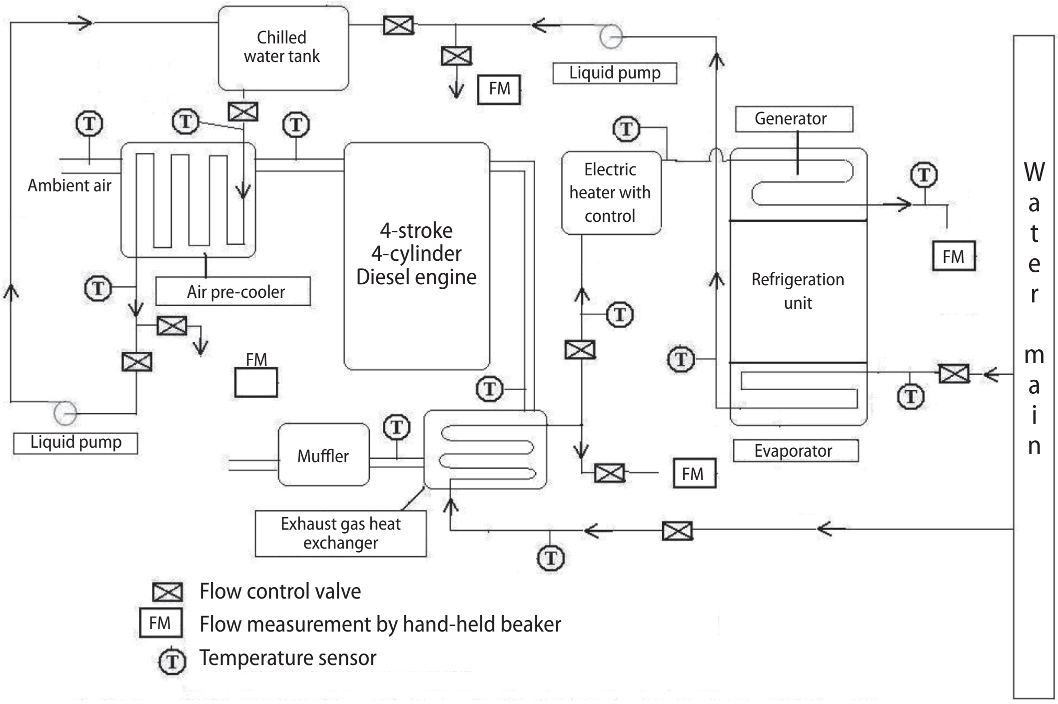

Figure 1. Schematic diagram of experimental set-up

Condenser and absorber are heat exchangers applicable for heat rejection in atmosphere. Condenser is air cooled fin heat exchanger to convert the refrigerant vapor into liquid refrigerant while absorber is shell and tube heat exchanger.

The schematic diagram of diffusion absorption refrigeration set-up is shown in fig. 2. In this system ammonia is used as refrigerant, water as absorbent, and hydrogen as auxiliary gas. The experimentation set-up contained a refrigerating space of 40 L capacity. As per the manufacturer's specifications, the refrigerant mass-flow rate through the evaporator is 2 gm/s and the concentration of ammonia in the rich solution is 0.3. The specification of absorption refrigeration system is shown in tab. 2.

The evaporator is in the form of a small tank (shell and tube heat exchanger) wherein certain amount of water is kept in a container and water is allowed to get chilled. Chilled water from the evaporator is either sent to an overhead tank or can be used for other purposes. Thermocouples are provided for measurement of temperature at various points of the refrig-

Table 1. Specifications of the Diesel engine

Number of cylinder	4
Number of strokes	4
Number of rev./cycle	2
Fuel	High speed diesel
Rated power	52 kW at 4500 rpm
Stroke length, *L*	79.5 mm
Cylinder diameter, *D*	75 mm
Compression ratio	18.5:1

Table 2. Specification of absorption refrigeration system

Refrigerant	NH_3
Refrigerator temperature	0-8 °C
Working fluid	Ammonia, water, and hydrogen
Volume	40 L
Electricals	AC/220V/50Hz/single phase

eration system with a multi-channel temperature indicator. The cold water from the overhead tank is used to flow through the air pre-cooler to cool the inlet air to the engine and is recirculated back to the tank.

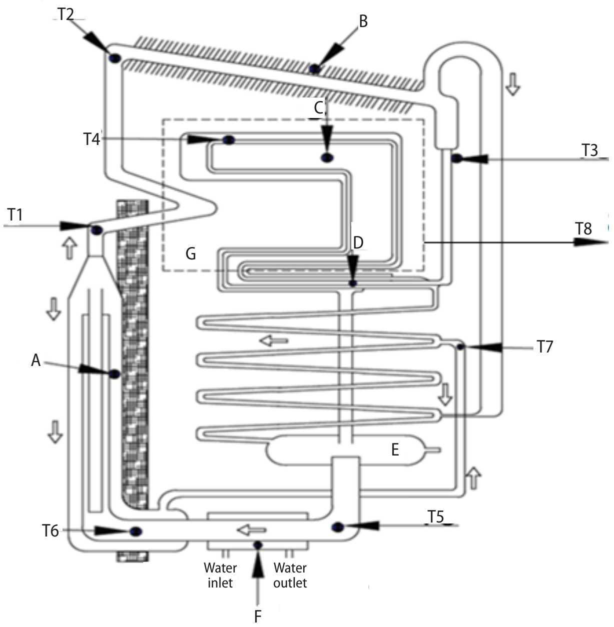

Figure 2. Schematic diagram of the refrigeration system; *A – generator, B – condenser, C – evaporator, D – gas heat exchanger, E – absorber, F – solution heat exchanger, and G – refrigerating space*

Results and discussion

Variations of refrigerating effect, heat addition in generator and the COP of the cycle with generator temperatures are shown in figs. 3-5. Both refrigeration effect, fig. 3, and rate of heat supply in the generator, fig. 4, increase with increase in generator temperature. With increase in generator temperature, there is increased rate of evaporation of the refrigerant from the generator. Thus, there is higher mass-flow rate of refrigerant through the evaporator causing higher refrigeration effect, fig. 3. It is found that the refrigerating effect increases from 68.13 W to 96.74 W during increase of generator temperature increases from 100 °C to 220 °C, while the rate of heat addition in the generator increase from 502.4 W to 1390.4 W during the similar increase of generator temperature.

But it is found that the heat addition in the generator, due to increase in generator temperature, increases at higher proportional rate compared to the increase in refrigeration effect, mainly due to increased rate of heat losses in the rectifier and condenser. Thus, although there is increase in refrigeration effect, the COP decreases, as the generator temperature increases, fig. 5. It is observed that the COP of the refrigeration unit decreases from 0.136 to 0.07 due to increase in generator temperature from 100-220 °C.

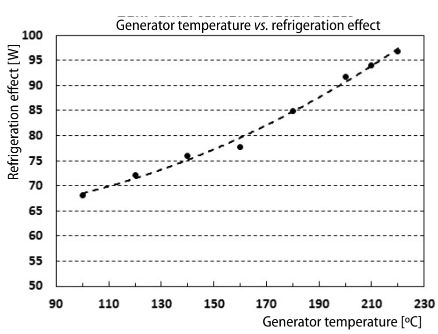

Figure 3. Variation of refrigerating effect with generator temperature

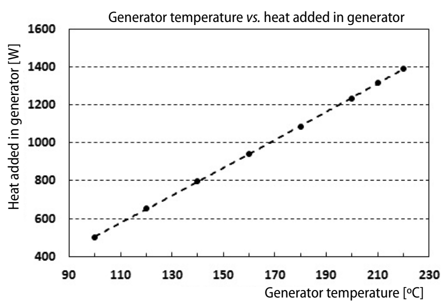

Figure 4. Variation of heat added in generator with generator temperature

Figure 6 shows the percentage heat addition by hot water, which absorbs heat from engine exhaust gases and supplies heat the refrigerant solution, decreases with increase in generator temperature. This is due to the fact that the temperature of the rich solution at the exit of the water heat exchanger is limited due to the restriction of hot water temperature from the engine exhaust to 95 °C. On the other hand, there is continuous increase in total heat addition in the generator with increase in generator temperature, resulting in decrease in percentage contribution of heat addition by exhaust gases.

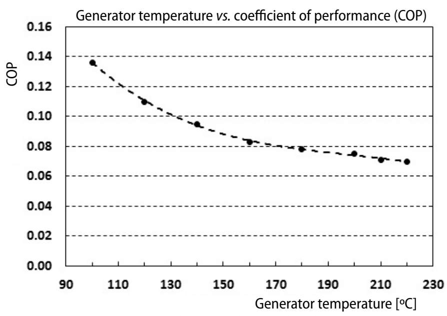

Figure 5. Variation of COP with generator temperature

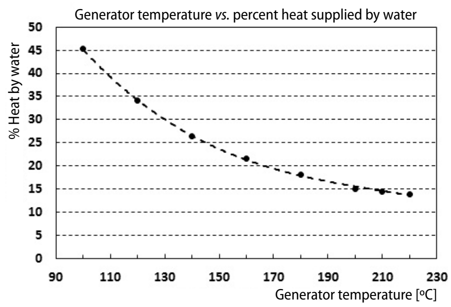

Figure 6. Variation percentage heat added by water (%) with generator temperature

Further, the engine has been tested and the performance parameters are estimated for four different engine speeds for the following four configurations: with no charge air cooling, with precooler (air is cooled before taken to the compressor of the turbocharger) only, with intercooler (compressed air is cooled before taken into the engine cylinder) only, and with both pre- and intercooler.

For a particular speed, brake power and air consumption of the engine increase when the precooler or intercooler is used compared to no charge air cooling configuration. Precooling and/or intercooling of air reduces the temperature and increases the density of the inlet air, which increase mass-flow rate of air and increase volumetric efficiency and power output of the engine. Figures 7 and 8 shows the variation of break power and brake thermal efficiency (BTE) of the engine under different configuration and at different engine speeds. It is found that there is improvement up to 6.90% in brake power and BTE with both precooling and intercooling of the charge.

Exhaust gas temperature, at a particular speed, is found to be lower with precooler and/or intercooler compared to engine operation without any cooling. Consequently there is

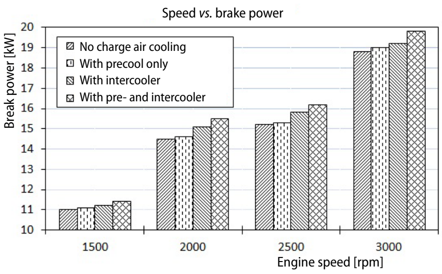

Figure 7. Comparison of brake power for different operating conditions

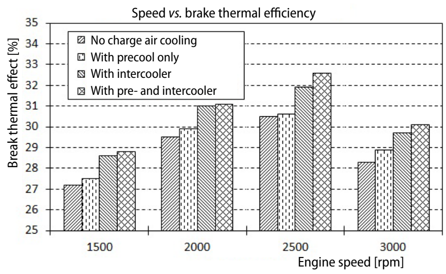

Figure 8. Comparison of brake thermal efficiency for different operating conditions

decrease in energy loss and percentage energy loss through the exhaust gases and the cooling water. Also, there is improvement in utilization of input energy to the engine leading to increase in thermal efficiency and decrease in brake specific fuel consumption (BSFC).

Volumetric efficiency and energy lost to exhaust gases obtained for different configurations and at different engine speeds are compared in figs. 9 and 10, respectively. Maximum improvement of volumetric efficiency of up to 8.6% and maximum reduction of energy loss to exhaust up to 14.2% were observed with both pre- and inter-cooling. Table 3 shows the comparison of various engine performance parameters obtained with precooling and/or intercooling with respect to the base configuration without any of the cooling systems.

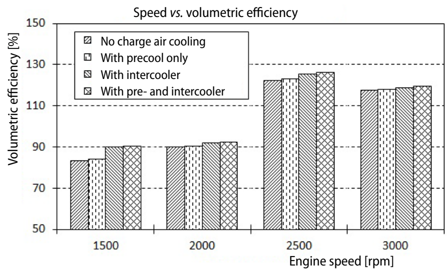

Figure 9. Comparison of volumetric efficiency for different operating conditions

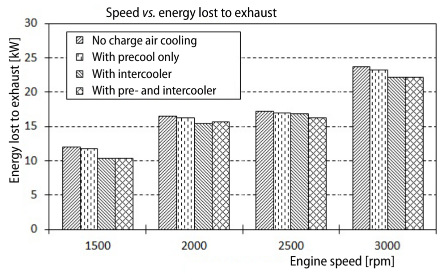

Figure 10. Comparison of exhaust energy loss for different operating conditions

Table 3. Performance comparison of various configurations with respect to base configuration

Engine parameters	Effect	With precooler	With intercooler	With precooler and inter cooler
Brake power	Increases	0.7-1.1%	1.8-4.1%	3.6-6.90%
Engine BSFC	Decreases	0.4-2%	4.3-4.8%	5.2-6.4%
Air consumption	Increases	0.3-0.8%	1.0-7.9%	1.4-8.7%
Engine BTE	Increases	0.3-2.1%	4.6-5.1%	5.4-6.9%
Volumetric efficiency	Increases	0.2-0.7%	1.0-7.8%	1.4-8.6%
Exhaust temperature	Decreases	1.9-3.5%	6.6-10.6%	8.4-12.5%
Energy lost to exhaust	Decreases	1.2-2.1%	2.3-14.2%	5.2-14.2%
% Energy lost to exhaust	Decreases	0.6-1.7%	1.7-11.1%	4.9-12.1%

From the results obtained, it is observed that:

- In comparison to the precooler, intercooler is more effective in improving the engine performance. Precooler reduces the temperature of air entering the engine by 4 °C to 5 °C, whereas the intercooler reduces the temperature of the compressed air up to 30 °C and is more effective in enhancing engine performance.
- Significant amount of energy is available in the exhaust gas for utilization for refrigeration purposes. Waste heat of the order of 22 kW is available with the exhaust gas and if this energy is suitably used for running a refrigeration system, then even with a COP of 0.1 of the refrigeration system, the exhaust gas from this engine is sufficient to produce a refrigeration effect of 2.2 kW without any recurring cost for the energy input.

Conclusions

Vehicle air conditioning with an absorption refrigeration system driven by the waste heat associated with engine exhaust gasses is a feasible alternative to the conventional vapor compression system for cooling. These absorption refrigeration systems utilize environment friendly refrigerant and can operate without requiring power input from the engine.

An experimental set-up consisting of an absorption refrigeration system coupled with and commercial turbocharged Diesel engine has been developed. The maximum COP obtained from the system in 0.136 and it has been shown that it is possible to produce a refrigeration effect of 2.2 kW without any recurring cost for the energy input.

Normally, energy content of the exhaust gas from an engine of a medium or a heavy-duty vehicle is capable of producing much higher cooling effect than what is required for cooling a vehicle cabin. Hence, the additional cooling effect can be utilized for engine performance improvement of a mobile vehicle by using a precooler and/or an intercooler in which the chilled water produced by the refrigeration system is used as coolant.

Here it should be mentioned, that in the present study, waste heat of the exhaust gas could not be utilized directly for the refrigeration purpose. Only a fraction of waste heat has been extracted to heat water, whose temperature is restricted to 95 °C. Instead, if the generator of the refrigeration system could be placed directly in the path of exhaust gas, which has temperature higher than 400 °C and contains heat energy many times higher than that is required in the generator, it is possible to operate the refrigeration system with waste energy of exhaust gases only without requiring the heat input from the electric heater.

Nomenclature

Acronyms

BSFC – break specific fuel consumption
BTE – brake thermal efficiency
COP – coefficient of performance
DAR – diffusion absorption refrigeration
T1 – generator temperature, [°C]
T2 – rectifier temperature, [°C]
T3 – condenser temperature, [°C]
T4 – evaporator temperature, [°C]
T5 – absorber outlet temperature, [°C]
T6 – solution heat exchanger inlet temperature, [°C]
T7 – absorber inlet temperature, [°C]
T8 – inside refrigerating room temperature, [°C]

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