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AN APPLICATION OF ENGINE EXHAUST GAS DRIVEN COOLING SYSTEM IN AUTOMOBILE AIR-CONDITIONING SYSTEM

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Özet: Bu makalede egzoz gazı ile çalışan absorpsiyonlu soğutma sisteminin deneysel bir uygulaması tanıtılmıştır. Soğutma kapasitesi 2 KW olan hava soğutmalı absorpsiyonlu soğutma sistemi ve içten yanmalı bir motorun egzoz sistemine bağlanması için iki generator tasarlanmış ve imal edilmiştir. Isı kaynağı olarak 1.4 litrelik bir içten yanmalı motor kullanılmıştır. Deneylerde, imal edilen generatörlerin, değişik motor devri ve torklarında motor ve absorpsiyonlu soğutma sisteminin verimine etkisi incelenmiştir. Sonuçlar; motor boşta çalışırken 0.5 KW, tam yükte çalışırken ise 2.8 KW soğutma kapasitesi elde edildiğini göstermiştir. Ayrıca motor egzozundan boşta çalışırken 3 KW, tam yükte ise 16 KW ısı elde edilmiştir. İmal edilen soğutma sisteminin COP değeri yaklaşık olarak 0.18 olarak tespit edilmiştir. Ayrıca imal edilen generatörler, soğutma sisteminin performansını arttırmış, hem de geri basıncın çok küçük olmasından dolayı yakıt sarfiyatını azaltmıştır.
Anahtar Kelimeler: Absorpsiyonlu soğutma, Otomobil klima sistemi, İçten yanmalı motor, Ekserji analizi, Atık ısı.

OTOMOBİL İKLİMLENDİRME SİSTEMİNDE MOTOR EGZOZ ISISIYLA ÇALIŞAN SOĞUTMA SİSTEMİNİN BİR UYGULAMASI

Abstract: This paper describes an experimental application of engine exhaust gas driven absorption refrigeration system. An air-cooled absorption refrigeration system which has cooling capacity of 2 kW, and to integrate refrigeration system to engine, two generator models were designed and constructed for this study. A 1.4 liter internal combustion engine was used for waste heat source. In the experiments, the effect of the use of two generator models constructed on the performance of the engine and absorption refrigeration system was investigated according to various engine speed and torque. Experimental results indicated that at idle conditions the cooling capacity is 0,5 kW while at under full load conditions the cooling capacity increases to 2,8 kW. The waste heat from the exhaust was between 3 kW and 16 kW from idle to under full load, respectively. The absorption system shows a coefficient of performance around 0,18. In addition, the proposed heat exchangers were effective not only for improving the refrigeration system performance but also for decreasing fuel consumption on the engine due to the back pressure during the refrigeration.
Keywords: Absorption refrigeration, automobile air-conditioning system, internal combustion engine, exergy analysis, waste heat.

NOMENCLATURE

P	Pressure [kPa]
T	Temperature [^oC]
X	Concentration [%]
$\dot{m}$	Mass flow rate [kg/s]
h	Enthalpy [kJ/kg]
S	Entropy [kJ/kg.K]
Ψ	Exergy [kJ/kg]
COP	Coefficient of Performance [-]

INTRODUCTION

Automobile air conditioning currently is performed by vapor compression refrigeration systems, but the refrigerants in vapor compression refrigeration systems are mainly HCFCs and HFCs, which are not environmentally friendly, and the compressor uses a significant portion of the engine power (Peng Hu et al., 2009). During the past decade, more interests have been paid to the waste heat-driven refrigeration technologies, especially absorption and adsorption systems. The absorption refrigeration cycle uses environmentally-friendly refrigerants and can be driven by waste heat from the vehicle engine. Absorption refrigeration systems are currently being considered as viable alternatives to vapor-driven compression refrigeration. Fundamentally, driven by waste heat and zero-emissions aspect of absorption refrigeration provide an argument for investigating the possibility of replacing vapor-driven compression refrigeration for mobile applications.

The absorption cycle is similar in certain respects to the vapor compression cycle. A refrigeration cycle will operate with the condenser, expansion valve, and evaporator. If the low-pressure vapor from the evaporator can be transformed into high pressure vapor and delivered to the condenser. The vapor-compression system uses a compressor for this task. The absorption system first absorbs the low-pressure vapor in an appropriate absorbing liquid. Embodiment in the absorption process is the conversion of vapor into liquid; since the process is akin to condensation, heat must be rejected during the process. The next step is to increase the pressure of the liquid with a pump, and the final step releases the vapor from the absorbing liquid by adding heat shown in Figure 1.

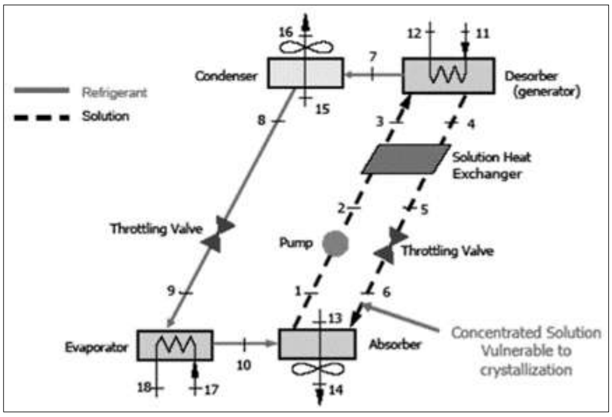
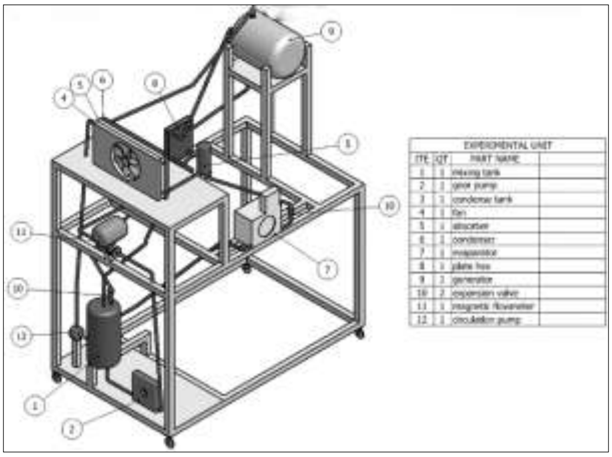


Figure 1. Diagram of single-effect air-cooled absorption cycle

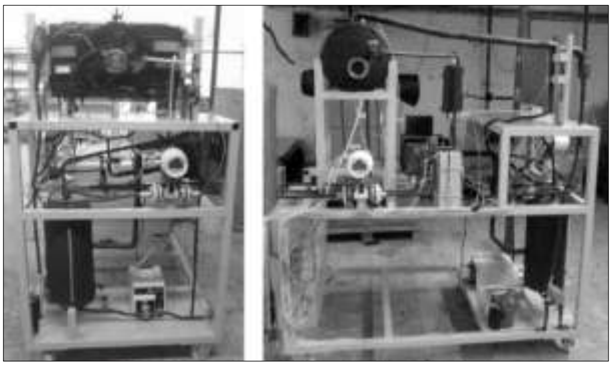
Ghassemi (1987), Koehler and Tegethoff (1997), Garrabrant (2003), Horuz (2004), Hilali (2007) and Hilali and Soylemez (2008) studied theoretically and experimentally the absorption refrigeration system for automotive air-conditioning. The objective of this study is to determine the performance and feasibility of using a waste heat driven absorption refrigeration system as an alternative to the conventional vapor compression system that has been used by the automobile industry for years. As first, a mathematical model was developed to simulate the performance of the absorption refrigeration system. Then absorption refrigeration system driven by engine exhaust gas for vehicles heat was designed to obtain the performance and energy requirements of the absorption system under different operating conditions. It was demonstrated that an absorption refrigeration unit can be integrated with the engine and the operating cost was almost negligible. The feasibility of exhaust gas actuated absorption refrigeration system by using Lithium bromide-Water combination has been demonstrated and the system can be suitably installed and successfully operated.

EXPERIMENTAL SET-UP DESCRIPTION

Figures 2 and 3 show the layout of experimental set-up. It was designed for continuous operation; the mixing tank receives concentrated solution and refrigerant vapor. The resultant dilute solution is pumped upward to plate heat exchanger by gear pump, and then flows to generator where it is again separated into concentrated solution and water vapor. This vapor is led to air-cooled condenser where it loses its latent heat to cooling air. The vapor changes back to liquid state and collects in condense tank. The condensed liquid drops through an electronic expansion valve into the evaporator below. While concentrated solution returns straight to the mixing tank from generator, it passes across the plate type heat exchanger where it gets the desired degree of sub-cooling before entering once again the mixing tank. The generator is a shell-and-tube type heat exchanger and all the other components are air-cooled finned pipe type except the solution-heat exchanger. This set-up has a heat transfer loop with a circulation pump between mixing tank and air-cooled absorber. The heat of absorption in mixing tank should be transferred to surrounding so that the absorber pressure is as low as possible. If the absorber temperature increases, the absorber pressure increases. Consequently, the evaporation temperature increases. The heat should be transferred directly through the fan of air-cooled absorber. So, air-cooled absorber should play the roles of partitioning and transferring heat at the same time (Homma et al., 1994; Reisler, 2004)



(a)



(b)

Figure 2. **(a)** Schematic diagram of the experimental setup and **(b)** refrigeration system used in the experiments

The experimental internal combustion engine test rig, which is illustrated in Figure 4, consists of three main components which are the internal combustion engine, a hydraulic dynamometer and dynamometer control unit. The engine chosen as a test engine for the refrigeration system was a spark ignition engine. It has an overhead valve design and is water cooled. As seen Figure 5, the controller is an intelligent digital controller for refrigeration system control functions and management. The controller operates on a network, allowing connectivity with other devices and systems which comply with the program developed by us. The control of set-up was designed and programmed according to two alternative states.

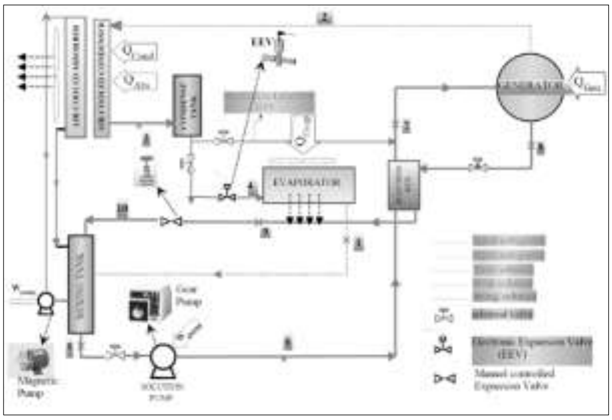


Figure.3. Detailed flow diagram of set-up

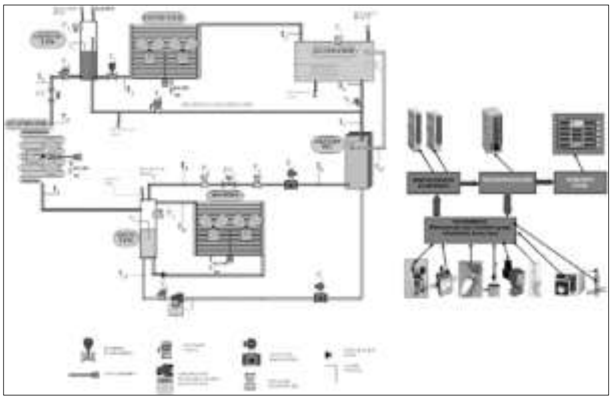


Figure 4. Complete test rig

The first state is manual control. According to this state, the system's entire points can be controlled manually. For example, the valves can be opened, pumps and heater and fan can be turned on or off, EEV can be adjusted to set pressure drop. The second sate is automatic control. In this state, the system runs automatic with respect to default parameter. Solution flow rates to the generator and absorbers are most important parameters in determining the capacity and COP of the set-up., those flow rates would have been controllable parameters for our system. Crystallization ordinarily commences when the solution temperature falls below the normal crystallization temperature for a particular salt concentration. This can occur unless special precautions are taken when the system is shutdown. In the present work, decrystallization line was added on the return line from generator. Therefore, crystallization problem can be avoided by diluting the solution throughout the system prior to shut down. The experimental air-cooled absorption system used was a unique unit designed to be driven by electrical heater. To integrate air-cooled absorption system to engine, two generator models that we designed and constructed were coupled to the internal combustion engine. The generators modeled in this study consist of two different shell-and-tube heat exchangers given in Table 1 (Incropera and Dewitt, 1990). Details of the heat exchangers proposed are shown in Figures 6 and 7. The exhaust pipe line is illustrated in Figure 8.

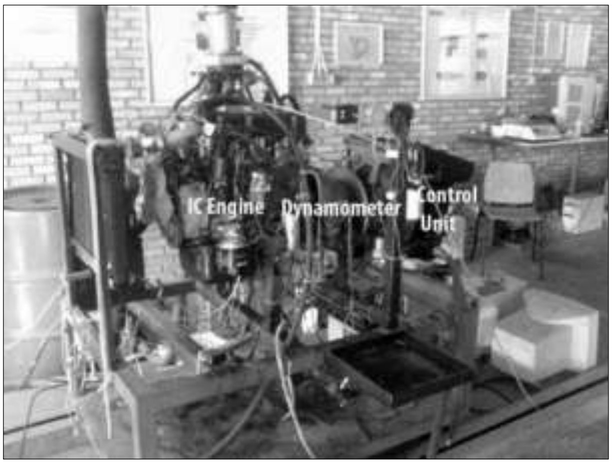


Figure 5. Schematic diagram for instrumentation of the experimental set-up

As Figure 8 shows, thermocouple probes and pressure transducers were connected convenient points to determine pressure drops and the amount of heat transferred. The generator is placed to the engine exit and connected with flexible metal hose.

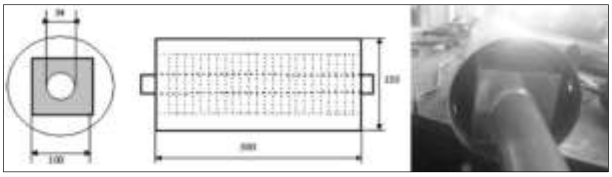


Figure 6. First type generator model

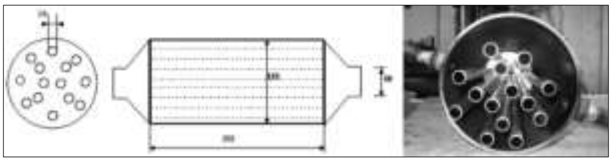


Figure 7. Second type generator model

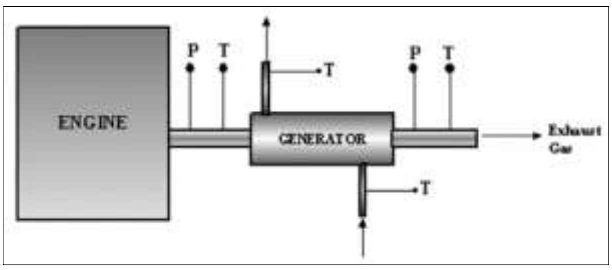


Figure 8. Exhaust pipe line

Table 1. Design details of exhaust heat exchangers

	1st Type Exhaust HEX	2nd Type Exhaust HEX
Outer shell diameter (mm)	155	155
Number of tubes	1	14
Total tube length(mm)	500	500
Height of HEX(mm)	550	700
Outer diameter, fin (mm)	100	-
Root diameter, tube (mm)	54	-
Tube wall thickness (mm)	4.5	3
Fin pitch (fins/cm)	2	-
Material	copper-nickel tubes, copper-nickel fins, cast iron shell and cast iron end covers	copper-nickel tubes, cast iron shell and cast iron end covers

UNCERTAINTY ANALYSIS OF MEASUREMENT SYSTEM

All instruments and measurements have certain general characteristics. An understanding of these common qualities is the first step towards accurate measurements. Errors and uncertainties are inherent in both the instrument and the process of making the measurement. Final accuracy depends on a sound program and on correct methods for taking readings on proper instruments. Errors and uncertainties in the experiments can arise from instrument selection, instrument condition, instrument calibration, environment, observation, and reading (Holman, 1994). Table 2 shows instrumentation with the associated error for each sensor. It should be noted that all data collected by the data acquisition systems used in this experimental study was subjected to small errors.

Table 2. Instrumentation and sensor errors

Measurement	Sensor	Error
Solution flow rate	magnetic flowmeter	±0.5% of rate
Inlet-outlet temperatures	J type thermocouple	±0.6° C or ±0.075% (0 to 750° C)
Air flow rate for condenser-absorber and evaporator	Hotwire flowmeter	±,% 1
Pressure Measurement	transducer	±0.4%
Torque	Bourdon type gage	±3%
Speed	Tachometer	±1 %
Load	Water brake dynamometer	±0.25%

RESULTS AND DISCUSSION

The thermodynamic analysis of the system which is shown schematically in Figure 9 is given below. The mass balance and the first and second laws of thermodynamics are used to analyze the absorption refrigeration system (Mostavavi and Agnew, 1998; Agnew and Talbi, 2000; Izquierdo, 2000; Chuang et al., 2003 and Mroz, 2006). The exergy analysis emphasizes that both losses and irreversibility have an impact on system performance. In states 13, 15 and 17, the exergy flow from the ambient environment is equal to zero, because the temperature of the considered system is equal to the ambient temperature. In terms of availability, the principle of conservation does not exit. In this case, the inlet and outlet exergy do not match (Table 3).

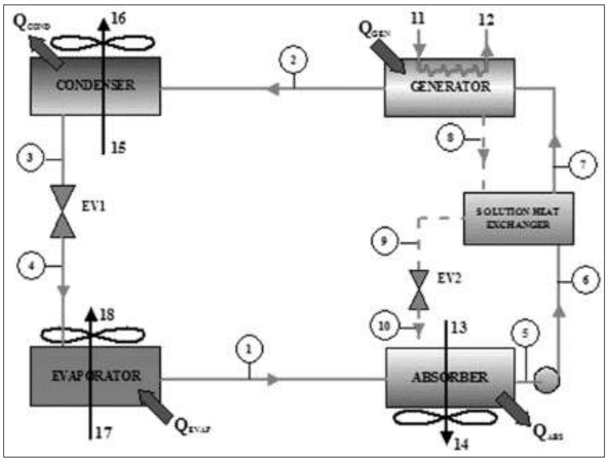


Figure 9. Diagram of single-effect air-cooled absorption cooling system

The difference is the amount of availability consumed in the process. Table 4 ranks the order of the components of the system based on the significance of their contribution in the exergy losses. The generator has the highest exergy loss of 50%, basically due to the temperature difference between the generator and the exhaust gas. This can be reduced by increasing the surface area of the generator, consequently, increasing the cost of the generator. In order to improve the performance of the cycle, special attention must be made to reduce the irreversibilities that exist in this component in the overall design. Due to the temperature difference between the absorber and the surrounding, the next largest exergy loss occurred in the absorber. This can be reduced by increasing the surface area of the absorber; consequently, increasing the cost of the absorber. The exergy loss in the evaporator results mainly from the temperature difference between the environment and the evaporating refrigerant. Determining the engine capability to drive the experimental refrigeration system required the study of the power and heat distribution of the engine under various conditions. In our study measurements are taken between 1500 and 4000 rpm due to use of a gasoline engine. The first type generator was called 1st type, while the second type generator was called 2nd type.

Table 3. State points for the single effect air-cooled LiBr absorption system at design condition

Statepoint	P (kPa)	T (^oC)	X (%)	$\dot{m}$ (kg/s)	h (kJ/kg)	S (kJ/kg.K)	Ψ (kJ/kg)
1	1.00	7	0.0	0.00105	2513.0	8.97	1254
2	5.63	85	0.0	0.00105	2659.0	8.64	1499
3	5.63	35	0.0	0.00105	146.60	0.50	1370
4	1.00	7	0.0	0.00105	146.60	0.50	1370
5	1.00	37	55.6	0.00897	89.450	0.26	1384
6	5.63	37	55.6	0.00897	89.450	0.26	1384
7	5.63	59.2	55.6	0.00897	135.00	0.40	1389
8	5.63	85	63.0	0.00791	215.90	0.50	1441
9	5.63	57	63.0	0.00791	164.30	0.38	1424
10	1.00	57	63.0	0.00791	164.30	0.38	1424
11	101.2	500	-	0.04200	594.80	0.99	1675
12	101.2	300	-	0.04200	515.70	1.10	1565
13	101.2	22	-	1.56600	295.50	5.69	0.01
14	101.2	24	-	1.56600	297.60	5.69	0.03
15	101.2	20	-	1.31800	293.50	5.68	0.00
16	101.2	22	-	1.31800	295.50	5.69	0.01
17	101.2	20	-	0.27600	293.50	5.68	0.00
18	101.2	11	-	0.27600	284.50	5.65	0.14

Table 4. Exergy difference for air-cooled LiBr absorption system proposed at design condition

Component	Exergy(kW)		Exergy Difference ($\Delta\psi$)	Contrubition (%)
	Input	Output		
Generator	12.98	12.46	0.5242	49.65
Absorber	12.59	12.42	0.1762	16.69
Evaporator	1.447	1.325	0.1221	11.56
Condenser	1.583	1.447	0.1362	12.90
Solution HEX	23.82	23.73	0.08975	8.5
Exp. Valve I	1.447	1.447	0	0.0
Exp. Valve II	11.27	11.27	0	0.0
Solution pump	1384	1383.99	0.0074	0.7
Entire System	1449.14	1448.1	1.0556	100

The effect of generators on the performance parameters of engine for various speeds is shown in Figures 10-13. When experimenting with the combined system, particular attention was given to examining the effect on the performance of the IC engine of inserting the generators of refrigeration system into the engine exhaust system. The pressure measured in generator inlet increase as amount of pressure loss due to generator. Figure 10 shows that as engine speed increases engine back pressure increases. Thereby, the power loss is calculated with respect to the back pressure. The first type generator did not affect exhaust pressure. But the second type generator affected exhaust pressure approximately 12% higher than the first type generator. Because the second type generator created more head loses due to its construction with respect to no generator and first type generator (Figure 11). Fuel consumption, exhaust pressure, power loss and engine efficiency are functions of engine speed. As engine speed increases fuel consumption increases as shown in Figure 12. The first type generator didn't affect fuel consumption with respect to no generator. But the second type generator effected at the ratio of 8%. The most important effect of generators on the engine performance is shown in Figure 12 as power loss.

As the engine speed is increased, the power loss increases slightly. The increase of power loss affects fuel consumption. So, the higher fuel consumption caused lower engine efficiency. Engine efficiency did not decrease until 2750 rpm and then, as engine speed increases further, the engine efficiency decreases as shown in Figure 13. The engine efficiency increases until the speed of the engine reaches at 2750 rpm, at which the engine runs most efficiently, and then the efficiency starts decreasing as engine speed increases further.

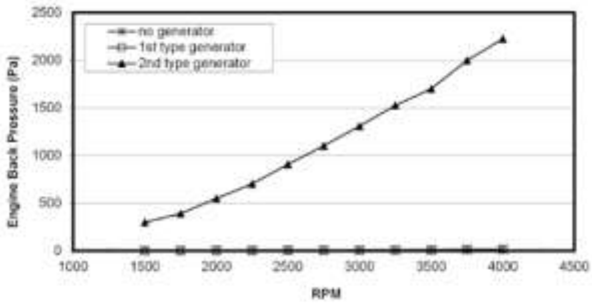


Figure 10. Engine back pressure against speed

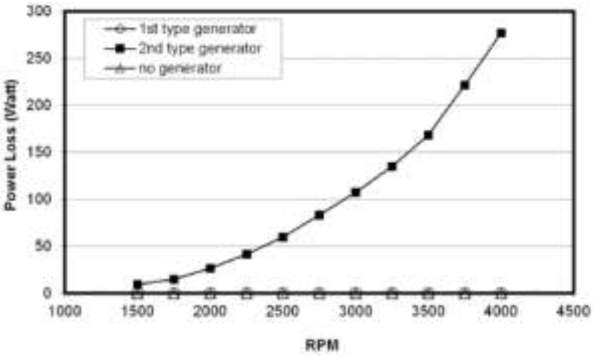


Figure 11. Power loss against speed

The variation of cooling capacity with engine speed is shown Figure 14. While the engine speeds were varied between 1500 and 4000, the torques were set at 100, 120 and 135 Nm. As engine speed increases cooling capacity increases as shown in Figure 14.Likewise, as seen Figure 15, as the engine speed increases, the recovered heat energy also increased. Because, when the engine speed increases, the exhaust gas temperature and flow rate increase. Therefore, generator capacity increases. At the absorption refrigeration system, the engine can provide sufficient heat capacity at 2500 rpm. This heat capacity reaches to approximately 7,0 kW. The variation of COP with engine speed is shown in Figure 16. COP initially increased with engine speeds and then it decreased for higher engine speeds. This trend can be explained considering that the main irreversibilities in absorption cycles are mixing losses (associated with the evaporation of the refrigerant from a concentrated solution) which increase with the concentration difference at the generator and circulation losses (associated with the imperfect heat transfer in the regenerative heat exchangers), which increase with solution flow rate. The generator temperature enhances the concentration difference, increasing mixing losses, and at the same time reduces the solution flow rate, decreasing circulation losses (Longo, 2005). Also in this case for each operative condition considered, it is possible to identify an optimum generator temperature.

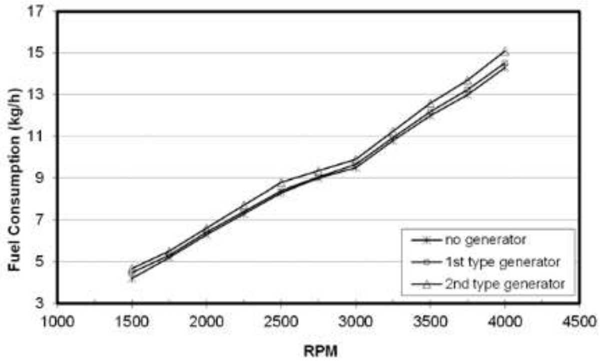


Figure 12. Fuel Consumption against speed

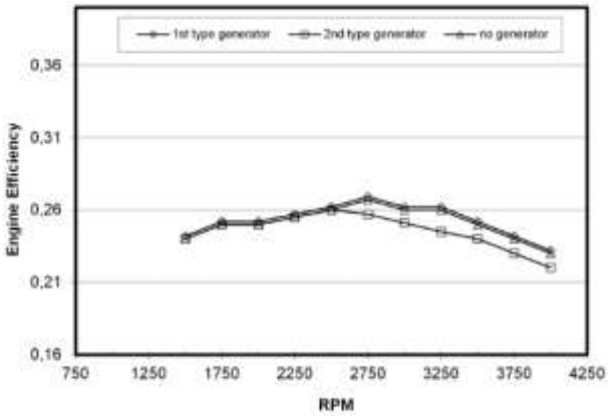


Figure 13. Engine efficiency against speed

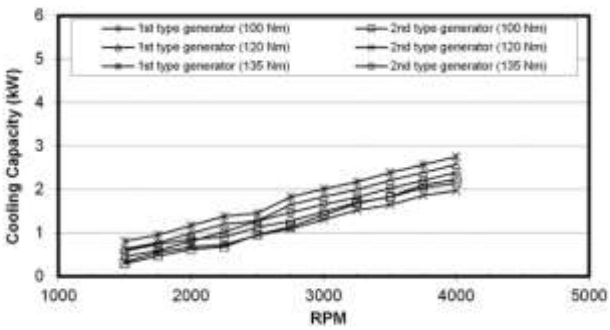


Figure 14. Cooling capacity against speed

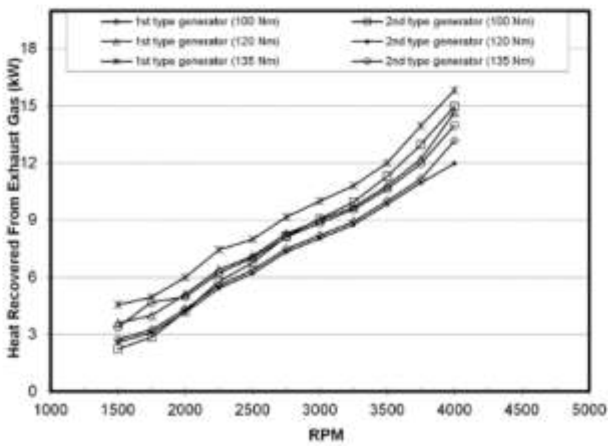


Figure 15. Heat recovered from exhaust gases against at different torques at different torques

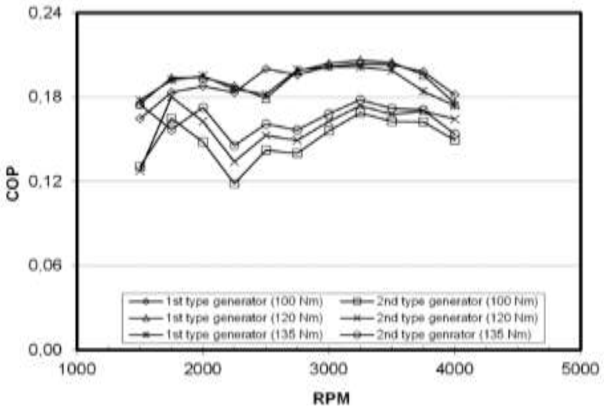


Figure 16. COP against speed at different torques

DISCUSSION

When the effect of the generators of absorption refrigeration system on the performance of the IC engine is concerned, Figures compare the fuel consumption, exhaust pressure and power loss against speed. In the first type generator, the engine power loss is about the same as without heat exchanger and hence fuel consumption is about the same. In the second type generator, engine pressure is higher than the first because of restricted flow area. This caused higher fuel consumption and hence, higher power loss and lower engine efficiency. In respect of absorption refrigeration system, as figures indicate , more heat recovered from the exhaust gas of the IC engine the more heat transferred to the generator and hence this caused an increase on the cooling capacity of the experimental refrigeration system. This is due to the fact that, in the refrigeration system, the cooling capacity is directly proportional to the heat input to the generator.. At normal driving conditions, the waste heat available from the exhaust gas would be sufficient, but the waste heat available from the engine exhaust gas is more than sufficient. As shown Figure 14, at idle conditions the cooling capacity is 0,6 kW while at under full load conditions the cooling capacity increases to 2,8 kW. According to these results, the waste heat from the exhaust was between 3kW and 16 kW from idle to under full load, respectively. Using this range, the effect of the available heat to be used in the generator was evaluated for different engine speeds. The worst case scenario (when the system has the smaller cooling capacity) is at idle when the available waste heat from the exhaust system has the smaller value.

CONCLUSION

The absorption refrigeration system is a feasible alternative to the traditional vapor compression system for automotive case. The absorption refrigeration systems use an environmentally-refrigerants and very little power for operation when compared to traditional vapor compression systems. The reduction in power can be achieved because the system can be operated using the waste heat rejected from the engine coolant system and because no compressor is required. An experimental investigation was carried out to analyze the absorption refrigeration system in detail and investigate the use of the absorption system utilizing the waste heat in the exhaust gases The study included the experimental analysis air-cooled absorption system in detail, the experimental analysis of the availability and recovery of the exhaust waste heat from engine and experimental study of the integrated system performance. As far as the absorption system is concerned, air-cooled absorption system which uses water as the refrigerant and LiBr as the absorbent was constructed for experiments in the laboratory. The system which had a cooling capacity of approximately 2,0 kW was originally designed and constructed for automobile air-conditioning system. A 1.4 liter internal combustion engine was also analyzed experimentally by carrying out the study of the power and heat distribution under various speed and load conditions. Experimental results show that the experimental engine was capable of driving the experimental absorption refrigeration system by using waste exhaust heat. In addition, combining generators into the exhaust system of the engine caused an increase on the engine back pressure and this caused higher fuel consumption and lower efficiency. The effect can be reduced by designing a generator with a minimum pressure drop. If a generator is designed with a minimum pressure drop, but a maximum heat transfer efficiency, more cooling effect can be obtained even in the lower engine speed and loads. The corrosion effect of the exhaust gas to the generator material can be reduced by using the materials which can accommodate the exhaust gases, such as galvanized or stainless steel. The solution will overcome the corrosion problem but will increase cost. Sufficient cooling capacity in automobile low speeds can be obtained by employing a generator combining heat source. The absorption refrigeration system can be mounted to the same location on the automobile as the conventional system, and generator can be connected to the automobile's exhaust pipe by flexible pipe work. The generator should be as close as the exhaust manifold in order to reduce the heat loses and the pressure drops along the flexible pipe. This suggests that such a system could be used in automobiles.

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