Tr. J. of Engineering and Environmental Science
22 (1998) , 211 – 222.

An Alternative Road Transport Refrigeration

İlhami HORUZ
University of Uludağ,
Faculty of Engineering and Architecture, Dept. of Mec. Eng.,
Bursa-TURKEY

Received 10.01.1997

Abstract

The refrigeration units currently used in road transport vehicles are predominantly of the vapour compression refrigeration (VCR) type. In such a unit, the compressor requires an input of energy in the form of work. Although in smaller systems, the compressor can be belt driven from the main propulsion engine, in large systems, it is normally driven by a dedicated internal combustion (IC) engine. In order to obtain refrigeration, the use of vapour absorption refrigeration (VAR) systems utilising the waste heat in the exhaust gases from the main propulsion unit of the vehicle was experimentally investigated and proved possible. Hence, there is no need for the IC engine and compressor of the VCR system. Money can therefore be saved, and there is a reduction in the weight of the unit. Additionally, the VAR system runs quietly and is almost maintenance-free, and the primary energy used to drive the independent engine of the VCR system can be saved. The study included and experimental investigation into the effect on the performance of the IC engine of introducing the VAR system into the exhaust system and also the provision of appropriate off-road/slow running cooling systems, in order to take account of the reduction in exhaust gas flow in slow running traffic or stationary situations or when the vehicle is parked and cooling is still required.

Key Words: Refrigeration, Absorption Refrigeration, Road Transport Refrigeration, Internal Combustion Engine.

Karayolu Taşımacılığında Alternatif Bir Soğutma

Özet

Karayolu taşımacılığı yapan araçlardaki soğutma üniteleri yaygın olarak Buhar Sıkıştırmalı Mekanik Soğutma (BSMS) Sistemini kullanırlar. Bu ünitelerde kompresör, mekanik enerji gerektirir. Küçük sistemlerde, kompresör, kayış kasnak mekanizmasıyla tahrik edilir. Bu çalışmada, soğutma elde etmek için, karayolu taşımacılığı yapan aracın egsoz gazındaki atık ısıyı kullanan Absorpsiyonlu Soğutma (AS) sistemlerinin kullanımı deneysel olarak araştırılmıştır. Bu konuda deneysel olarak yapılan benzersiz bu çalışma, egsoz gazındaki atık ısıyla çalışan AS sisteminin kullanılmasının mümkün olduğunu ispatlamıştır. Böylece, BSMS sisteminin kompresörüne ve ilave bir İY motora gerek yoktur. Bu sebeple, yatırım maliyeti düşer ve ünitenin ağırlığında bir azalma olur. Bunlara ilave olarak , AS sistemi sessiz çalışır, hemen hemen bakım gerektirmez ve BSMS sisteminin İY motorunu tahrik etmek için kullanılan enerji tasarruf edilmiş olur. Bu çalışma, egsoz sistemine AS sisteminin bağlanmasının İY motorun verim üzerindeki etkisinin deneysel olarak araştırılması ve aracın park edilmesi ve/veya yoğun trafik şartlarındaki yavaş hareketinin egsoz gazındaki düşüşe sebep olmasınıda göz önüne alarak elde edilen soğutmanın değişimini de deneysel olarak incelemiştir.

Anahtar Sözcükler: Soğutma, Absorpsiyonlu soğutma, Karayolu taşımacılığında soğutma, içten yanmalı motorlar.

1. Introduction

It might be said, quite simply, that refrigerated road transport did not exist prior to 1914. This is due to the fact that, the first motor cars driven by petrol engines were introduced just before 1890, and in 1898 there were only 1000 cars in the whole world (Theveont, 1979). The main types of refrigeration systems used and reported to date in refrigerated vehicles are as follows: water ice systems, liquid nitrogen or carbon dioxide injection system (cryogenic cooling), refrigerated road transport vehicle cooling tunnels, eutectic system and mechanical systems (Slocombe, 1986), (Thevenot, 1979).

Although there are some studies on the utilisation of exhaust gases from refrigerated road transport vehicles, all are theoretical (Ghassemi, 1987), (Keating, 1954), (McNamara, 1972). (Vincent et. al., 1979). The unique feature of the present work is the experimental investigation of utilising the exhaust gases from the refrigerated road transport vehicles for the purpose of refrigeration. It was experimentally proven that it was possible to use the VAR system driven by the waste heat in the exhaust gases.

2. Conventional Road Transport Refrigeration

Vapour compression refrigeration (VCR) systems are widely used in refrigerated transport. Evaporation of a fluorocarbon refrigerant takes place in a ventilated evaporator in the vehicle load space. Refrigerants for road transport are R-12, R-22, R-500 and R-502. Although ammonia is cheaper than Freons, manufacturers prefer the halogenated hydrocarbon refrigerants.

VCR systems have the obvious advantage over other systems that they run indefinitely without exhausting the supply of refrigerant. They provide a forced air circulation which is capable, in conjuction with proper loading of ensuring even temperature distribution throughout the cargo. Moreover, VCR systems have the capability of heating as well as cooling the load space.

In these systems, the compressor may be driven by an independent diesel engine, an electric motor, or an engine-motor combination. The motor of the later type is operated by current from a platform connection during loading or parking. Others are driven by utilising the power plant of the vehicle, through some power take-off drive that may be direct by belt, hydraulic system, flexible shaft and/or some type of variable-speed clucth. An indirect method is to drive a generator which, in turn, supplies current to an electric motor driving the compressor.

On small delivery vehicles, it is common practice to mount a light-alloy compressor in the vehicle engine compartment, and belt drive it from the engine cranksahft. An electromagnetic clucth on the compressor responds to load space thermostat demand to energise drive when refrigeration is called for. The advantages of the system are its simplicity and its cheapness. Installation however, requires that the system be split to connect the compressor via long flexible hoses to the refrigerator and therefore, the responsibility for evacuating and charging the system rests with the assembler or installer rather than the manufacturer. Because of the critical efffect that these operations have on the subsequent reliability of the unit, proper supervision is essential. The long suction and discharge hoses to the compressor also tend to lose some refrigeration capacity.

On larger delivery vehicles, it has become accepted that a higher level of reliability can be achieved by mounting the compressor within the unit and providing a remote drive from the vehicle engine via a simple hydraulic transmission. This system is operationally very attractive. The quietness, freedom of maintenance and low weight are the features of this system. However, the disadvantage of this system is that oil contamination or over-speeding may cause damage to the high pressure hydrostatic pump, which is particularly expensive to repair or replace.

Independent internal combustion engines are used as a prime mover in the majority of mechanical vehicle refrigeration units. Diesel engines are chosen to give high reliability. Another advantage is that it can provide constant and predictable refrigeration for unlimited periods without depending on the engine speed. Thus, it can continue to provide refrigeration even if the vehicle is stationary. On the other hand, there are several disadvantages to this system: the capital cost is very high, it is quiet heavy, it runs noisily, it has high running costs, it often requires maintenance, it causes atmospheric pollution and it results in more waste energy.

3. Alternative Refrigeration System

The study included an investigation into the use of vapour absorption refrigeration (VAR) systems in road transport vehicles using the waste heat in the exhaust gases of the main propulsion unit as the energy source.

VAR systems have been in use for some time, but recently they are of more interest because of their potential use as part of an energy-saving plant; they use more enviromentally friendly refrigerant than current VCR systems.

A VAR system operates with a condenser, a throttle valve, and an evaporator in the same way as a VCR system, but the compressor is replaced by an absorber and generator, as shown in Figure 1.

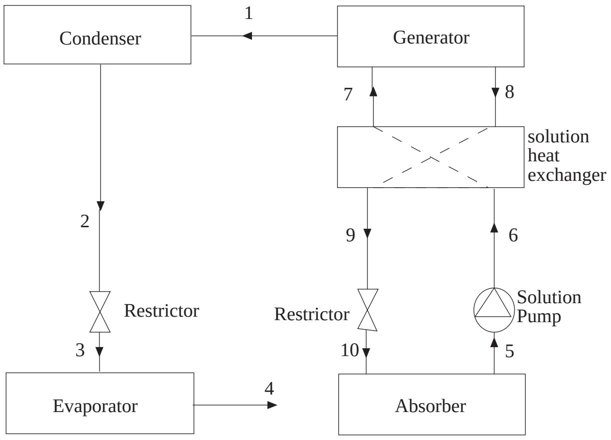

Figure 1. The basic VAR system

The refrigerant on leaving the evaporator is readily absorbed in a low-temperature absorbing medium, some heat being rejected during the process. The refrigerant-absorbent solution is then pumped to the higher pressure and is heated in the generator. Due to the reduced solubility of the refrigerant-absorbent solution at the higher pressure and temperature, refrigerant vapour is separated from the solution. The vapour passes to the condenser and the weakened refrigerant-absorbent solution is throttled back to the absorber. A heat exchanger placed between the absorber and generator makes the system more efficient by transferring heat from the weak solution coming from the generator to the stronger solution pumped from the absorber, as shown in Figure 1. The work done in pumping the liquid solution is much less than that required to compress the vapour in the compressor of an equivalent VCR cycle. The main energy input to the system is the heat supplied in any convenient such as a fuel-burning device, direct electrical heating , steam if already available, solar energy, or waste heat. A refrigerant and absorbent must be found which have suitable solubility properties. Two combinations are in general use: in one, ammonia is used as the refrigerant with water as the absorbent; in the other, water is used as the refrigerant with lithium bromide as the absorbent. The principle of operation is the same for both types.

The ammonia-water VAR system has been used in large capacity industrial applications requiring low temperatures for process cooling. The water-lithium bromide VAR system is used to produce hot water for comfort heating, process heating and domestic purposes, as well as for cooling. This system can also be used to deliver heat at a temperature higher than that of the driving heat source, but is predominantly for air-conditioning applications.

4. Experimental Results

The aim of this research is to investigate the utilisation of exhaust gases from an internal combustion engine to drive a VAR system for refrigeration purposes. In order to do so, a "Robur Servel ACB-3600" gas VAR system was experimentally analysed in detail stand alone. The commercially available VAR system uses aqua-ammonia solution with ammonia as the refrigerant and water as the absorbent and has a rated cooling capacity of 10kW (see Figure 2). Furthermore, a range of experiments was carried out on a Ford 150 (Dover), fuel injection, 6-litre turbo diesel engine using different combinations of speed and torque to obtain a range of engine power output.

Experimental results proved that the 6-litre turbo diesel engine used was capable of providing enough energy to drive the VAR system via its waste exhaust heat. In order to utilise heat fom the exhaust gases, a plenum was built around the existing generator and experiments were carried out for two different cases, one with large free-flow area (Case 1) and the other with a restricted free-flow area (Case 2) (see Figure 3.) A two-valve arrangement was used to control the flow of the exhaust gas to the generator of the VAR system. When there was no requirement for exhaust gas to the refrigeration system, the valves were set to allow the exhaust gases to be discharged directly to the normal engine exhaust system.

The cooling water heat can also be used. However, it is worth mentioning, firstly, that its magnitude is not as high as the exhaust gas heat capacity, and secondly, that the maximum cooling water temperature is about 80°C, which limits its use as a heat source for VAR systems using ammonia-water.

While the main purpose of the study was to measure the performance of the VAR system, when experimenting with the combined system, particular attention was given to examining the effect on the performance of the IC engine of inserting the VAR system into the engine exhaust system. An excessive drop in pressure in the exhaust system could have a detrimental effect on engine performance.

A range of experiments was carried out, and the experimental results are graphically presented in Figures 4-12. The comparison between the experimental and theoretical results is given in Figures 13 and 14.

Two different theoretical analyses were applied to the heat exchanger to determine the heat transfer.

Briggs and Young correlation for radially finned circular tube (Al-Khafaji, 1991) was used in Theoretical Analysis 1.

$$h_0 = \left[\frac{k_{exh}}{d_t}\right] 0.134 Pr^{0.33} Re^{0.681}$$

$$\left[\frac{p - t_f}{R - r}\right]^{0.2} \left[\frac{p - t_f}{t_f}\right]^{0.1134} \tag{1}$$

Theoretical Analysis 2 was based on the correlation of ESDU, 1967 and 1968, as defined by Saunders (1988).
Transition flow (2000≤Re≤10000)

$$h_0 = 0.1\langle\frac{k_{exh}}{d_e}\rangle(Re^{2/3} - 125)Pr^{0.495}$$

$$[exp\{-0.0225(lnPr)^2\}] \left\{1 + \frac{d_e}{L}\right\}^{2/3} \tag{2}$$

The correlation given below is used to determine the effect of engine back pressure on engine performance (Rogowski, 1986).

$$\frac{\eta_{v2}}{\eta_{v1}} = \frac{\varepsilon - \langle\frac{P_{exh}}{P_{airman}}\rangle_2^{1/k}}{\varepsilon - \langle\frac{P_{exh}}{P_{airman}}\rangle_1^{1/k}} \tag{3}$$

where, $\eta, \varepsilon, P_{exh}$ and P_{airman} show the volumetric efficiency, the compression ratio, engine back pressure and pressure at the air manifold, respectively.

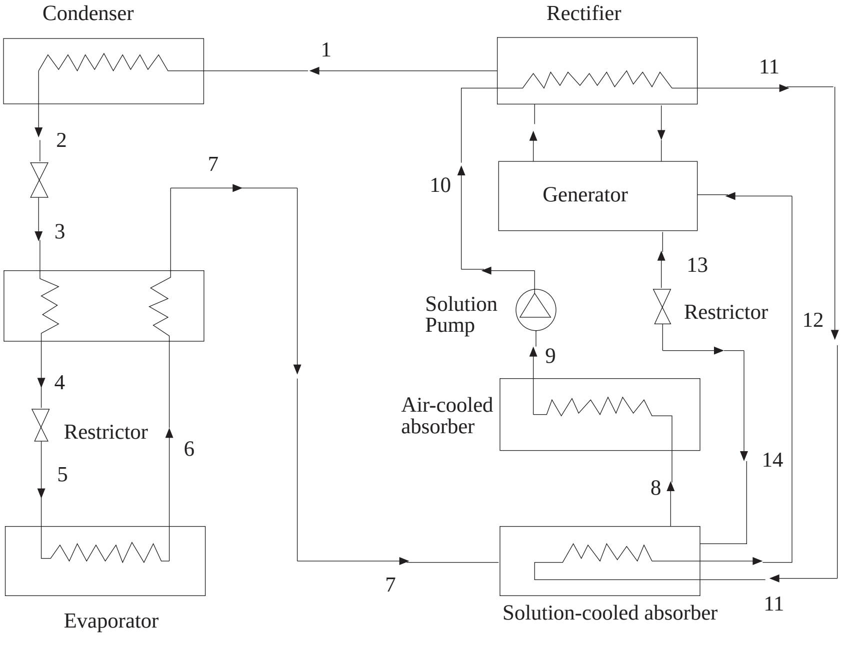

Figure 2. Illustration of Robur Servel ACB-3600 VAR system

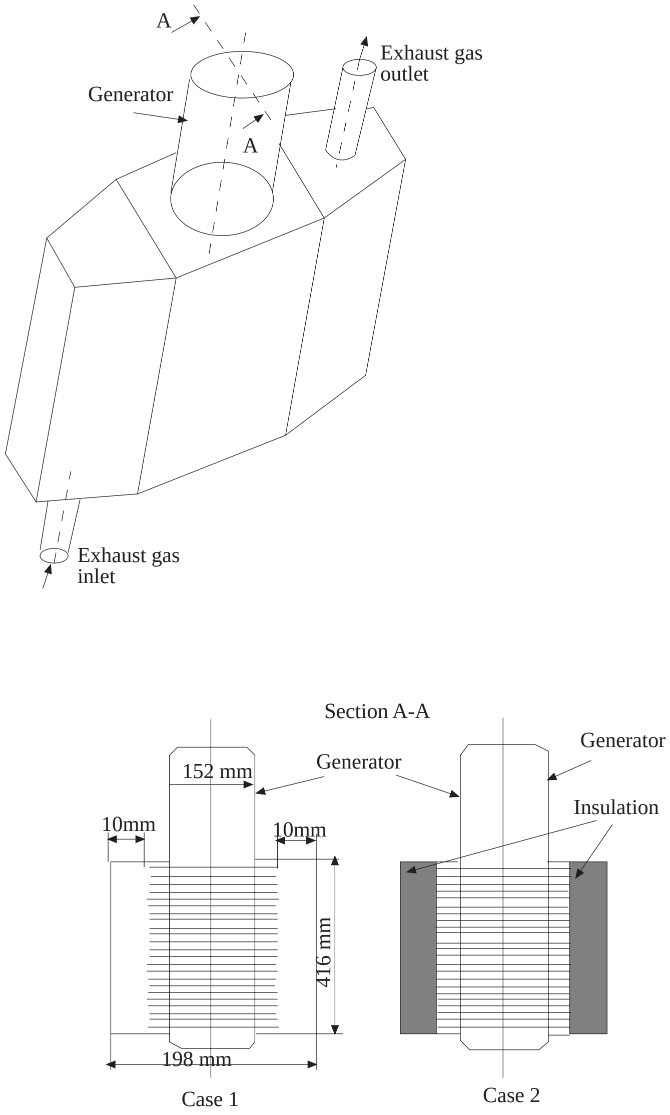

Figure 3. Heat exchanger details

5. Discussion of Experimental Results

Figures 4-6 present the exhaust gas flow rate, temperature and heat capacity against speed. When the engine speed increases, the air consumption, the fuel consumption and hence the exhaust gas flow rate increase. An increase in engine speed also cause an increase in exhaust gas temperature, and, consequently, in exhaust gas heat cacity. Figure 6 shows the exhaust gas heat capacity when it is cooled down to the ambient temperature against speed. This has been described in the capacity in the exhaust gases.

The effect on the performance of the IC engine of introducing the generator of the VAR system into the engine exhaust system is shown in Figures 7-9. In Case 1, with a large free flow area, the engine back pressure is about the same as that of the engine-only test, and hence, the fuel consumption, the exhaust gas temperatures and the engine efficiency are about the same. However, in Case 2, the engine back pressure is higher because of the more restricted exhaust gas temperatures and the engine efficiency are about the same. However, in Case 2, the engine back pressure is higher because of the more restricted exhaust gas flow area. This caused higher fuel consumption and, hence, higher exhaust gas temperature and fuel energy. Thus, higher fuel energy caused lower engine efficiency. The engine efficiency was penalised up to

2% by introducing the heat exchanger with smaller free flow area (Case 2) (see Figure 9). To avoid this, the gas flow characteristics of the generator of the VAR system should have the same pressure loss characteristics as those of the normal exhaust system.

As far as the performance of the VAR system is concerned, Figure 10 indicates that the higher the engine power, the greater the cooling capacity of the VAR system. This is entirely what would be expected in the VAR system, i.e., for the cooling capacity to be directly proportional to the heat input to the generator (see Figure 11 and 12). The results also confirmed that sufficient waste heat could be recovered to obtain the rated cooling effect of approximately of 10 kW. There is, however, a significant reduction in cooling effect with engine output which would reflect the units performance under slow vehicle speeds or stationary conditions.

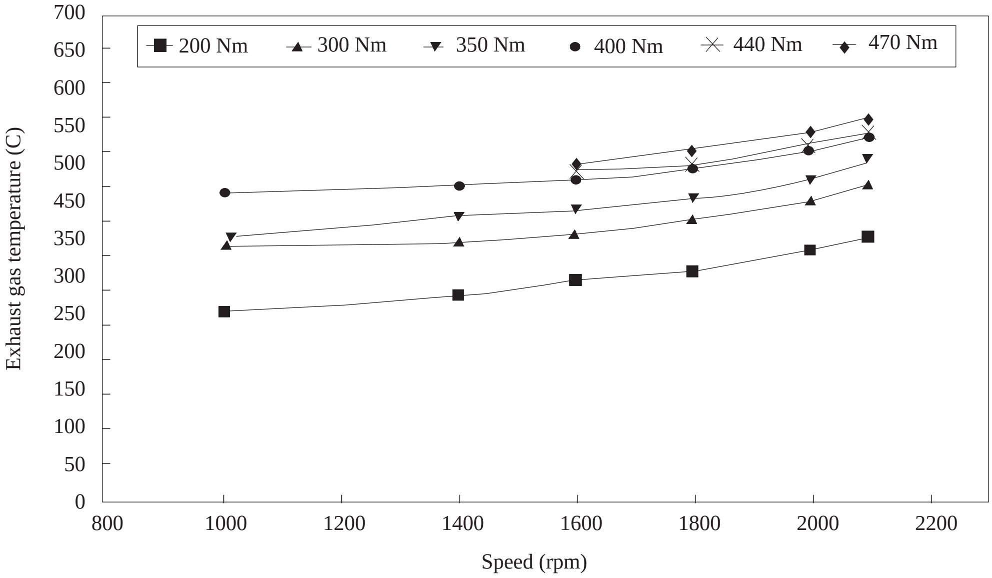

Figure 4. Exhaust gas temperature against engine speed

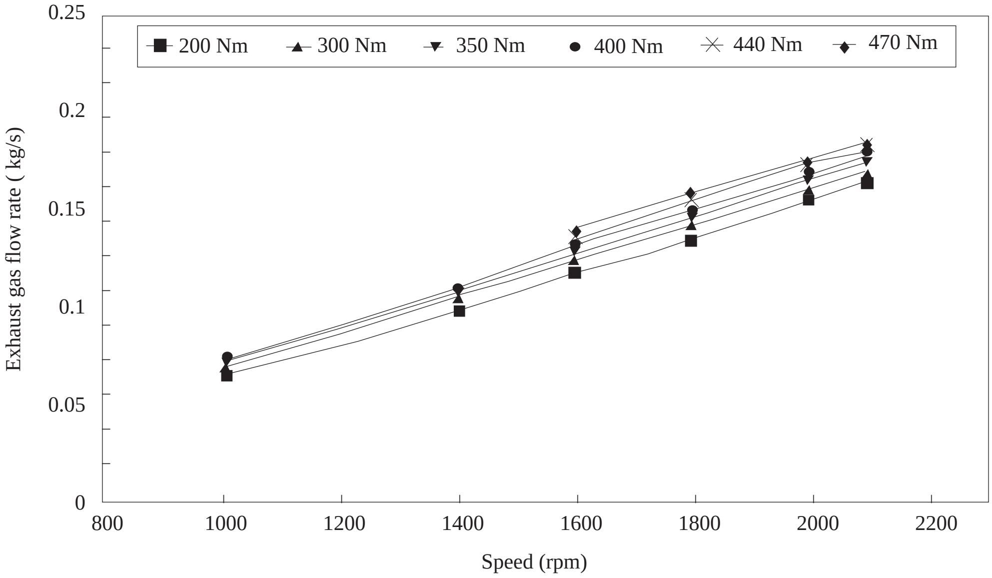

Figure 5. Exhaust gas flow rate against engine speed

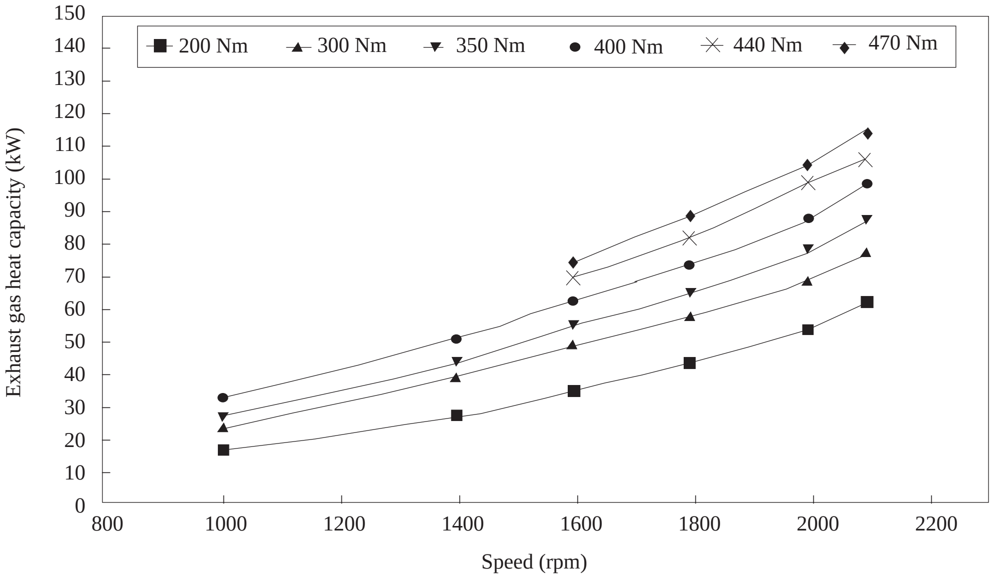

Figure 6. Exhaust gas heat capacity against engine speed

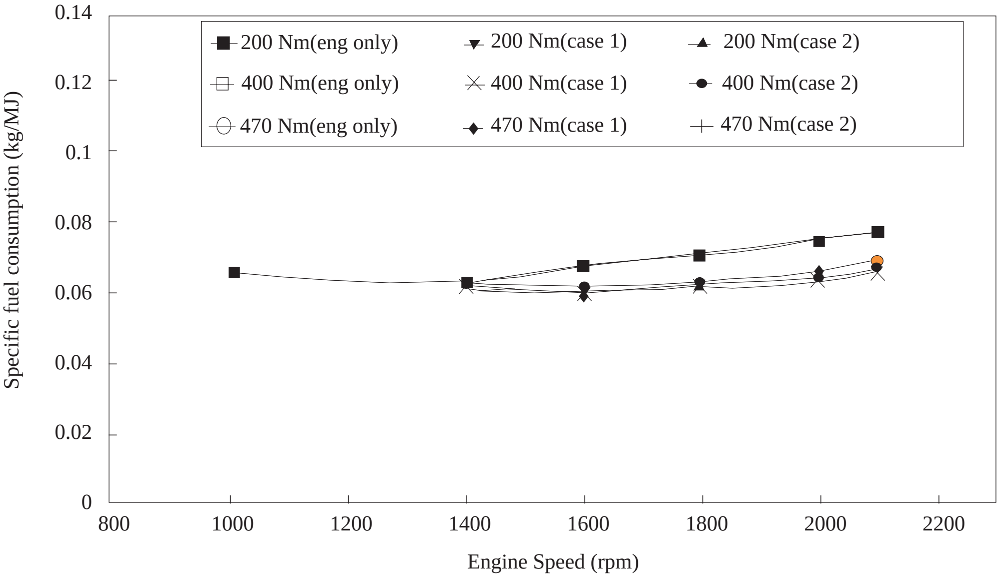

Figure 7. Engine specific fuel consumption against engine speed

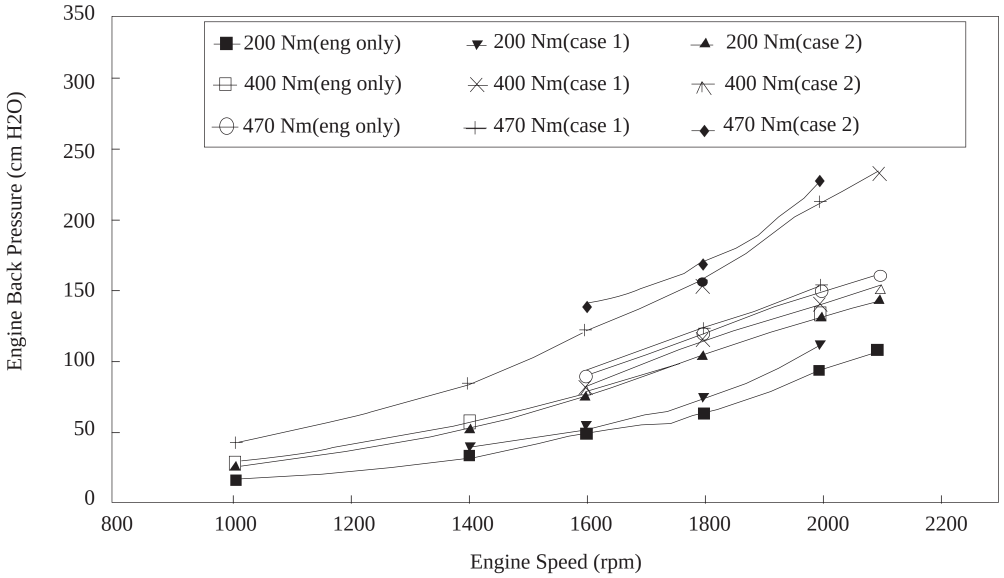

Figure 8. Engine back pressure against engine speed

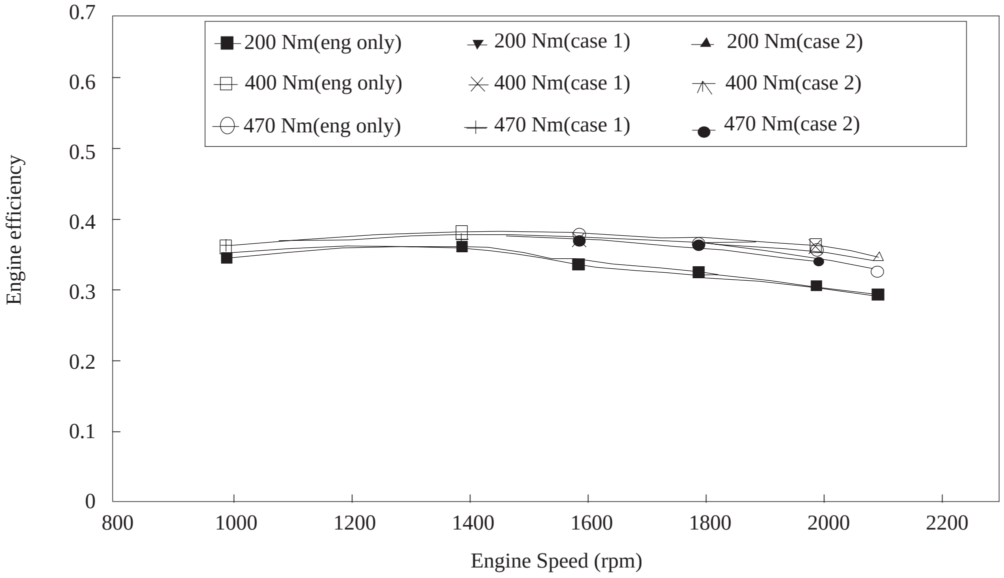

Figure 9. Engine efficiency against engine speed

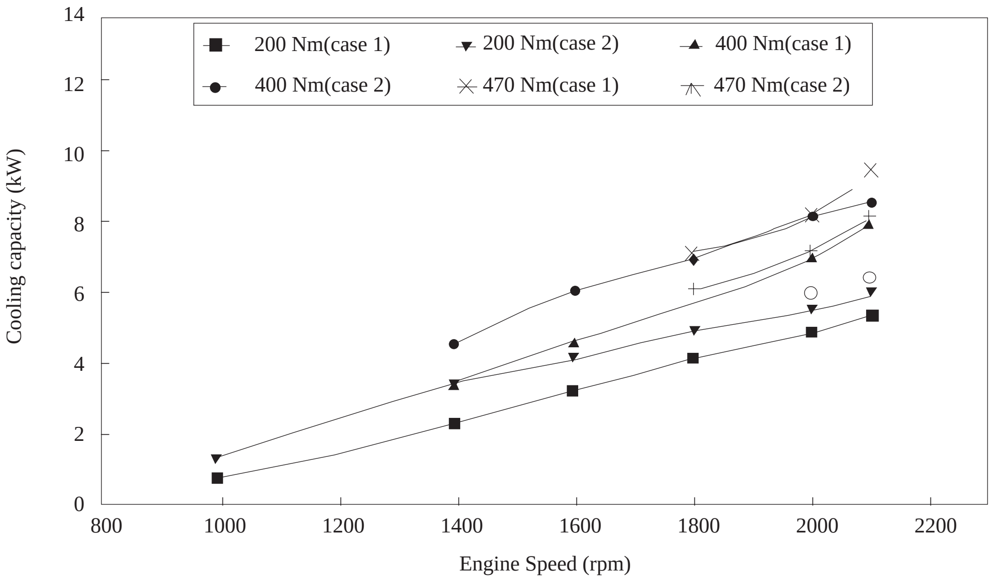

Figure 10. Cooling capacity against engine speed

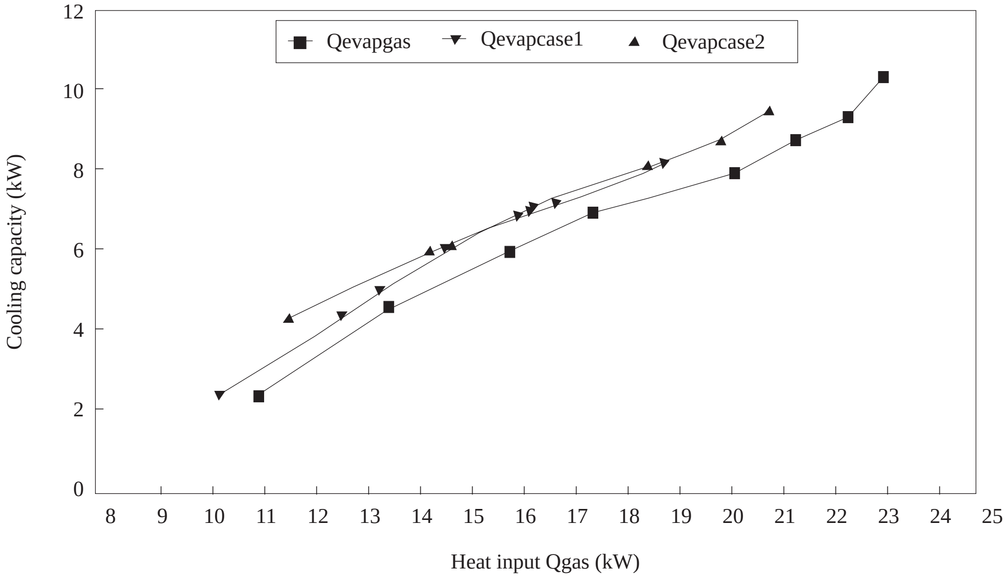

Figure 11. Cooling capacity against heat input

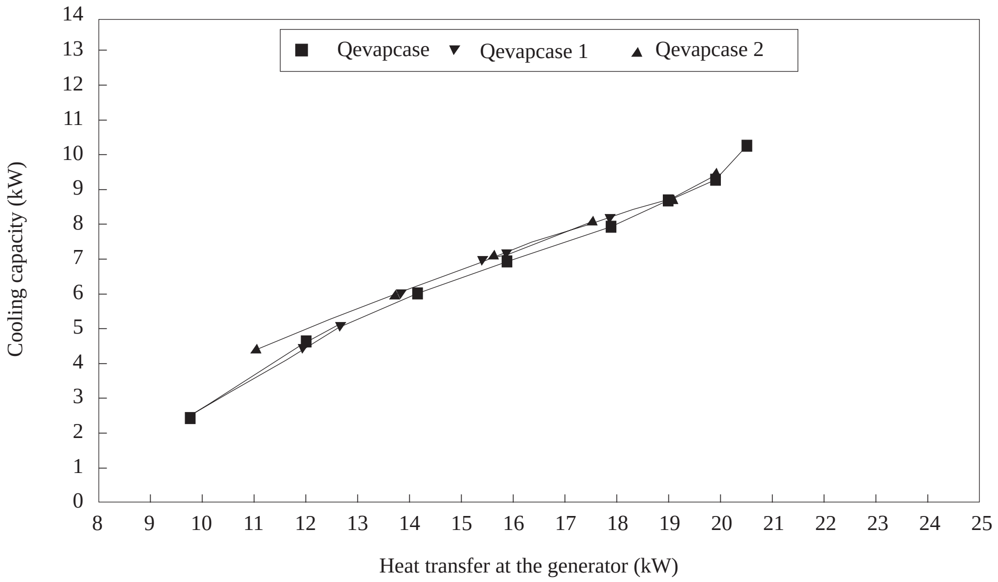

Figure 12. Cooling capacity against heat transfer at the generator

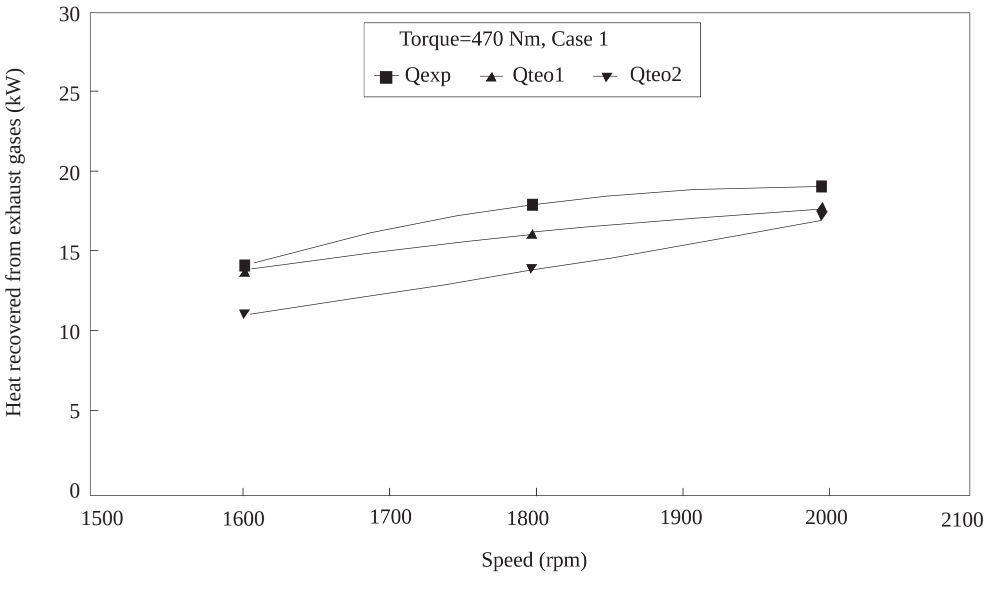

Figure 13. Heat recovered from exhaust gases against engine speed

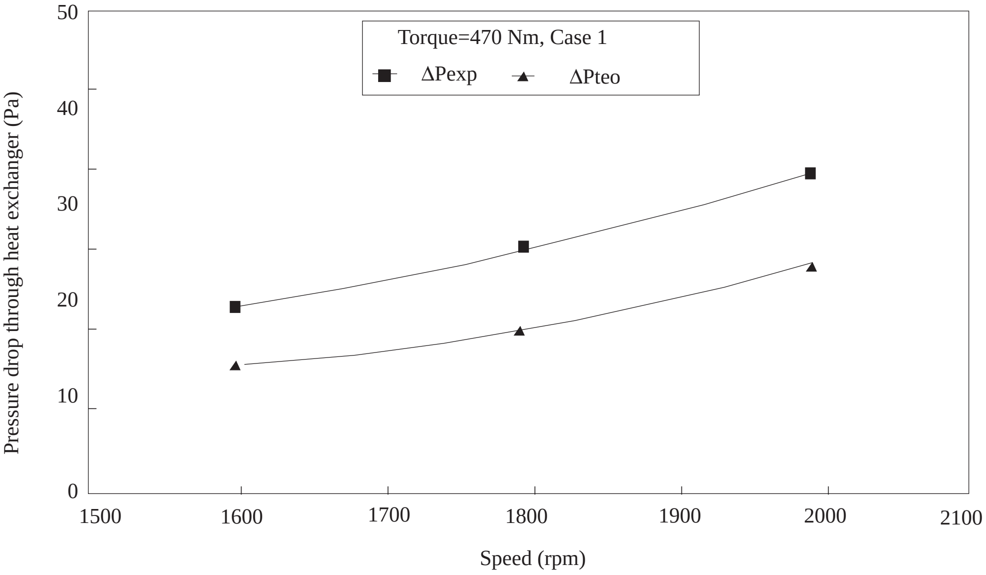

Figure 14. Pressure drop through heat exchanger against engine speed

As 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.

The comparison between natural gas powered and IC engine powered VAR system performance is presented in Figures 11 and 12. As seen in Figure 12 which shows the cooling capacity of the experimental VAR system against the heat input to the generator, the greater the heat transferred, the greater the cooling effect.

The experimental results prove that the VAR system behaves in essentially the same manner, no matter whether the heat input is from natural gas or from the exhaust gases of the IC engine.

As seen in Figures 13 and 14, the theoretical results are in good agreement with the experimental values.

6. General Discussion

The use of VAR in road transport vehicles has the advantage of reducing the dedicated IC engine, refrigerant compressor, unit weight, capital cost, fuel costs, maintenance, atmospheric pollution and noise pollution.

It should be noted, however, that there are difficulties that would need to be overcome should the VAR system be used in road transport vehicles. One such difficulty would occur should the vehicle be at rest or in very slow moving traffic conditions. In either of these conditions the resulting reduction in heat input to the generator would cause a corresponding drop in the cooling effect of the system. Built-in eutectic plates could provide temporary cooling under such conditions. Such plates could be recharged by redirecting the cooling effect from the main body to the eutectic plate during off-load periods of continuous full-load travel. Longer stopover periods as, for example, in a depot may also be accommodated using eutectic plates.

The current development of natural gas powered IC engines together with the provision of a network of refueling centers would ease the solution of some of the above problems. With such a provision, the VAR system could be designed to utilise engine exhaust gases or those from a gas burner, depending on the prevailing conditions. Under the off-road situation mentioned above, it would be possible to connect the system to a mains or bottled gas supply which would provide the necessary heat input.

7. Conclusion

Experimental results proved that it was possible to drive a vapour absorption refrigeration system using the exhaust gases from a diesel engine. This suggests that such a system could be used in road transport vehicles. However, further consideration is required with respect to the following: the design of a heat exchanger to extract waste heat without excessive pressure drops in the exhaust systems, the effect of increased back pressure on the engine performance, the corrosion effect of the exhaust gases on the heat exchanger material, the fluctuations in the cooling capacity due to variations in vehicle speed, and alternative energy input while vehicle is stationary, the effect of varying ambient conditions on the system performance, and accommodating the system on the vehicle.

The author believes that this area of study is worth pursuing in terms of energy and cost savings, and suggests that a protoype design study be undertaken.

Nomenclature

d : Diameter (m)
h : Convection heat transfer coefficient (W/m^2 K)
L : Length (m)
P : Pitch (m)
p : Pressure (kPa)
Pr : Prantl number
r : Outside radius of tube (m)
R : Outside radius of the fin (m)
t : Fin thickness (m)

Subscripts

e : equivalent
exh : exhaust
f : fins
o : exhaust gas side
t : tube

Greek Symbols

η : Volumetric efficiency
ε : Compression ratio

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