Application of Energy Efficient Scroll Compressor for Small Cars

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ABSTRACT

The AC compressor becomes the focal point of any energy efficiency improvement initiative in automotive climate control systems as; it is the single largest consumer of energy. The objective of this work is to evolve a methodology to assess the potential of energy efficiency of compressors through experimental evaluation. The methodology consists of; a) performance evaluation on compressor calorimeter b) bench testing under 'moderate' and 'severe' test conditions c) verification of power consumption on a test vehicle. The main theme is, to reduce compressor load by using an energy efficient compressor; without compromising on cooling capacity and changing the other aggregates in the AC system. This paper critically assesses the comparative performance of a reciprocating and scroll compressor having different displacement, internal construction and compression mechanism. Bench test results with the scroll compressor demonstrate that, power consumption reduces up to 25.3% and cooling capacity is up to 5% higher. This indicates that it can be a good option for small cars.

Key words: Climate control, scroll compressor, compressor calorimeter, performance.

1. INTRODUCTION

The purpose of an automotive climate control system is to provide a comfortable environment inside the cabin with minimum energy consumption. Automotive AC applications are characterized by significant thermal load variations which depend on the time of the day and the number of passengers in the cabin. The AC system must provide comfort under highly transient conditions and at the same time be compact and efficient. Small cars may experience low pick-up when the AC is switched on. The car is perceived to be under powered with AC and sometimes the compressor has to be switched off while overtaking or climbing a gradient. In commonly used reciprocating piston type swash/wobble plate compressors, the reciprocating motion of pistons past the walls of the cylinders, results in higher frictional losses thereby lowering efficiency. In a scroll compressor two spiral-shaped members fit together forming crescent shaped pockets. One member remains stationary while the second orbits relative to the first. As the spiral movement continues, refrigerant is drawn in and forced toward the center of the scroll form gradually increasing refrigerant pressure. The high pressure refrigerant is then discharged from the center port of the fixed scroll member. This method of compressing refrigerant results in lower frictional losses thereby increasing efficiency.

Literature survey shows that limited work has been published with respect to efficiency of compressors and heat exchangers as this field is production oriented and strongly influenced by competition. Jabardo *et al.* (2002) developed a steady state simulation model for refrigeration circuits of an automobile AC system with a variable capacity compressor. Recently Urchueguia *et al.* (2003) have carried out experiments with scroll and reciprocating compressor using R22 and propane as refrigerant, for a commercial type refrigeration unit of nominal capacity of about 20kW. Agarwal and Paramane (2003) have developed an empirical mathematical model for the performance of hermetically sealed reciprocating compressor. More recently, Li *et al*. (2003) carried out experiments with the use of internal heat exchangers and R134a refrigerant on the AC system of a medium sized car and found an increase in capacity and COP up to 7%.

In this work, the performance of a 60 cc/rev fixed displacement scroll compressor and a 110 cc/rev fixed displacement reciprocating compressor are compared. A methodical approach of experimental evaluation has been evolved to evaluate comparative performance. This consisted of calorimetric test of compressor as a stand alone machine and bench test of the compressor with other AC system aggregates. Finally, a power consumption test with the compressor and AC system packaged on a small car was performed on a chassis dynamometer. This approach can be adopted to assess the suitability of any type of AC compressor for an automobile application.

2. DESCRIPTION OF THE EXPERIMENTAL TEST BENCH

An automotive AC system test bench is used to measure thermal performance of an AC loop. The experimental set up consisted of original components from the R134a system of a typical small car air conditioner; arranged in a way to emulate those in the actual vehicle. The compressor is run by an electrical motor acted upon by frequency converter in order to cover the whole range of rotational speed in the actual vehicle. The experimental set up shown in Figure 1 consists of three environmental chambers for the compressor, condenser and evaporator. The compressor drive motor is housed in a fourth chamber. The compressor chamber holds the compressor at a desired temperature to simulate temperature conditions in the engine compartment of the car. Compressor power is obtained by shaft torque and speed measurement. Condenser and evaporator chambers contain a wind tunnel with variable speed blower and temperature controller, enabling a wide range of air flow rates and temperatures for the condenser and evaporator chambers respectively. The evaporator chamber also has a steam supply and humidity controller to provide latent heat load. In addition the evaporator was kept in the original plastic housing to preserve the same air circuit and flow rate as in the actual vehicle. The air inlet and outlet temperatures are measured with thermocouples placed upstream and downstream of the evaporator. The humidity entering and leaving the evaporator is determined by two dew point meters. Cooling capacity is calculated using psychrometry, from air flow rate and temperature and humidity differences at the inlet and outlet of the evaporator.

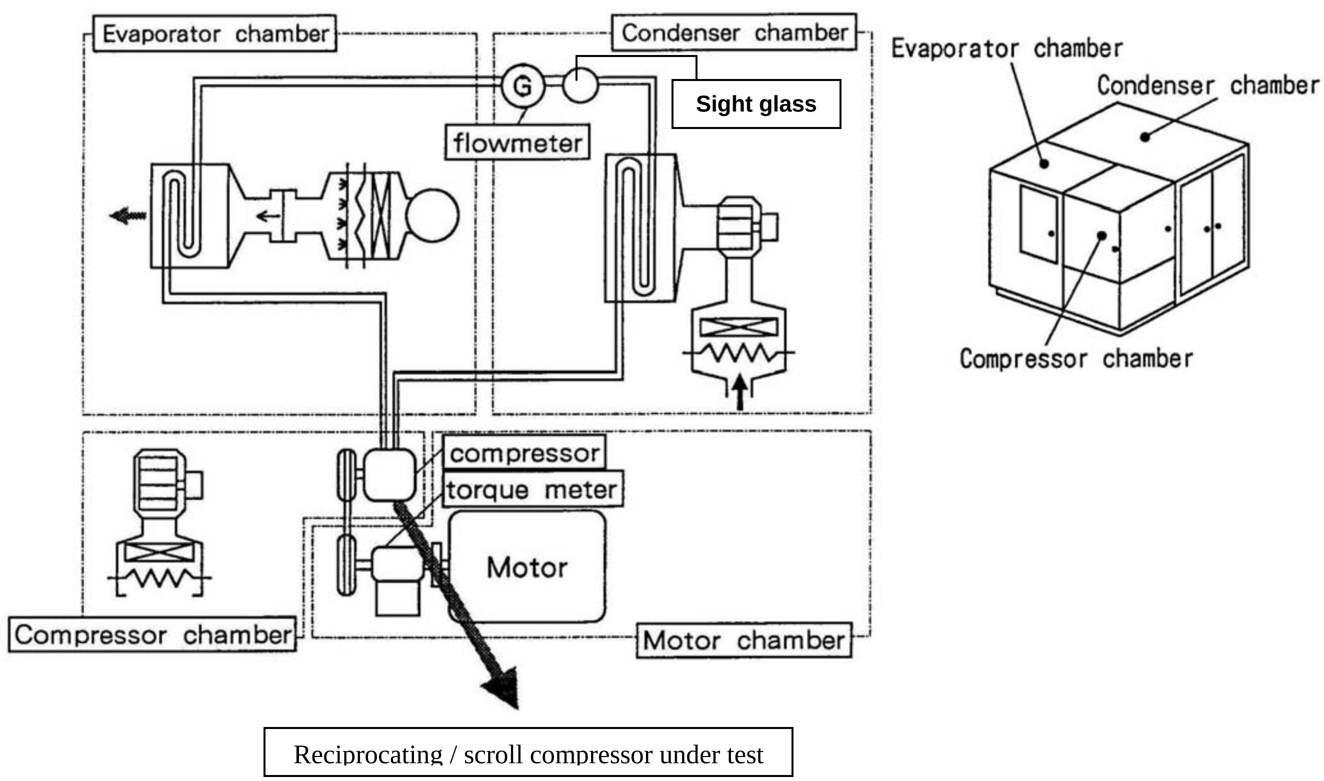

Figure 1: Experimental test bench set up

3. TEST CONDITIONS

3.1 Compressor Calorimetric Test

Both the compressors were tested as stand alone on a compressor calorimeter, under identical test conditions (LP=1.96bar, HP=16.4bar, SH=10°C, SC=5°C). The test conditions selected for compressor calorimeter test represent actual operating conditions on the vehicle, under moderate climatic conditions. The compressor speed was set corresponding to engine speed as on the vehicle. The compressor cooling capacity, power consumption and volumetric efficiency were evaluated at three different engine speeds.

3.2 Bench Test

The test conditions have been shown as a test matrix. The test matrix was designed to represent actual vehicle operating conditions. Case A and Case B represent moderate and severe climatic conditions respectively. Table 1 illustrates the detailed information about each test condition in the matrix. On the test bench, the compressor speeds for both compressors were set corresponding to engine speed as on the vehicle. There are five engine speeds from 750 rpm to 2500 rpm simulating vehicle idling to high cruising speeds. There are two ambient conditions for the compressor (70°C and 100°C) and the condenser (35°C and 45°C). Air flow rate across the condenser is related to vehicle speed. In stationary idling condition, the velocity was restricted to 1m/s whereas at cruising speed of 80 kmph, the velocity was set to 4 m/s. There are two conditions for the evaporator (27°C / 50% RH and 35°C / 60% RH). Air flow rate over the evaporator was set at 400m^3/hr. This typically is the air flow rate at the maximum blower speed on a small car. In the bench test, cooling capacity, air discharge temperature at the outlet of evaporator, power consumption, AC system pressures and COP have been evaluated across engine speeds.

Table 1. Test matrix

Parameter	Unit	Case A (Moderate Test Condition)					Case B (Severe Test Condition)				
Engine Speed	rpm	750	850	1500	2000	2500	750	850	1500	2000	2500
Vehicle Speed	kmph	Idle	Idle	Idle	40	80	Idle	Idle	Idle	40	80
Condenser inlet air velocity	m/s	1.0	1.0	1.0	2.5	4.0	1.0	1.0	1.0	2.5	4.0
Condenser inlet air temperature	°C	35					45				
Evaporator inlet air temperature	°C	27					35				
Evaporator inlet air RH	%	50					60				
Evaporator inlet air flow rate	m^3/hr	400					400				
Compressor ambient temperature	°C	70					100				

3.3 Vehicle Test

A small car was tested on a chassis dynamometer with the reciprocating and scroll compressors. The tests were conducted under identical test conditions to evaluate the load from AC system. The test was done at five vehicle speeds, in 5th gear and full throttle condition. To ensure that the AC system is fully loaded and the compressor works continuously during the test, the windows were kept open and the anti-icing device was bypassed.

4. EXPERIMENTAL RESULTS

4.1 Compressor Calorimetric Test

Figure 2 shows comparative performance of the two compressors. Cooling capacity of scroll compressor is 7.7% lower than reciprocating compressor at low engine idling speeds. A crossover in cooling capacity takes place at 1375 rpm. Above 1375 rpm the cooling capacity of scroll compressor is 1.5 to 10.8% higher than reciprocating compressor. Power consumption is 4.9 to 18.8% lower across the full range of engine speeds. Volumetric efficiency of the scroll compressor ranges from 89 to 94% (increasing trend) and that of the reciprocating compressor ranges from 66 to 58% (decreasing trend) across the full range of engine speeds.

4.1.1 Fitting equations to calorimetric data: During the present work, the performance of both the compressors was evaluated at three different engine speeds on a compressor calorimeter. In order to facilitate the process of simulation and optimization, a mathematical statement from the calorimetric test data has been developed through curve fitting using MATLAB (Release 12) software. A linear equation in one independent variable (engine speed)

for cooling capacity and power consumption and; a second degree polynomial equation for volumetric efficiency have been obtained. Compressor cooling capacity, power consumption and volumetric efficiency are expressed as a function of engine speed, where cooling capacity and power consumption are in kW, volumetric efficiency is in % and engine speed is in rpm.
Cooling capacity of the reciprocating compressor is given by

$$Q_r = 0.00191 N_e + 0.44926 \tag{1}$$

Cooling capacity of the scroll compressor is given by

$$Q_s = 0.00234 N_e - 0.10432 \tag{2}$$

Power consumption of reciprocating compressor is given by

$$P_r = 0.00143 N_e - 0.20782 \tag{3}$$

Power consumption of scroll compressor is given by

$$P_s = 0.00108 N_e + 0.0447 \tag{4}$$

Volumetric efficiency of reciprocating compressor is given by

$$\eta_{vr} = -0.000002 N_e^{\ 2} + 0.001168 N_e + 66.250000 \tag{5}$$

Volumetric efficiency of scroll compressor is given by

$$\eta_{vs} = -0.000004 N_e^{\ 2} + 0.017308 N_e + 77.387500 \tag{6}$$

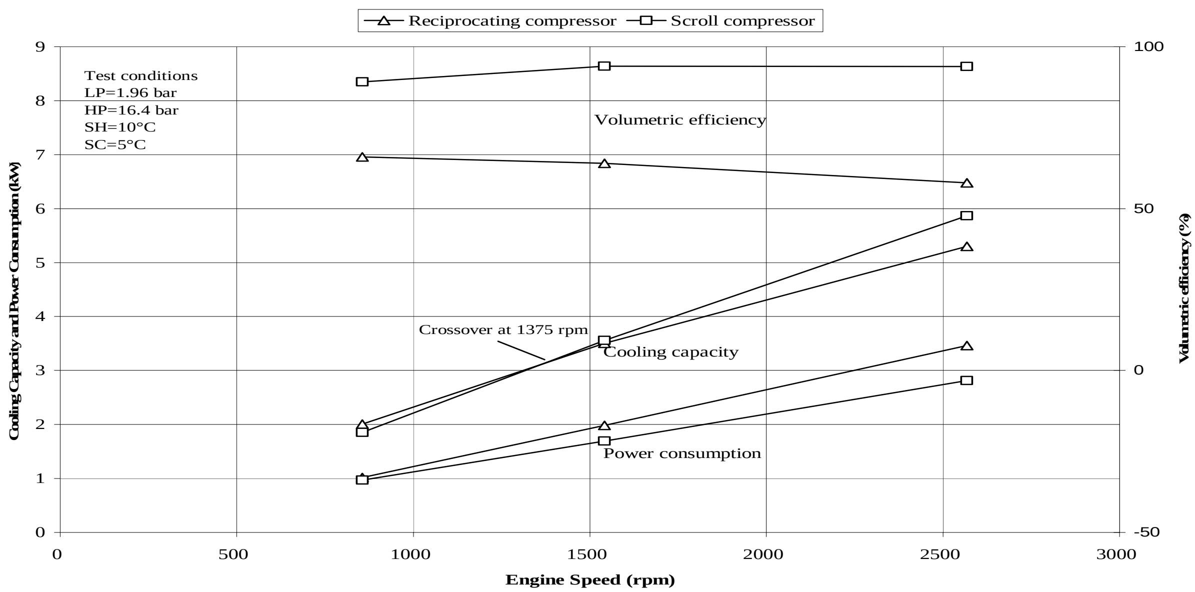

Figure 2: Compressor calorimetric test

4.2 Bench Test

These tests were conducted on an experimental AC system test bench with reciprocating and scroll compressors, under two sets of test conditions; moderate (Case A) and severe (Case B), as shown in Table 1. The test results are summarized in the following sections.

4.2.1 Refrigerant charge: The layout of the refrigerant circuit was modified with respect to the original one due to space limitations. Actual refrigerant inventory of a small car air conditioning system considered in the present study is of the order of 700 g of refrigerant R134a. Since the liquid and suction lines in the experimental set up were slightly longer than the original, the corresponding refrigerant charge is higher. Charge determination test was carried out using the charge criterion – maximum COP and cooling capacity and in addition, 5 – 10 K sub-cooling at the condenser exit. The refrigerant charge determined by this method is 920 g for a reciprocating compressor and 960 g for a scroll compressor.

4.2.2 Cooling capacity: Figure 3 shows the cooling capacity of reciprocating and scroll compressor across engine speeds. Cooling capacity of both compressors is higher under the severe test condition. This is due to a higher enthalpy difference between inlet and outlet air across evaporator. Cooling capacity of scroll compressor is 8.6 to 11.6% lower than reciprocating compressor at low engine idling speeds, considering both test conditions. A crossover in cooling capacity takes place at 1375 rpm after which, the cooling capacity of scroll compressor is 1.9 to 5% higher than reciprocating compressor. The cross over engine speed remains the same for both bench test conditions and compressor calorimetric test.

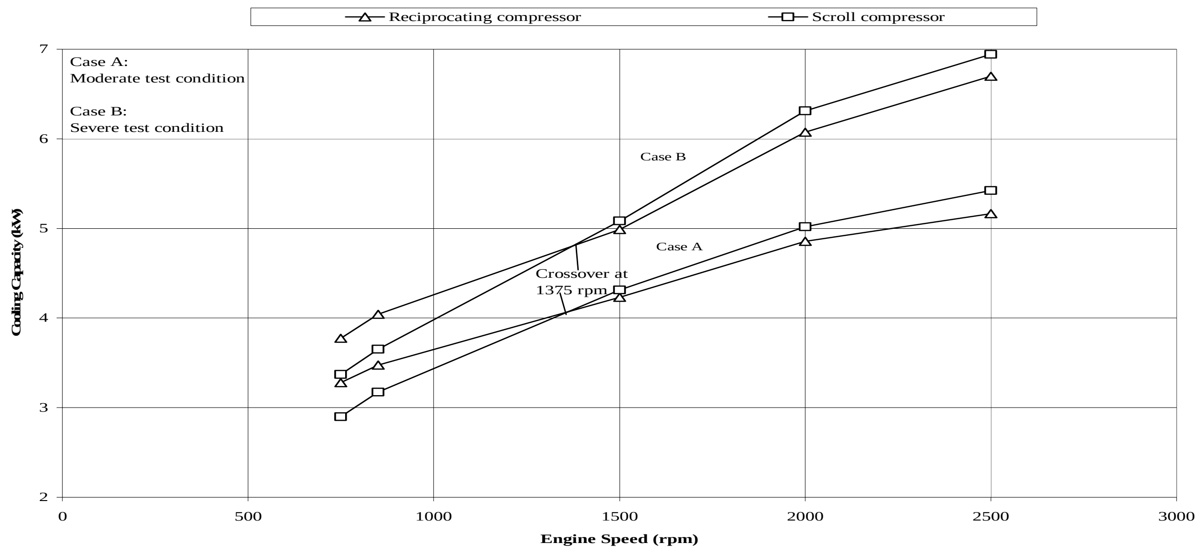

Figure 3: Cooling capacity

4.2.3 Air discharge temperature: Figure 4 shows the air discharge temperature across engine speeds, measured at the outlet of evaporator. The air discharge temperature with both compressors is higher under the severe test condition. This is due to application of a higher thermal load on the AC system. Air discharge temperatures are 0.8 to 1.1°C higher with scroll compressor at low engine idling speeds. A cross over in air discharge temperature takes place at 1250 rpm after which, the air discharge temperature with scroll compressor is 0.6 to 1°C lower than reciprocating compressor; considering both test conditions. The cross over engine speed remains the same for both bench test conditions.

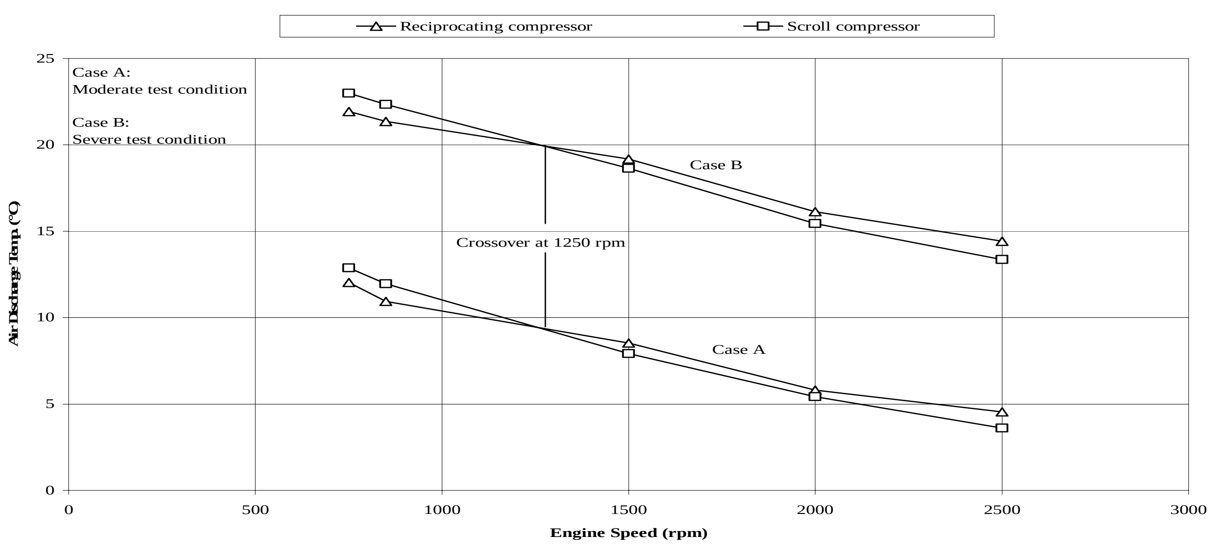

Figure 4: Air discharge temperature

4.2.4 Power consumption: Figure 5 shows the power consumption of reciprocating and scroll compressor across engine speeds. Power consumption of both compressors is higher under the severe test condition due to a higher compression ratio. Power consumption of scroll compressor is 15.6 to 25.3% lower than reciprocating compressor across full range of engine speeds, considering both test conditions. A similar trend was observed in compressor calorimetric test.

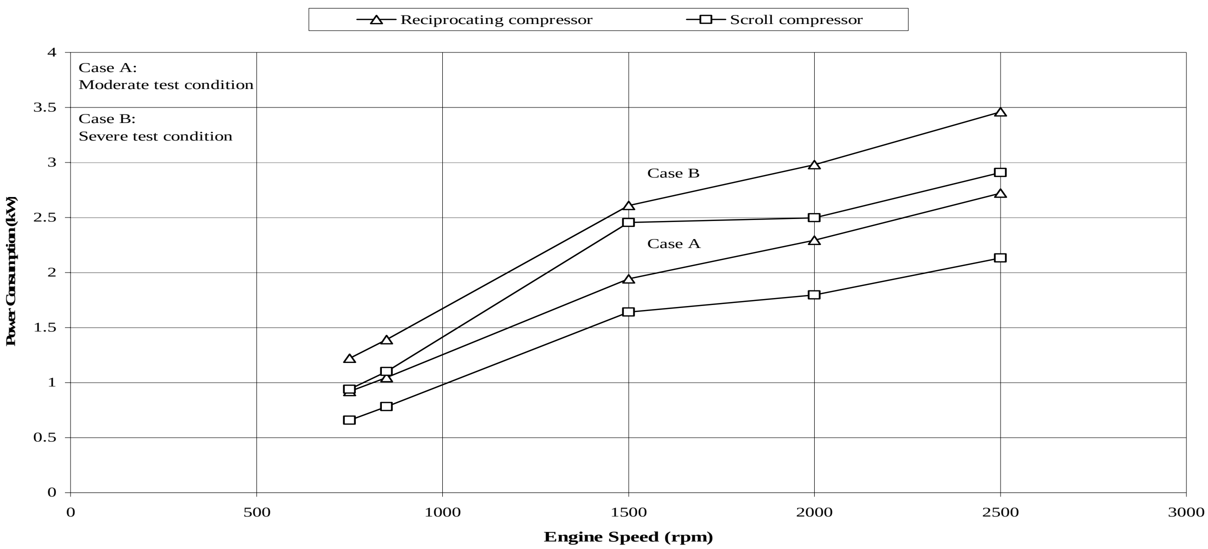

Figure 5: Power consumption

4.2.5 Pressure variation: Figure 6 shows the AC system pressure (low and high side) of reciprocating and scroll compressor across engine speeds. Compression ratio is higher under severe test condition for both compressors. High side pressures of the compressors are identical beyond 1500 rpm under both test conditions. Low side pressures of the compressors are identical across full range of engine speeds. Compression ratio being the same for both compressors beyond 1500 rpm, the lower power consumption of scroll compressor can be attributed solely to its internal construction and compression mechanism.

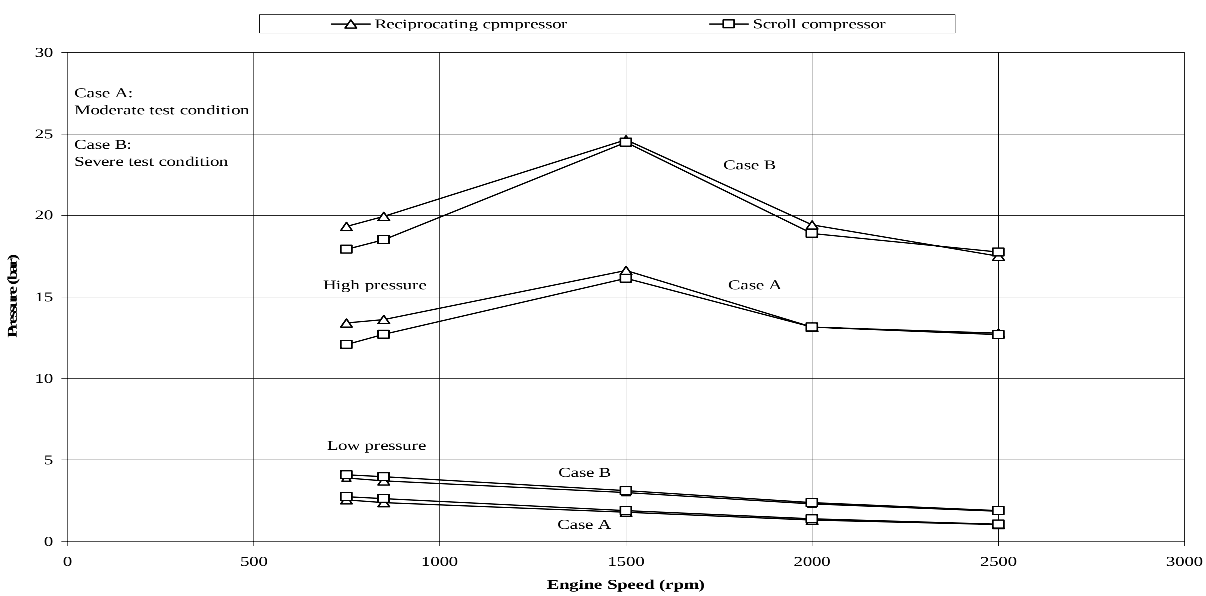

Figure 6: System pressure

4.2.6 COP: Figure 7 shows the COP of reciprocating and scroll compressor across engine speeds. COP shows a decreasing trend with increase in speed as the rate of increase in compressor work is more than corresponding rate of increase in cooling capacity. COP of scroll compressor is 14.1 to 31.9% higher than reciprocating compressor across full range of engine speeds, considering both test conditions. This indicates that the scroll compressor is an energy efficient machine.

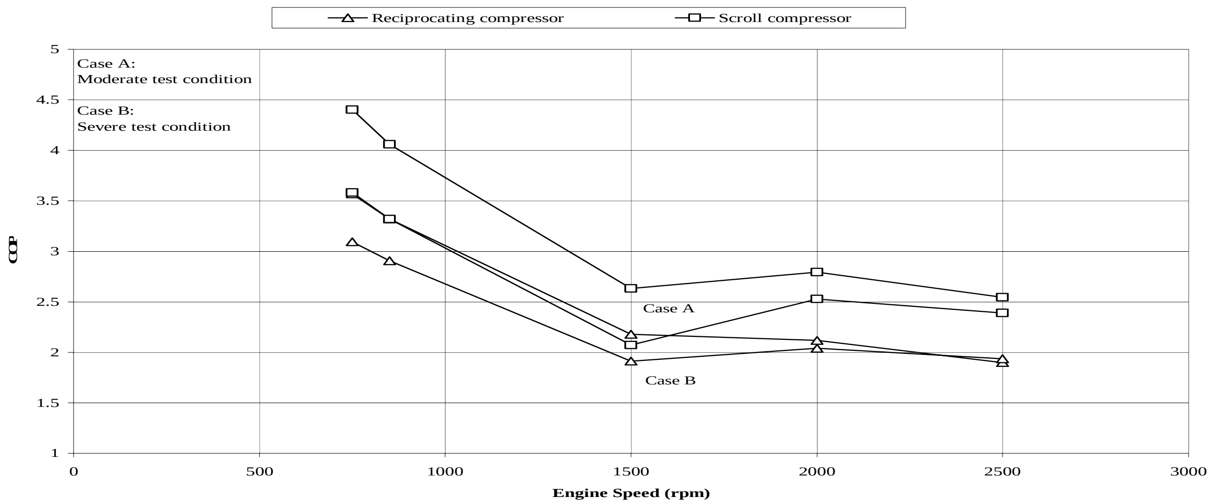

Figure 7: COP

4.3 Vehicle Test

Figure 8 shows the AC system power consumption across vehicle speeds with reciprocating and scroll compressor. Test results demonstrate that, load on engine from AC system reduces by 11.8 to 20% with use of scroll compressor.

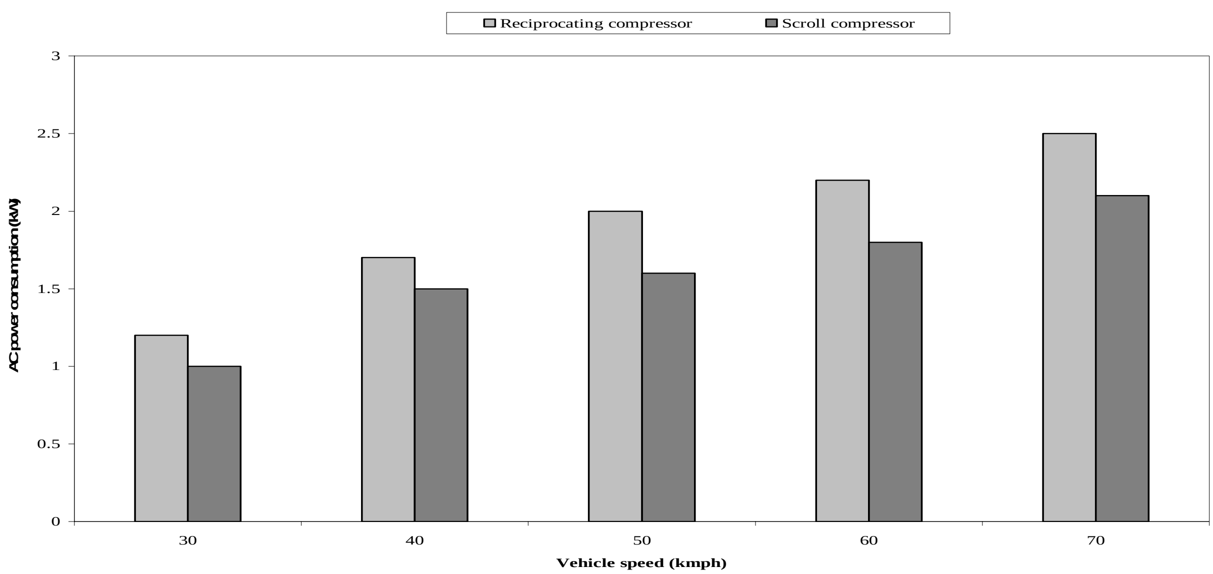

Figure 8: Chassis dynamometer test

5. CONCLUSIONS

The main focus of the present work was to critically assess the comparative performance of two compressors with different displacement, internal construction and compression mechanism. A methodical approach through experimental evaluation on calorimeter, test bench and on the car has been followed to realize this objective. The results obtained by this approach show that a 60 cc/rev scroll compressor performs better than a 110 cc/rev reciprocating compressor except at low engine idling speeds, as seen from the following:

- Cooling capacity is higher up to 10.8% in calorimetric test and up to 5% in bench test.
- Air discharge temperatures are lower by 0.6 to 1.0°C in bench test.
- Power consumption is lower up to 18.8% in calorimetric test and up to 25.3% in bench test
- Reduction in power consumption up to 20% on chassis dynamometer.
- COP is higher up to 36.5% in calorimetric test and up to 31.9% in bench test.

The compact, lightweight scroll compressor demonstrates high energy saving capability, and higher volumetric efficiency. In addition, it offers the added benefits of low noise, higher continuous speeds and improved drivability due to compressor on – off jerk not being felt. Future work can consist of applying this methodology for evaluating the suitability of any type of compressor for climate control systems on medium and big sized cars.

NOMENCLATURE

N_e	Engine speed	rpm
P_r	Power consumption of reciprocating compressor	kW
P_s	Power consumption of scroll compressor	kW
Q_r	Cooling capacity of reciprocating compressor	kW
Q_s	Cooling capacity of scroll compressor	kW
η_{vr}	Volumetric efficiency of reciprocating compressor	%
η_{vs}	Volumetric efficiency of scroll compressor	%

ABBREVIATIONS

AC	Air Conditioning
COP	Coefficient of Performance
HP	High pressure
LP	Low pressure
RH	Relative Humidity
SC	Sub cooling
SH	Superheating

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