2004

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Perevozchikov, Michael M. and Pham, Hung M., "Scroll Compressor for Mobile HVAC/R Application" (2004). *International Compressor Engineering Conference.* Paper 1656.
https://docs.lib.purdue.edu/icec/1656

SCROLL COMPRESSOR FOR MOBILE HVAC/R APPLICATION

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ABSTRACT

Comfort or food preservation and performance are always the primary emphasis for the mobile industry, but today protection of the environment is becoming increasingly important. This has driven interest in electric hybrid system with low refrigerant leakage and more efficient A/C and refrigeration components. To serve this market need, a compact/low weight and highly efficient hermetic variable speed scroll compressor has been developed using comprehensive simulation models. The new compressor embodies several design features like a high efficiency brushless permanent magnet motor with a 1600-5800 rpm speed range controlled by an inverter-drive, asymmetric scroll with vapor injection, and oil pump for low speed oil management. The developed scroll compressor is highly efficient across a wide speed and pressure ratio range, and proven reliable under off design operating conditions and can operate at 45 deg tilt. In addition to the above advantages, the compressor operation is independent of engine speed and can match load requirements, thus minimizing power consumption. Included below is a review of the compressor design features in terms of efficiency, durability and controls as well as system performance.

1. INTRODUCTION

Today the mobile industry is using belt driven compressor for A/C system which means compressor speed is a function of the engine speed. Therefore, the engine has to run when a/c system is needed. When the vehicle is not moving, the engine needs to be left idling for long period of time consuming power and operating at less than optimum conditions. There are different types of open drive compressors in use today, but they all have something in common. First, they need additional mechanical parts like magnetic clutch, belts to connect to pulley, and these components have to be as reliable as the compressor. Second, the displacement is typically oversized in order to compensate for refrigeration capacity loss due to low volumetric efficiency and high 4-6% oil circulation, and to insure adequate cooling capacity at engine idling condition. Another inherent drawback shared by all open drive compressors is high refrigerant leakage. In spite of significantly improved shaft seal and flexible hoses technology during recent years, the refrigerant leak is still high enough causing some environmental groups to push for HFC phase out in favor of CO_2 or flammable hydrocarbons. In response to the environmental regulation to reduce emissions causing the greenhouse effect, the industry is already taking steps towards developing hybrid, electric vehicles with low leak packaged A/C system. The greenhouse effect can also be reduced by using hermetic compressor which eliminates compressor refrigerant leakage and by reduction of fuel consumption which, from A/C system point of view, means using high efficiency compressor independent of speed of engine.

2. ELECTRIC VARIABLE SPEED COMPRESSOR

2.1 Compressor Design

Today the compressor performance for mobile applications is judged by satisfying demand for quick pull down of compartment temperature. Therefore, compressors are designed to have large displacement to get enough cooling capacity. High overall isentropic and volumetric efficiencies were not a primary concern for designers. Low volumetric efficiency was easy to fix by using a large compressor and the corresponding large power consumption was not seen as a problem in the past. The same approach can not be used today when hybrid or all-electric vehicles are considered and when the power on board is limited.

To comply with environmental regulations and support maximum comfort or food preservation an electrically driven, high efficiently hermetic variable speed compressor has been developed. Figure 1 shows the dimensions and

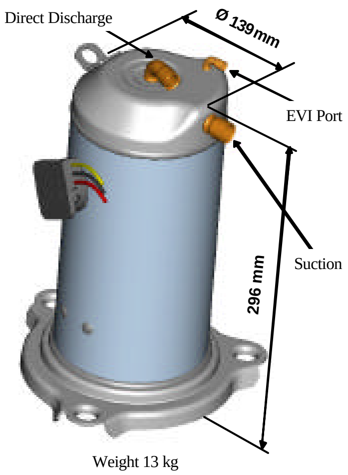

Figure 1: Hermetic Mobile Scroll compressor

weight for this new variable speed compressor which can be used to reach most system refrigeration capacity requirement by running up to 5800 rpm. The compactness and low weight were achieved by using a reduced displacement scroll driven at higher speed by a compact brushless permanent magnet (BPM) variable speed motor. The asymmetric scroll design helps reduce the scroll elements size at equivalent displacement and also increase volumetric efficiency by reducing suction gas preheat. Implementation of direct discharge eliminates the discharge plenum, decreasing suction gas preheat. The economized vapor injection (EVI) was applied to increase efficiency at full capacity and to further downsize the compressor by providing mechanical subcooling. In addition to performance gain, the compressor operating envelope is improved due to discharge temperature reduction from vapor injection. A centrifugal variable speed oil pump was used to insure proper oil delivery at low speed. In addition, the compressor is capable to run at 45° tilt while maintaining low oil circulation.

2.2 Economized Vapor Injection

The economized vapor-injection (EVI) cycle is well known and was available for staged or screw compressors in the past. The nature of the scroll compression process with intermediate compression pockets makes it possible to apply EVI to a single scroll compressor to increase capacity and efficiency. Figure 2 depicts the refrigerant flow schematic of this scroll compressor with EVI for typical operation condition of 35°F(1.7°C) evaporator and 153°F(67.2°C) condenser temperatures. A portion of the condenser liquid is expanding through the thermostatic expansion valve (TXV) into a counter flow brazed-plate heat exchanger (HX). The superheated vapor is then injected into an intermediate pocket of the scroll compressor via the injection port. The remaining portion of the condenser liquid is subcooled from a typical liquid temperature of 140°F(60°C) to 90°F(32.2°C) which is well below ambient and increases evaporator capacity by reducing inlet enthalpy. In this fashion, the required scroll displacement can be downsized by the percentage enthalpy gain thus providing higher compressor efficiency than a normal compressor sized for the same capacity. In other words, the added capacity from subcooling is achieved with less power since the incremental vapor used for the subcooling process is compressed from a higher intermediate pressure rather than from the lower suction pressure. In addition, the injected vapor improves the compression acting to increase the scroll built-in volume ratio and reduce the power loss due to back flow and by reducing preheat loss.

Thermodynamic and dynamic simulations of compressor were conducted to analyze compressor performance with vapor injection. The scroll parameters such as built-in volume ratio and discharge port have been optimized to satisfy EVI operation. The size and location of the injection port have been defined for best performance. It has to be noted that the asymmetric scroll profile helps further optimize EVI and reduce power losses associated with injection line pressure pulsation, and also simplifying the manufacturing of the injection path.

All key components such as vapor-injected compressor, HX, TXV, injection line and flow controls have been coupled together and sized for optimum cycle performance and cost. The practical HX and TXV sizing approach as defined by Beeton and Pham (2003) were used. The iteration between compressor simulation model and HX model was used to find the optimum capacity gain and predict the overall compressor efficiency.

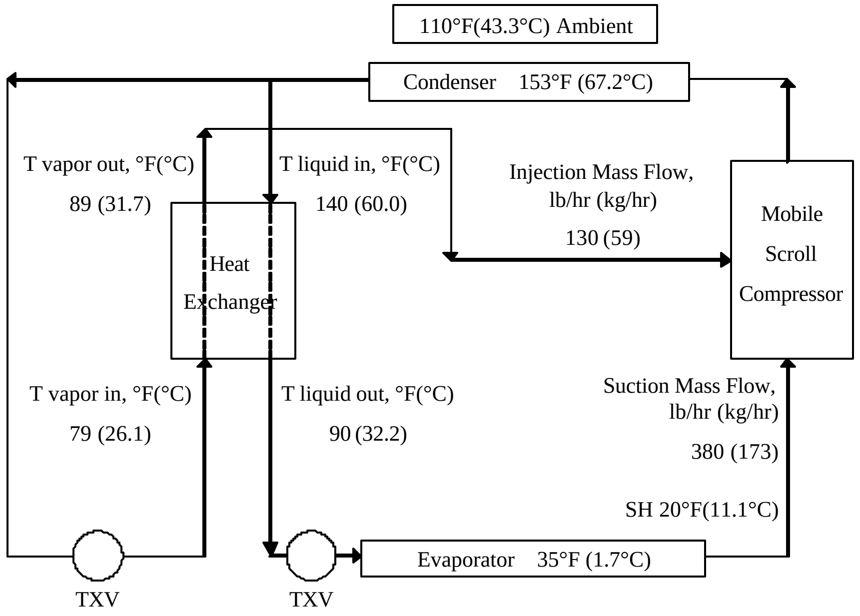

Figure 2: Economized vapor injection. Refrigerant flow schematic.

2.3 Compressor Performance

To predict the performance of the compressor, a comprehensive simulation model was used. The model is based on the conservation laws of mass, momentum and energy. The model prediction was found to be well correlated with test data. Figure 3 presents the capacity and power of a typical open drive compressor of comparable capacity versus this new scroll compressor as a function of speed at 35°F(1.7°C) evaporating temperature and 153°F(67.2°C) condenser temperature. The published data of a typical open drive compressor were used for comparison. It can be seen that the new compressor delivers a wide range of capacity with relatively lower power. To enable proper efficiency comparison each compressor is appropriately sized for equal capacity as illustrated in Figure 3. The overall isentropic and volumetric efficiencies for each compressor at these particular conditions are summarized in Table 1. The new variable speed compressor has up to 40% higher overall efficiency and significantly better volumetric efficiency which helps reduce its displacement significantly over open drive.

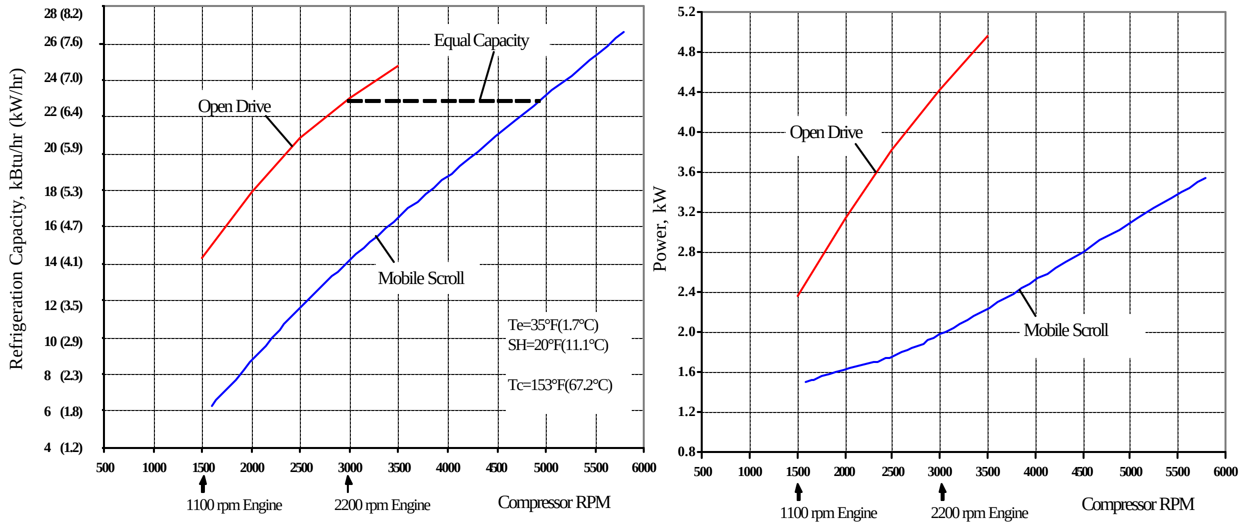

Figure 3: Performance of Mobile Scroll and Open Drive compressors

Table 1: Efficiency comparison

	Overall Isentropic Efficiency		Volumetric Efficiency	
Te/Tc, °F(°C)	Mobile Scroll	Open Drive	Mobile Scroll	Open Drive
	5000 rpm	3000 rpm	5000 rpm	3000 rpm
35°(1.7°)/153°(67.2°)	70%	50%	95%	50%
	3500 rpm	1500 rpm	3500 rpm	1500 rpm
35°(1.7°)/130°(54.4°)	70%	58%	95%	66%

When sized for equal full load capacity, Figure 4 shows flatter capacity slope for mobile scroll versus open drive at lower condenser temperature and load, thus less cycling loss. In addition, the better capacity slope also delivers more capacity at max-load condition where it is needed most for faster pull down.

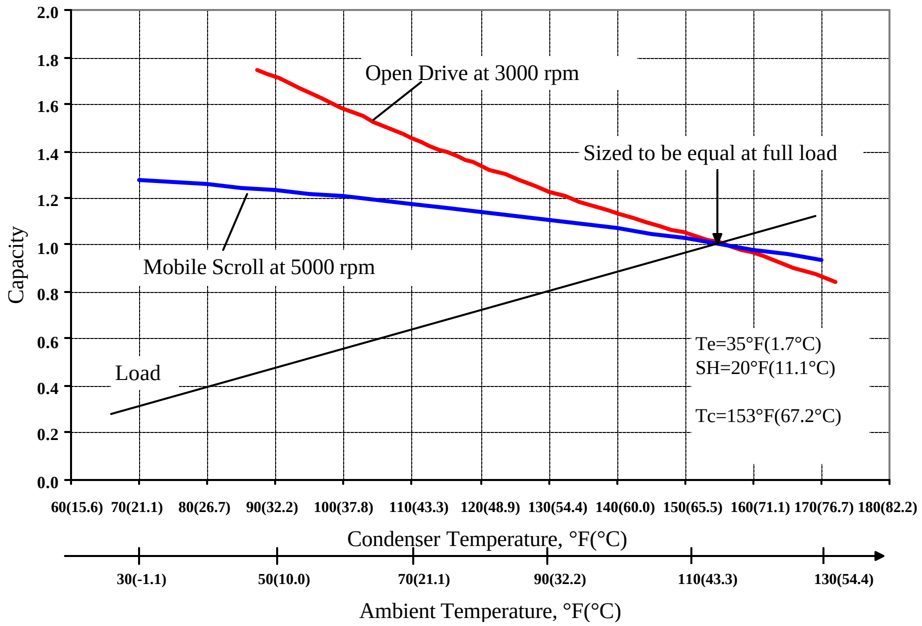

Figure 4: Capacity vs. Load

In addition it has to be noted that new compressor has very low, less then 1%, oil circulation even at 5800 rpm and max load conditions. The open drive compressor typically has 4-5% oil circulation thus about 4-5% capacity loss due to worse heat transfer and pressure drop and the oil heat effect. The efficiency penalty for 1% oil circulation is almost negligible.

It also has to be stated that developed compressor is more reliable due to: scroll durability and reliability 20,000 plus hours life vs. traditional belt-driven open drives with 2,000-3,000 hr life; elimination of mechanical components such as suction line accumulator, oil separator, clutches, belts and pulleys; reliable oil management over wide speed range.

3. SYSTEM APPLICATION BENEFITS

While this compressor can be potentially used in any application where a wide load range is expected, it has been designed to provide best overall environmental and fuel economy benefits when applied to the future hybrid or all-electric Mobile A/C and Refrigeration systems.

The key improvements of this new compressor are as follows: 1) the use of asymmetric scrolls with a BPM motor improves the compressor efficiency significantly over the traditional engine-driven open-drive counterparts. 2), the compact hermetic design results in a no-leak, low-charge packaged system using short copper lines, which enables continued use of an enhanced system operating with HFC refrigerant R134a providing altogether lower LCCP (Life-cycle-climate Performance). 3) its 5800 rpm high-speed capability coupled with economized vapor injection (EVI) insures a compact and light weight compressor, thus saving space and fuel consumption. Moreover, an inverter drive and protection control have been designed for high operation reliability and fault tolerance, but discussion of its design is outside the scope of this paper. 4) Lastly, its wide-speed and envelope capability not only provide faster pull-down but also improved temperature control at part-load.

Figure 5 shows an example of temperature pull down tests after the unit has been soaked at 110°F (43.3°C) ambient. As can be seen, the evaporator outlet air temperature is pulled down to less than 53°F (11.7°C) within less than 30 minutes, which corresponds typically to a cabin temperature of less than 75°F (24°C) in a full-cabin tests. This was readily achieved at high efficiency due to high-speed 5800-rpm operation with EVI sub cooling. Figure 6 shows the contributions of EVI during pull down (due to enhanced sub cooling) versus no EVI.

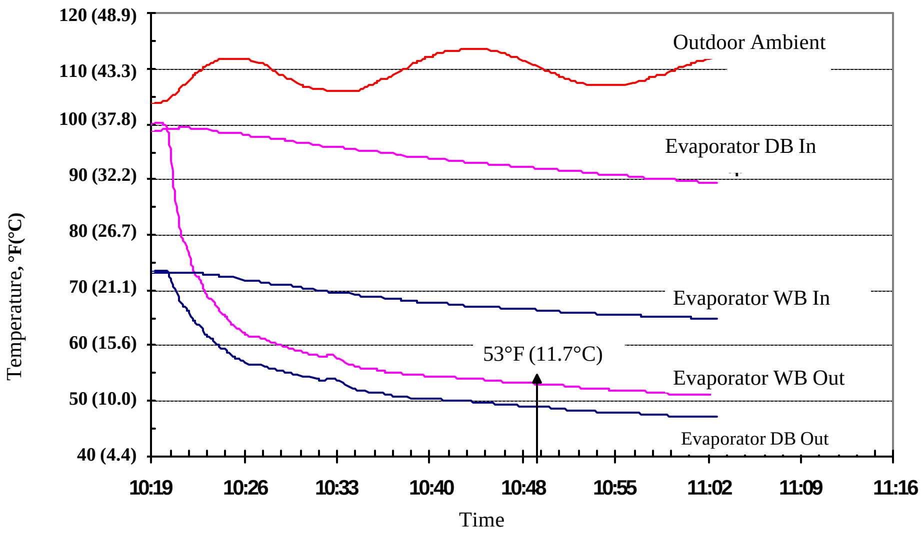

Figure 5: A/C System pull down test results at high speed

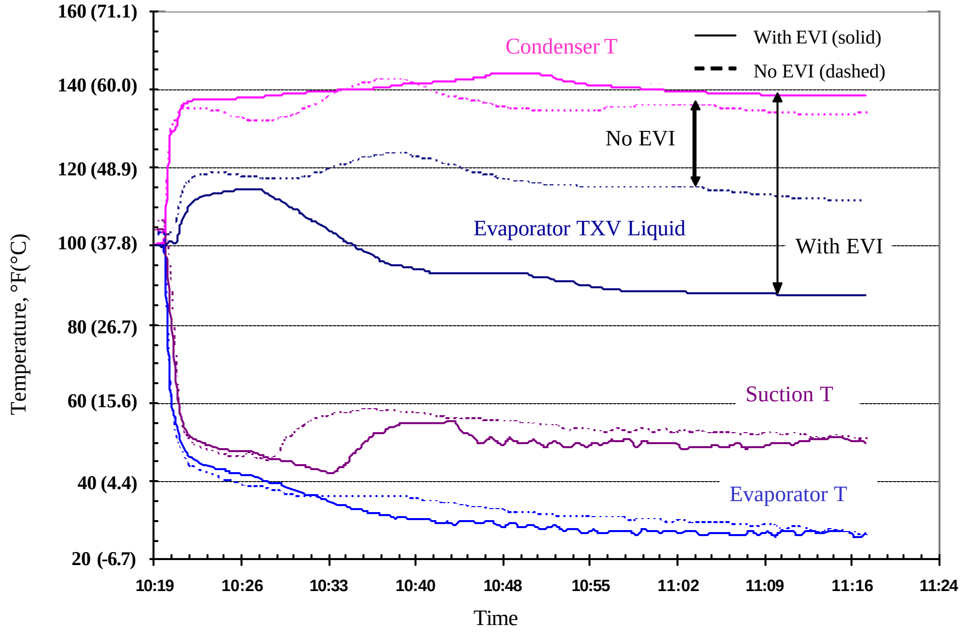

Figure 6: Subcooling gain during pull down. EVI vs. No EVI (4900 rpm, TXV-Evaporator)

In contrast to engine driven compressor, under normal or lower-ambient part-load conditions, the new compressor speed can be readily reduced independent of engine. In addition, the high volumetric efficiency of the asymmetric scroll and EVI provide flat capacity slope versus ambient resulting in improved load matching ability. Figure 7 illustrates the effect of being independent of speed versus the traditional engine-driven compressor at idle conditions. Assuming both compressors are sized to be equal maximum capacity at full-load pull down, then the scroll compressor can provide up to 50% higher capacity than the open-drive at engine-idling conditions.

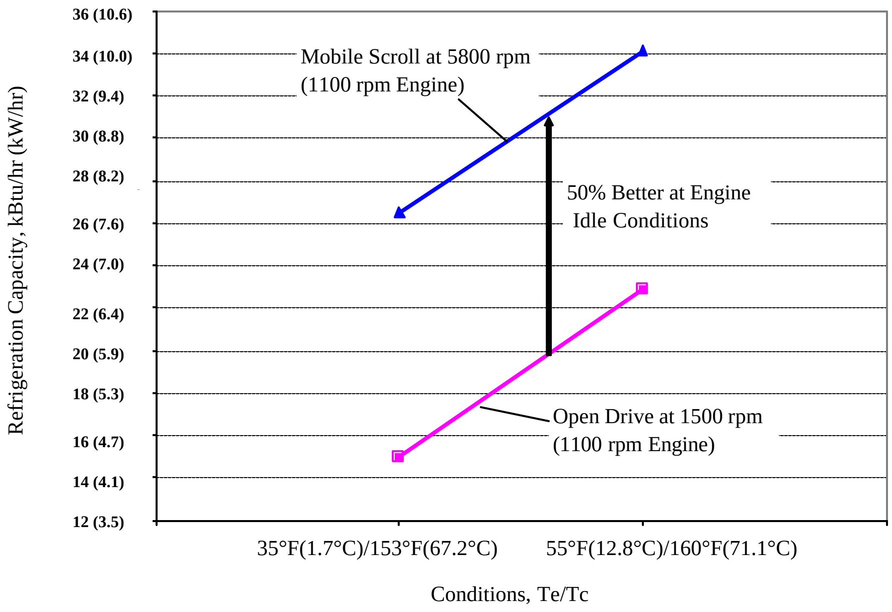

Figure 7: Pull down at engine idling conditions

Important design and application aspects should be considered for optimum system performance. First, to achieve best control of the variable-speed coupled with two-stage EVI operation, it is best to use individual TXV for both the evaporator and the EVI subcooler. Figure 8 illustrates the wide range of variable flow openings required for optimum system performance for various compressor speeds, evaporator fan air flows and outdoor/indoor ambient conditions.

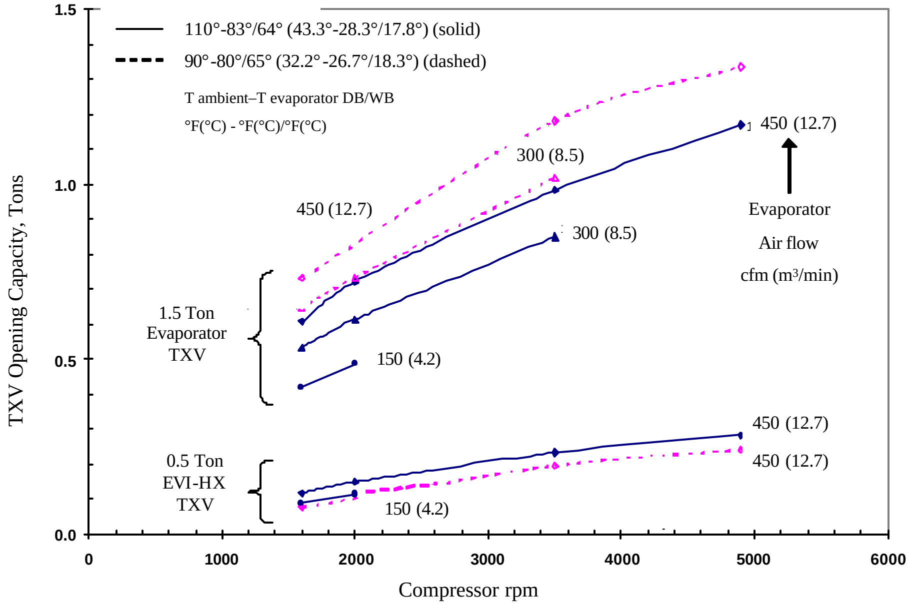

Figure 8: Variable-Speed and EVI 2-stage operation with TXV control

A TXV is better than a fixed-orifice tube in providing optimum efficiency and in controlling wide-ranging capacity modulation systems, and also to avoid over or under-injection performance. Since the compressor power is fairly low at low-speed part-load operation, the use of modulated fans is highly desirable for best part-load system efficiency as illustrated in Figure 9.

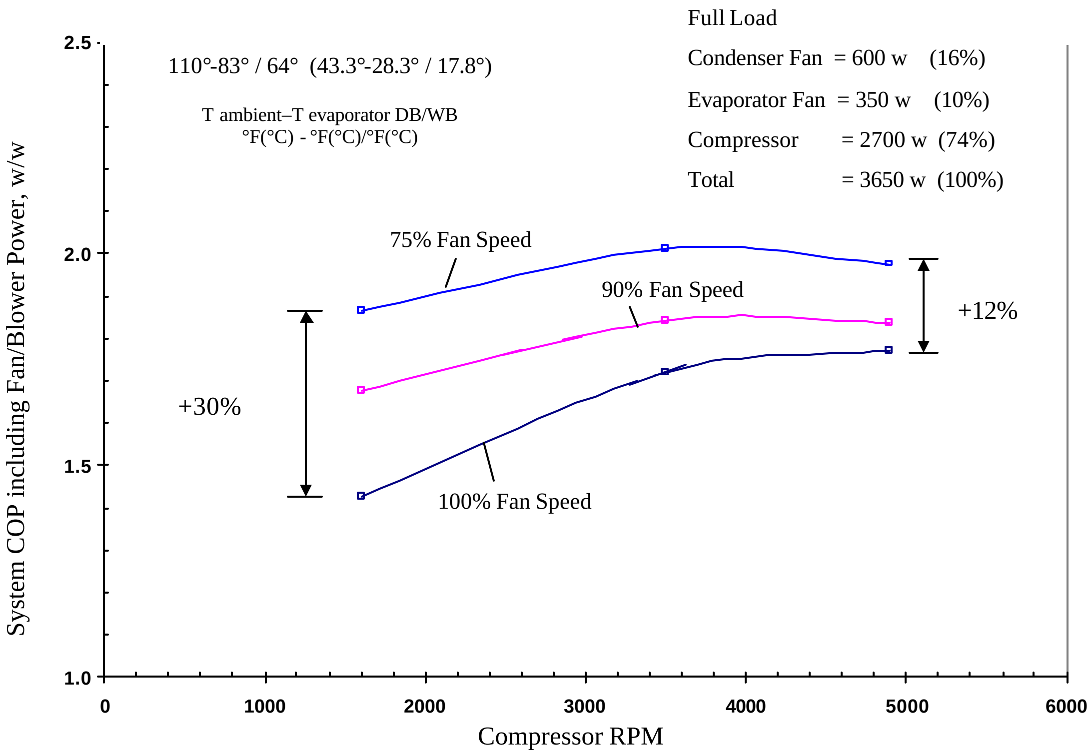

Figure 9: Optimizing condenser fan speed vs. compressor speed

Table 2 shows a representative comparison of steady-state system efficiency between an all-electric packaged system with this variable-speed scroll compressor versus a conventional system with the open-drive compressor at the same condition of 122°F(50°C) outdoor ambient. This variable-speed scroll compressor at 4900 rpm delivers about the same capacity as the baseline open-drive at 2978 rpm, but gives as much as 48% higher operating efficiency in the system. The contribution from the individual components is also shown, particularly the significant 11.1°F(6.1°C) higher in evaporating temperature due to elimination of the suction line accumulator, and 5.0°F(2.8°C) reduction in condensing temperature due to BPM motor and EVI.

Table 2: A/C System efficiency comparison Mobile Scroll vs. Open Drive at 122°F (50°C) outdoor ambient

	Contribution Effect	**Mobile Scroll**	**Open Drive**	**% Gain**
Compressor rpm		**4900**	**2978**	
Gross Evaporator Capacity, Btu/hr (w/hr)		**20071 (5882)**	**19368 (5676)**	**+3.6%**
Compressor Power,w		3224 (945)	4600 (1348)	-30%
Condenser Heat Rejection, Btu/hr (w/hr)		28397 (8323)	27699 (8118)	+2.5%
Compressor COP		**1.82**	**1.23**	**+48%**
Condenser In T	BPM motor and EVI	178° (81.1°)	187° (86.1°)	-9° (-5.0°)
Compressor Tc		153° (67.2°)	158° (70.0°)	-5° (-2.8°)
Compressor Te	Suction Pressure Drop	35° (1.7°)	24° (-4.4°)	+11° (+6.1°)
Evaporator Te		40° (4.4°)	37° (2.8°)	+3° (+1.7°)
Condenser SC	Effect of EVI	11° (-11.7°)	27° (-2.8°)	-16° (-8.9°)
Evaporator SC		56° (13.3°)	28° (-2.2°)	+28° (+15.6°)
Evaporator SH	TXV vs. Orifice	9° (-12.8°)	<0° (<-17.8°)	+9° (+5.0°)
Compressor SH		24° (-4.4°)	16° (-8.9°)	+8° (+4.4°)

4. CONCLUSIONS

A new compact variable-speed asymmetric scroll compressor with BPM motor and economized vapor injection has been developed for hybrid, or all electric, mobile A/C and Refrigeration applications. It has shown to deliver superior performance over conventional engine driven open-drive compressors in terms of efficiency, reliability, and lower oil circulation over a wide capacity range. The new scroll hermetic design is highly suitable for the new-generation of packaged electric hybrid mobile A/C system. Moreover, it is a no-leak design and features very high overall isentropic efficiency which enables continued use of HFC-134a refrigerant.

NOMENCLATURE

T	temperature	(°F/°C)
SH	super heat	(°F/°C)
DB	dry bulb	(°F/°C)
WB	wet bulb	(°F/°C)

Subscripts

e	evaporator
c	condenser

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ACKNOWLEDGEMENT

The authors would like to thank Mr. Roy Doepker and Mr. Wayne Warner at Copeland Corporation for their contribution to this project.