An Investigation of Liquid Injection in Refrigeration Screw Compressors

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Abstract

Screw compressors are regularly used in refrigeration and air conditioning. They have advantages over some other types of positive displacement compressors because they can be operated with liquid in their compression chambers, in such forms as dispersed droplets of oil and liquid refrigerant, in a two-phase mixture with the compressed vapour. They can also operate with injection of saturated or superheated vapour. This paper presents an analytical and numerical study and an experimental investigation of various combinations of injection fluids, including oil, liquid refrigerant and liquid-vapour mixtures and how they affect the compressor efficiency, noise and reliability.

Keywords*: Screw compressor, Liquid refrigerant injection, Economiser flow, Motor cooling*

1. INTRODUCTION

Screw compressors are becoming increasingly popular in refrigeration and air conditioning. They have several advantages over some other types of positive displacement compressors because they can be operated with liquid in their compression chambers, in such forms as dispersed droplets of oil and liquid refrigerant, or in a two-phase mixture with the compressed vapour. These are as follows:

Oil injection lubricates the rotors, seals the leakage gaps and cools the gas being compressed. As a consequence, the rotors may make direct contact and the compressor volumetric efficiency and, on occasion its adiabatic efficiency, will be increased.

If liquid refrigerant is injected, it will partially or fully perform in the same way as oil and lubricate the rotors and seal the gaps. Furthermore, it will be more effective than oil as a coolant since it may also evaporate during the compression process.

If refrigerant vapour is injected into the compressor chamber at an intermediate pressure, this will increase the compressor capacity and may improve its efficiency. This is well known as superfeed. If accompanied by superfeed, liquid injection may have enhanced effects. This opens new fields of investigation to be undertaken to get the maximum design advantage. For example superfeed vapour alone, or combined with the injection of high pressure liquid, may be used as the electric motor coolant in semihermetic compressors.

2. LIQUID INJECTION INTO THE COMPRESSOR WORKING CHAMBER

The ability of screw compressors to compress gases or vapours in the presence of liquids, which are incompressible, was realised very early and abundant quantities of oil for lubrication, sealing and cooling have been injected in them for almost fifty years. However, the injection of liquid refrigerant came later and, typically, was proposed by Shaw in 1988, when screw compressor clearances became small enough to reduce the amount of liquid required for sealing purposes. In the case of refrigeration compressors, the vapour isentropic exponent is low and hence the temperature during rise during compression is not large. However, in the case of air or other gases with a higher isentropic exponent more coolant is needed during compression.

2.1 Oil injection

The advantages of lubrication, sealing and cooling brought about by oil injection, greatly extended the range of applications of screw compressors. To some extent these were countered by the negative effect of greater frictional drag on the rotors, induced by the oil. Thus to avoid excessive power input, oil flooded compressors have to operate at far lower speeds than dry ones and therefore have to be larger machines.

It follows that oil flow in refrigeration compressors should be kept to the minimum needed for sealing requirements or by the amount required for bearing lubrication, for which the same oil is used, rather than for cooling.

2.2 Injection of liquid refrigerant

Liquid refrigerant may partially or fully meet the requirements for the sealing of screw compressors and even for the lubrication of their rotors and bearings. It has a far lower viscosity than oil and consequently the adverse effects of its injection are less than those of oil injection. Therefore, it may be found to be an alternative to oil injection.

If the liquid is injected after the suction is cut off, it will not affect the vapour suction flow and therefore the full capacity of the refrigeration plant will be retained. However, liquid injection will certainly increase the compressor power input and therefore will reduce the plant coefficient of performance (COP). This effect is dependant both on the liquid injection flow and pressure, the greater the flow and the lower its injection pressure, the larger will be the reduction in COP.

Apart from sealing and lubrication, liquid injection may be used for cooling the electric drive motor in semihermetic compressors in which case the liquid will evaporate due to heat transferred from the motor. In such a case the compressor power will increase not only because of the liquid drag, but also because of the additional vapour, thus formed, being compressed to the compressor discharge pressure.

All these effects can be quantified from performance calculations. Since some of the influences have opposite effects upon the compressor process, optimisation can be applied to determine the best working parameters.

2.3 Superfeed flow

Superfeed, as a means of increasing refrigeration plant capacity and efficiency, is a kind of fluid injection and therefore it is analysed here. Namely, vapour at an intermediate pressure, between the highest and lowest plant pressure, is separated from the liquid-vapour mixture, formed after partial throttling, and compressed by the compressor to the discharge pressure. This increases the amount of liquid entering the evaporator, without decreasing the compressor capacity. As a result, the refrigeration capacity is increased. To achieve this, the superfeed inlet must be after the compressor suction port is closed or the compressor capacity will be decreased. For the majority of refrigerants, the slope of the liquid saturation line in a pressure-enthalpy (p-h) diagram is substantially lower than the slope of the compression line. Hence, the rate of increase of plant refrigeration capacity due to superfeed is greater than the associated rate of increase of the compressor input power. Superfeed will, therefore, increase the plant COP.

Additionally, superfeed vapour may be used to cool the compressor motor. This will increase the compressor power input but it will not decrease the compressor capacity, which would be the case if suction vapour is used for motor cooling.

All these effects are quantified in performance calculations and presented in the diagrams of the following sections. From these, it may be noticed that the effect of superfeed is dependant on the pressure at which the superfeed vapour is injected into the compressor.

2.4 Combined superfeed and liquid injection

A combination of superfeed and liquid injection may be used in a compressor to replace the compressor oil or to enhance the motor cooling, if superfeed vapour only is not sufficient for this purpose. In such a case the influence of each type of injection and their combination should be analysed separately to determine the extent of their combined effect.

2.5 Compressor noise

It is well known that oil attenuates noise in a compressor. Therefore, any reduction in oil flow and its replacement by a less viscous fluid will increase the compressor noise.

However, another means of minimising compressor noise is to maintain a relatively large female rotor torque and thereby avoid its reversal during the compression cycle. Rotor contact is thereby made only on one pair of surfaces at all times, thus preventing what is commonly known as rotor rattle. Unfortunately, a high positive female torque is associated with reduced rotor displacement and relatively high contact forces. These cause low volumetric and adiabatic efficiencies and reduce the mechanical efficiency. An alternative approach is to aim for negative torque, which keeps the rotors in permanent contact, but on their flat side. In that case, low friction at the rotor tips will help maintain the negative torque since high viscosity oil, combined with high inertia forces, frequently raises the tip drag forces to a level that makes negative torque impossible to be achieved. Injection of liquid refrigerant, which has a lower viscosity, than oil will substantially decrease the drag force and, therefore, enable the female rotor torque to be always negative. Consequently, there will be no rattling and the compressor noise should be lower than in the case of oil injection, which is associated with female rotor torque reversal during rotation.

2.6 Compressor Reliability

Screw compressor bearings are designed for high pressure loads and must be properly lubricated to sustain them. This may not be possible if refrigerant is used to replace oil completely, because of the low viscosity of the refrigerant. However, if a residual amount of oil, of the order of 0.5-1% is retained in the refrigerant, the bearing lubrication would be substantially improved.

Since heat generated in the bearings will evaporate the liquid refrigerant, the oil will be left in the bearings. This will effectively make the bearings oil lubricated. If the bearing housings are designed to retain a certain amount of oil when the compressor is not in operation, this will ensure satisfactory bearing lubrication even during start up. It follows that compressor reliability should not be substantially affected by replacing the oil with liquid refrigerant This needs to be confirmed by long term laboratory and field testing.

More information on refrigeration screw compressors can be found in Stosic, 2004.

3. PERFORMANCE CALCULATION OF A COMPRESSOR WITH LIQUID INJECTION

The algorithm of the thermodynamic and flow processes used in performance calculations of a compressor subjected to liquid injection is based on a mathematical model comprising a set of differential equations of the conservation of mass and energy and algebraic equations of state and instantaneous compressor volume which fully describe the physics of all the processes within the screw compressor.

Leakage in a screw machine forms a substantial part of the total flow rate and plays an important role because it affects both the delivered mass flow rate and the compressor work and hence both the compressor volumetric and adiabatic efficiencies.

Injection of oil or other liquids for lubrication, cooling or sealing purposes, modifies the thermodynamic process in a screw compressor substantially. Special effects, such as gas or its condensate mixing and dissolving in or flashing out of the injected fluid must be accounted for separately if they are expected to affect the process.

NIST (National Institute for Standards and Technology) property routines, which include virtually all known pure refrigerants and their mixtures, are readily available and with them, compressor performance can be calculated for practically all existing fluids and even for hypothetical refrigeration fluids. Premixed fluid mixtures are also provided and, moreover, working fluids can be arbitrarily mixed to create new customised mixtures of refrigeration fluids.

Using these property routines, the set of algebraic and differential equations involved is performed numerically by means of the Runge-Kutta 4th order method, with appropriate initial and boundary conditions. The initial conditions are arbitrarily selected and convergence of the solution is achieved after the difference between two consecutive compressor cycles becomes sufficiently small. Once solved, the fluid pressure and temperature within the compressor working chamber are derived directly from the estimated internal energy and mass. Indicated work, power, specific power and volumetric and adiabatic efficiencies are then readily determined. A full and detailed description of the thermodynamic and fluid mechanics model used is given in Hanjalic and Stosic, 1997.

4. EXPERIMENTAL INVESTIGATION

A refrigeration screw compressor was tested at City University compressor laboratory to confirm the influence of liquid injection. This has a 5/6 lobe configuration with a main rotor outer diameter of 106 mm and an L/D ratio of 1.55 and it is shown, as installed in the test rig in the right hand photograph of Fig 1 and in close up on the left hand photograph, where the liquid supply pipe for cooling the compressor motor can be identified. A schematic diagram of the refrigeration fluid gas rig is also included. This test rig contains only one heat exchanger, for partial condensation of the refrigerant, and no evaporator. Refrigerant vapour is compressed to the discharge pressure by the compressor and the oil is separated either within the compressor itself if it is integrated with the oil separator, or in an externally located separator, which is a part of the test rig. After that, the discharge gas is divided into two streams, one of which goes to the cooler where it is cooled, partially condensed and throttled down to the suction pressure. This is then mixed with the second stream, which is separately throttled to the suction pressure. By this means, only the heat generated by the compressor motor is rejected in the condenser and the test rig is kept compact. Moreover, such a test rig is far more flexible and controllable than a full refrigeration plant and enables testing to be performed over a wider range of suction and discharge pressures.

The compressor delivery is measured at the compressor suction by an orifice plate. For that purpose the orifice pressure drop is measured, as well as the orifice pressure and temperature. Suction and discharge flange pressures and temperatures are also measured. Compressor motor power was estimated by use of current and voltage measured on the variable frequency converter, which takes account of all electrical losses. Specific power was calculated as a ratio of the compressor power and flow.

The refrigeration capacity was then estimated for an equivalent whole plant operating between the same suction and discharge pressures. The coefficient of performance, C.O.P. is thereby calculated as the ratio of the plant refrigeration capacity to compressor motor power. The measured performance is then incorporated in diagrams of the same type as used for predicted performance and this simplifies comparison between measured and predicted performance.

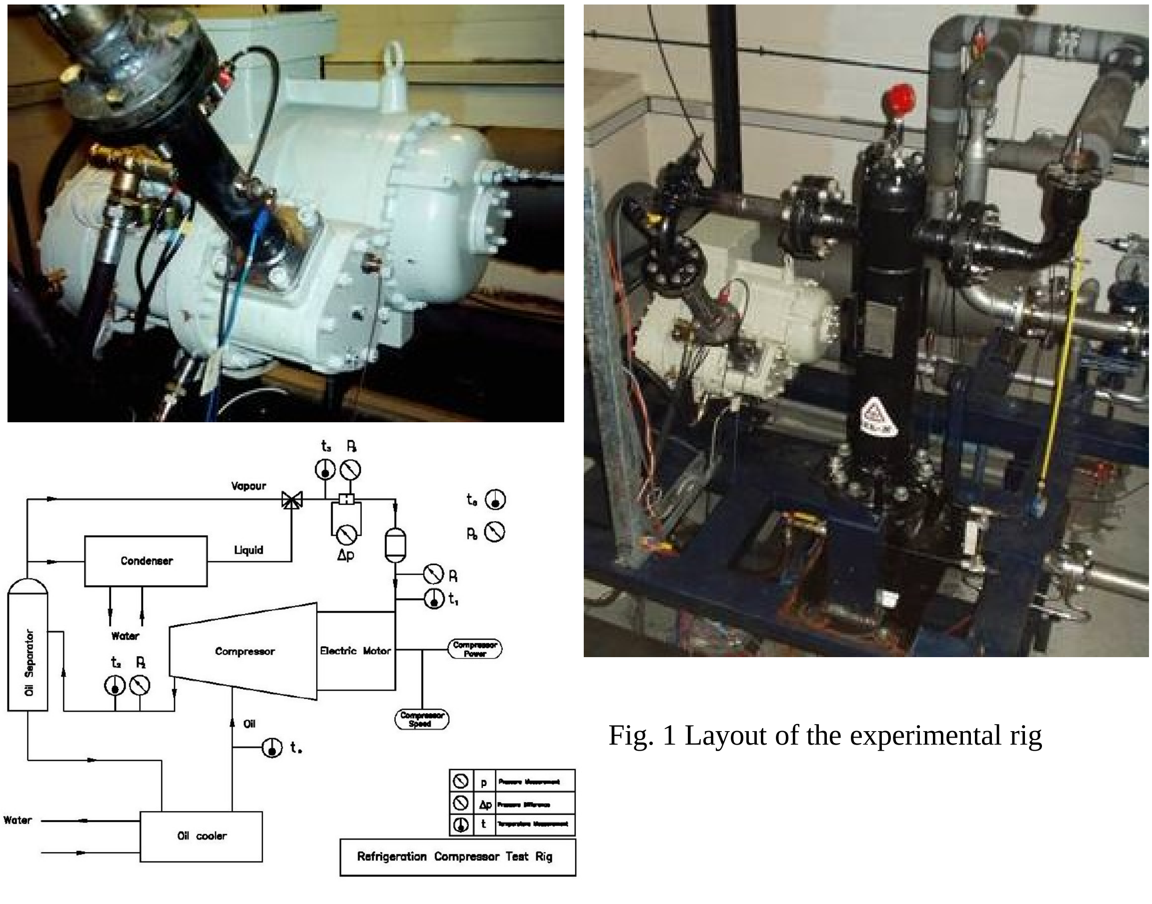

Fig. 1 Layout of the experimental rig

5. PRESENTATION AND DISCUSSION OF RESULTS

The effect of liquid injection varies with the choice of refrigerant, the screw compressor design and its operating duty. Three refrigerants, most commonly used today are presented here. These are R-134A which is currently very popular, R-407C which is a mixture designed with a temperature glide, as a replacement for R-22, and R-717 (ammonia) which, due to its widely accepted favourable features, still retains its popularity.

Performance calculations and experimental tests were performed at the compressor's normal motor operating speed of 2960 rpm. The oil was injected through a 15 nozzle port and adjusted itself with the actual pressure difference between the discharge and the oil injection point pressure.

The compressor duty was determined at evaporation temperatures of between -15 and 5°C, while the condensation temperature was kept constant at 40°C for all cases.

Superfeed pressure was retained at a pressure corresponding to a saturation temperature of 30°C in all cases and this was also the pressure of liquid injection.

The study produced a large number of results for various combinations of fluid injection. Only a limited number of these could be presented within the space allowed for this paper.

Experimental results for liquid injection were obtained for R-134A only and are included in the diagrams together with the calculated results for that fluid.

5.1 R-134A results

The effect of superfeed flow at 30 °C is presented in Fig. 2 where the refrigeration capacity and coefficient of performance are given in the left and right hand graphs respectively, as a function of the evaporation temperature. As can be seen, the increase in refrigeration capacity it induces is clearly detectable but the COP increases thus induced are barely detectable and only at the lowest evaporation temperatures.

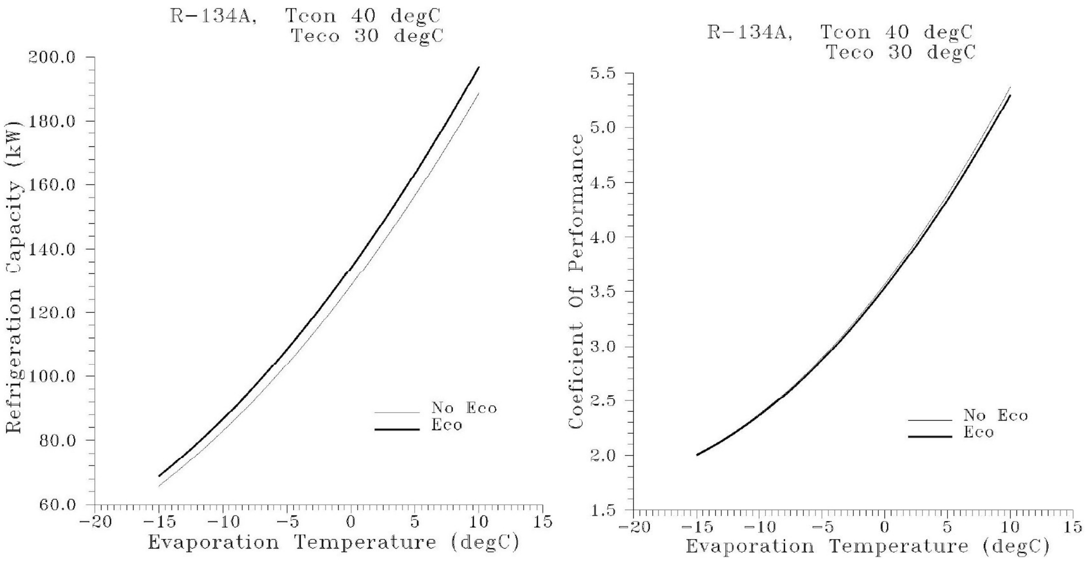

Fig. 2 Predicted refrigeration capacity and coefficient of performance for economizer flow, R-134A

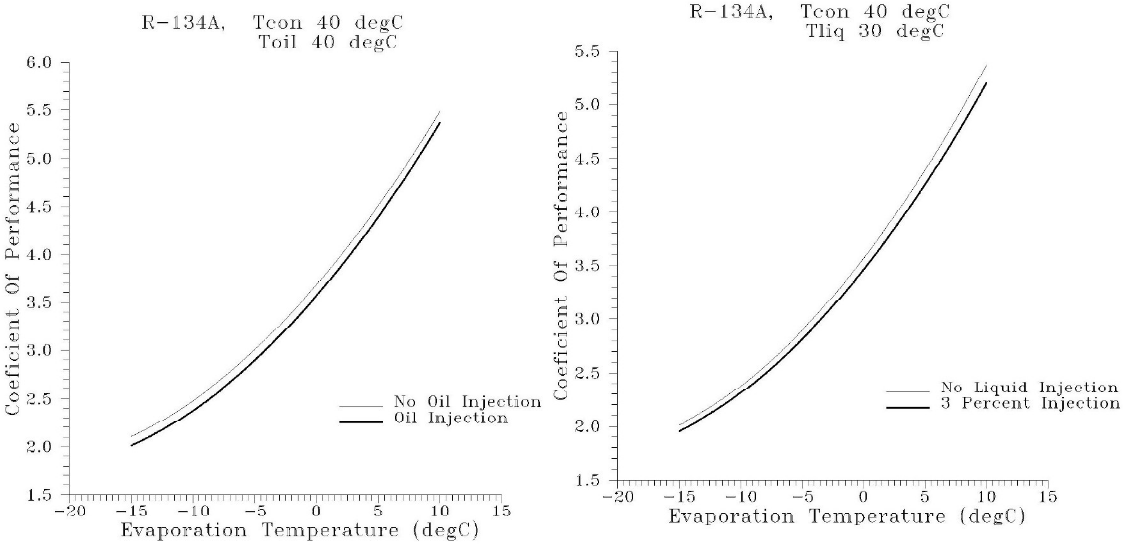

Fig. 3 Predicted coefficient of performance oil injection, left and for liquid injection, right, R-134A

The predicted COP for oil injection compared with no oil injection is given in the left hand graph of Fig. 3, while the same is presented for liquid injection in the right hand graph. It can be seen that oil injection causes less decrease of COP than the injection of 3 % liquid. This confirms that R-134A is not a fluid well suited for liquid injection.

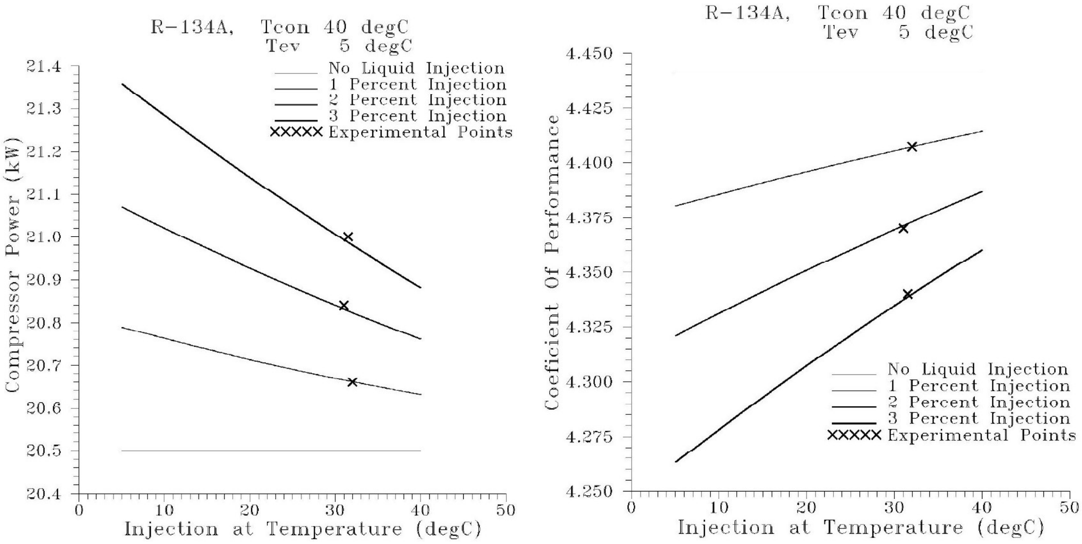

Fig. 4 Predicted and measured coefficient of performance for liquid injection, R-134A

Predicted and measured results are compared in Fig. 4 where the compressor power and COP are given in the left and right graphs respectively, for no injection and for 1, 2 and 3% by mass liquid injection at an injection pressure which corresponds to the temperature range between -15 and 5^{o}C. Apart from the good agreement between the predicted and experimental results, it can be seen that increasing the injection pressure is beneficial.

5.2 R-407C results

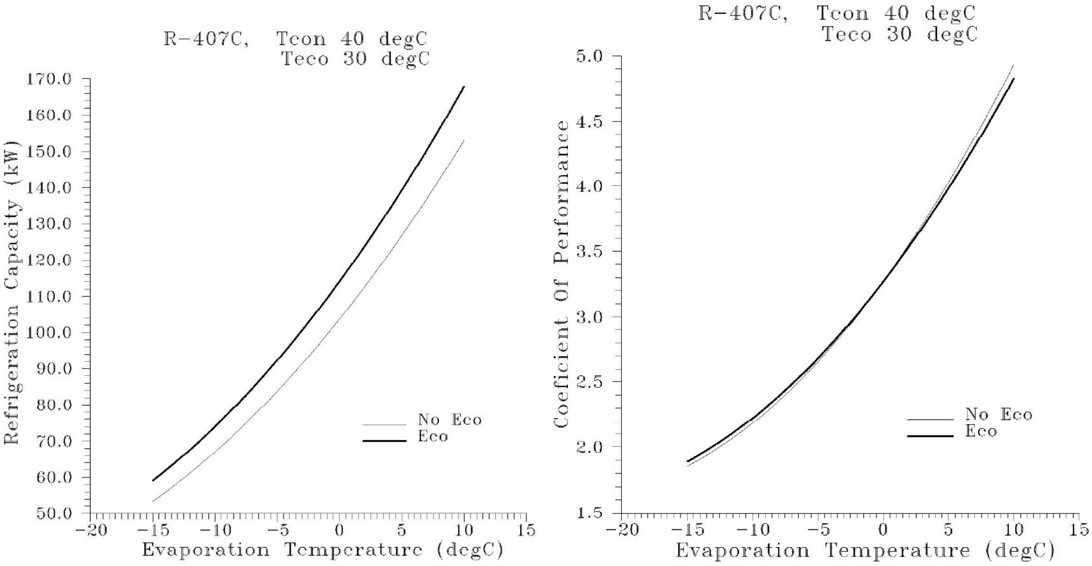

Fig. 5 Predicted refrigeration capacity and coefficient of performance for economizer flow, R-407C

Prediction of the superfeed effect at 30^{o}C is presented in Fig. 5 where the refrigeration capacity and coefficient of performance are given in the left and right hand graphs respectively, as functions of the evaporation temperature. As can be seen, there is a distinctive increase in the refrigeration capacity for the superfeed case, while the COP increases for lower evaporation temperatures.

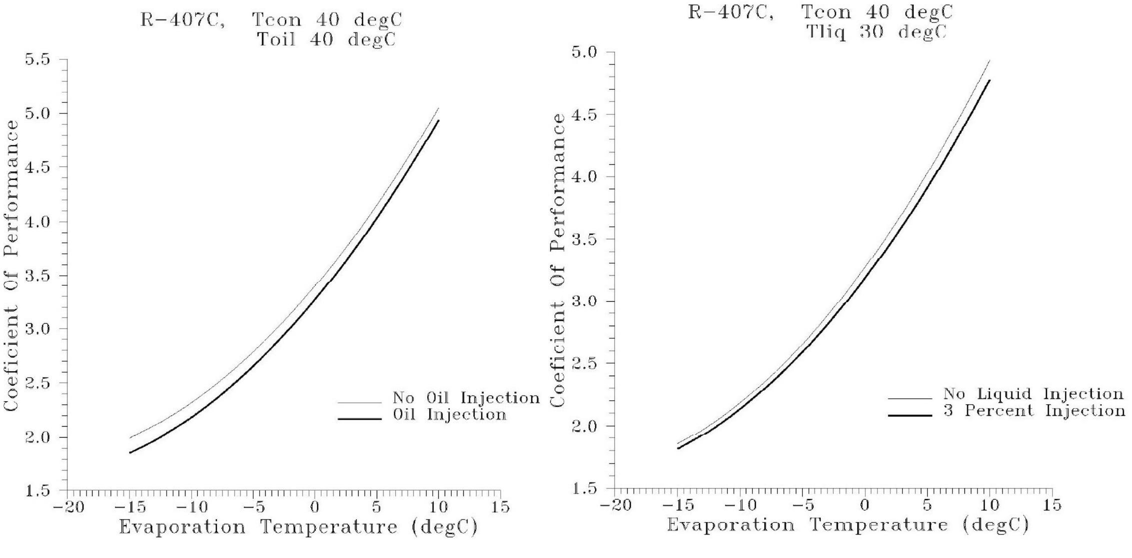

Fig. 6 Predicted coefficient of performance oil injection, left and for liquid injection, right, R-407A

The predicted COP for oil injection compared with no oil injection is presented in the left hand graph of Fig. 6, while that for liquid injection is in the right hand graph. It can be seen that oil injection causes a greater decrease of COP than 3 % liquid injection. Therefore, injection of R-407 liquid instead of oil may be beneficial for the compressor process.

5.3 Ammonia results

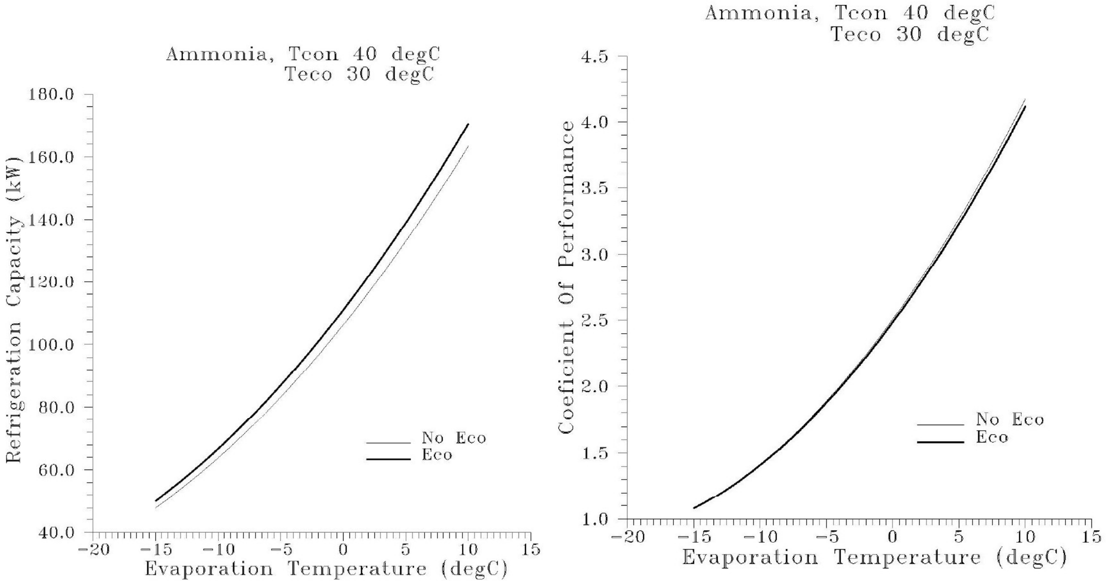

Fig. 7 Predicted refrigeration capacity and coefficient of performance for economizer flow, Ammonia

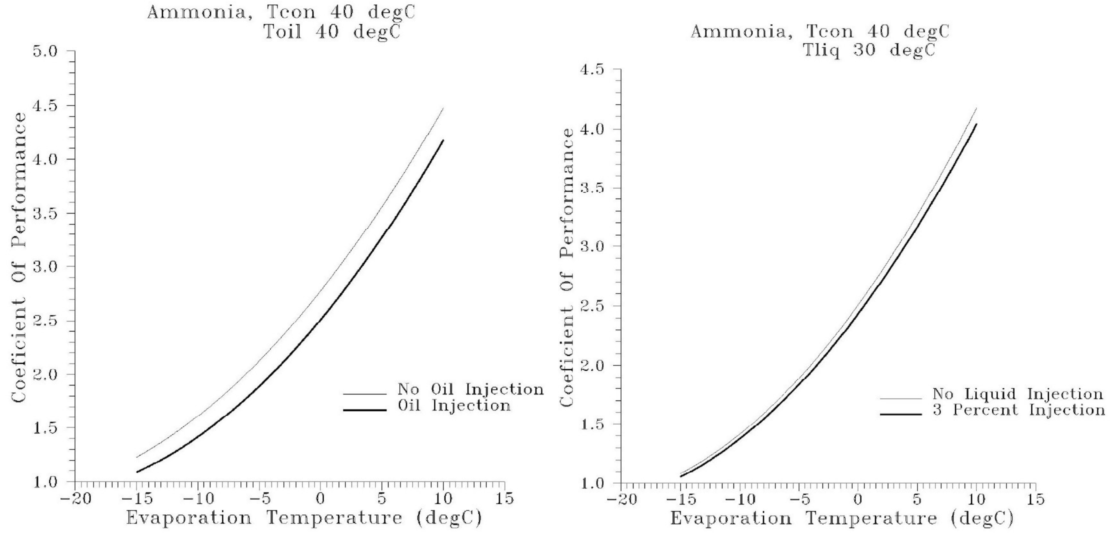

Fig. 8 Predicted coefficient of performance oil injection, left and for liquid injection, right, Ammonia

The predicted COP for oil injection, compared to no injection is given on the left hand graph of Fig 8, while that for liquid injection is on the right hand graph. It can be seen that oil injection causes a far greater decrease of COP than does 3 % liquid injection. It follows that ammonia is a fluid for which liquid injection is beneficial.

6. CONCLUSION

An extensive analytical study has been performed on various combinations of injection fluids, including oil, liquid refrigerant, refrigerant vapour and liquid-vapour mixtures to investigate the effect of liquid injection into a screw compressor working chamber. This has been complemented by experimental measurements with one fluid, namely R134a. The results confirm that for modern refrigeration screw compressors, in which clearances are small, liquid refrigerant injection may be more suitable for lubrication, sealing and cooling than oil injection. Of the fluids considered, R-134A appeared to be the least suitable for liquid injection, while R-407C and R-717 appear to offer greater advantages. The study also indicated how liquid injection can affect compressor efficiency, noise and reliability.

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