THE DESIGN OF EFFICIENT SCREW COMPRESSORS FOR DELIVERY OF DRY AIR

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ABSTRACT

This paper describes two high efficiency oil-free screw compressors designed for dry air delivery. Their design is based on the authors' own rack generated 'N' rotor profiles. The optimum rotor size and speed, together with the shape and position of the suction and discharge ports, were determined by mathematical modelling, taking full account of the limitations imposed by bearing and seal selection required to maximise endurance and reliability. Together, the two machines cover the discharge range of 350-1000 m^3/h. Prototype tests showed that both the volumetric and adiabatic efficiencies of these machines were higher than the published values of any equivalent compressors currently manufactured. This confirmed the advantages of both the rotor profile and the design procedure.

1 INTRODUCTION

Screw compressor design criteria vary with their application. Thus refrigeration and process gas compressors, which operate for long periods, must have a high efficiency and durability. In the case of air compressors, especially for mobile applications, efficiency may be less important than cost, portability and reliability.

The key factor for all applications of these machines is the rotor design. The principles on which this is based, were published explicitly some time ago by *Sakun 1960* [1]. However, screw compressors were produced successfully on a large scale only after 1973, following the introduction by the Swedish company, SRM, of first their 'A', and later their 'D' profile rotors to create an industrial standard. Despite the continuing development of screw compressors in recent years, little data has been published on their design. *Amosov et al 1977* [2] reviewed the contemporary profiles in their handbook, in Russian, *Rinder 1979* [3] gives a comprehensive description of the 'A' profile in his book in German. *O'Neill 1993* [4] produced a book on industrial compressors with a major part devoted to screw compressors while *Arbon 1994* [5] dedicated his book exclusively to twin shaft compressors.

This paper describes the design of high efficiency screw compressors specifically dedicated to dry air delivery. It was carried out using a comprehensive software package which included almost every aspect of geometric and thermodynamic modelling with the capacity to transmit derived output directly into a CAD drawing system. In particular the rotors were generated using the rack principle to produce the authors' own 'N' profiles, as published in *Stosic and Hanjalic, 1997* [6]. A well proven mathematical model of the thermodynamic process was used to determine the optimum rotor size and speed, the volume ratio and the shape and position of the suction and discharge port. More information can be found in *Hanjalic and Stosic, 1997* [7]. In addition, modern design concepts of screw compressors, such as late closing of the suction port and early exposure of the discharge port were included, together with improved bearing and seal specification, to maximise the compressor endurance and reliability, as described in *Stosic et al, 1997* [8].

Two sizes of compressors were designed to cover discharge range between 300 and 1100 m^3/min. Compressor XK18, for nominal 1000 m^3/h and XK12 for 500 m^3/h. Their prototypes were tested and the results obtained at delivery pressure between 2 and 3.5 bar abs. A pre-production batch of machines has already passed field tests and the product was launched in March 2001.

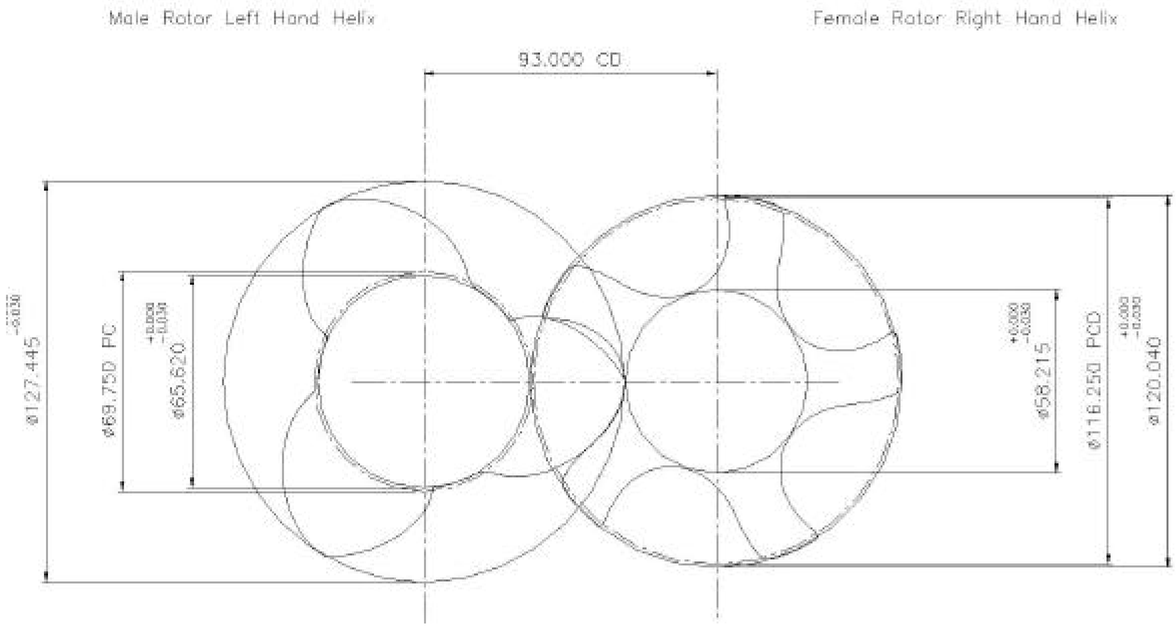


Fig. 1 Drawing of 3/5 'N' rotors used in XK12 and XK18 compressors

2 'N' PROFILE ROTORS IN 3/5 CONFIGURATION

An efficient screw compressor needs rotor profiles which ensure a large flow cross section area, a short sealing line and a small blow-hole area. The larger the cross section area, the higher the flow rate for the same rotor size and speed. Additionally shorter sealing lines and a smaller blow-hole reduce compressor leakage. Higher flow and smaller leakage rates both increase the compressor volumetric efficiency, which is the rate of flow delivered as a fraction of the sum of the flow plus leakages. This, in turn, increases the adiabatic efficiency as less power is wasted in compression of internally re-circulated gas.

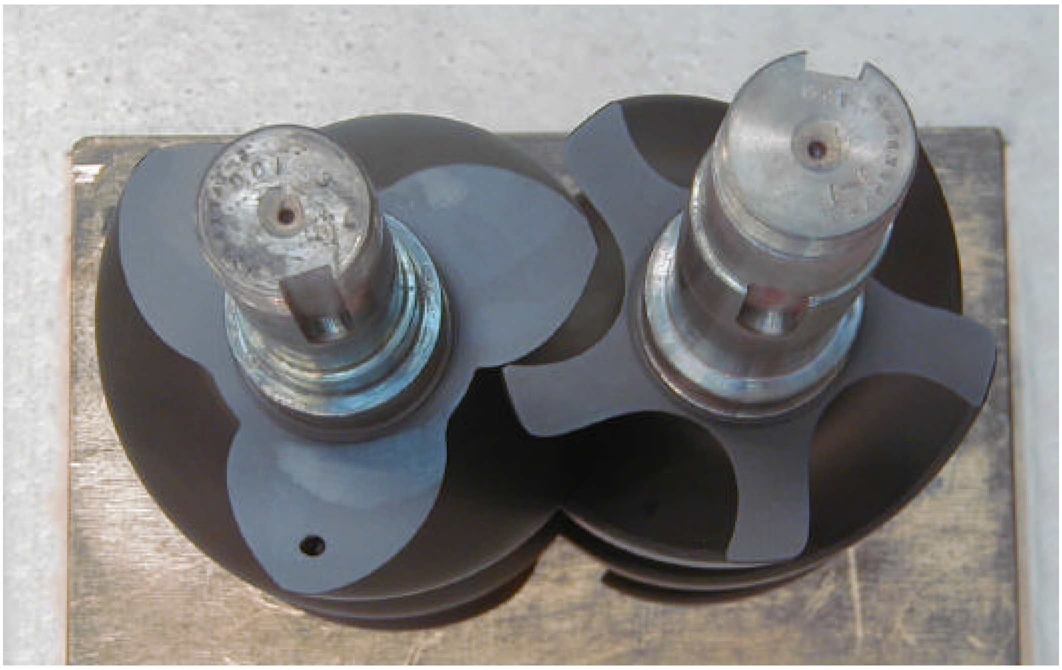


Fig. 2 Photograph of 3/5 'N' Rotors used in XK12 and XK18 compressors

The optimum choice between blow hole and flow areas depends on the compressor duty since for low pressure differences the leakage rate will be relatively small and hence the gains achieved by a large cross section area may outweigh the losses associated with a larger blow-hole. Similar considerations determine the best choice for the number of lobes as fewer lobes imply greater flow area but also result in an increase in the inter-lobe pressure differential.

As precise manufacture permits rotor clearances to be reduced, the likelihood of direct rotor contact is increased. Hard rotor contact leads to deformation which increases contact forces. Hence the profile should be designed to minimise the risk of seizure under such conditions.

In Figures 1 and 2 a pair of 'N' rotors is shown with 3 lobes in the main and 5 lobes in the gate rotor. This configuration gives a larger cross section area with stronger gate rotor lobes than any other known screw compressor rotor. Also by use of the timing gears to transfer the torque, the main rotor speed can by increased by 1.67:1. By this means a single stage gearbox can be used to connect the compressor to the main drive shaft, whereas for this application a two-stage gear box is normally required. 'N' profile rotors have a further favourable characteristic. This is that they maintain a seal over the entire contact length while maintaining a small blow-hole. Although selected in this case for dry air compressor applications, 3/5 'N' rotors are also suitable for process gases and for oil flooded machines.

3 DESIGN OF XK12 AND XK18 COMPRESSORS

Although advanced rotor profiles are a necessary for a screw compressor to be efficient, all other components must be designed and manufactured to enhance rotor superiority if their full advantage is to be achieved. Thus rotor to housing clearances must be properly selected.

A screw compressor is heavily loaded by axial and radial forces, which are transferred to the housing by the bearings. Rolling element bearings are normally chosen for small and medium screw compressors and these must be carefully selected to obtain a satisfactory design. Usually two bearings are employed on the discharge end of the rotor shafts in order to absorb the radial and axial loads separately. Also the distance between the rotor centre lines is in part determined by the bearing size and internal clearance. This practice was applied here.

Special care was given to minimise the flow losses in the suction and discharge ports. The suction port is positioned in the housing to let the air enter with the minimal restriction. The air approach velocity is kept low by making the flow area as large as possible. The discharge port size was first determined by estimating the built-in-volume ratio required for optimum thermodynamic performance. It was then increased in order to reduce the exit air velocity and hence obtain the minimum combination of internal and discharge flow losses. The cast iron casing was carefully dimensioned to minimize weight, while ensuring overall component stiffness.

The layout of the XK12 compressor is presented in Fig. 3. The entire programme of design and construction was performed in the period of 1998-2000. A photograph of the XK18 compressor is presented in Fig. 4.

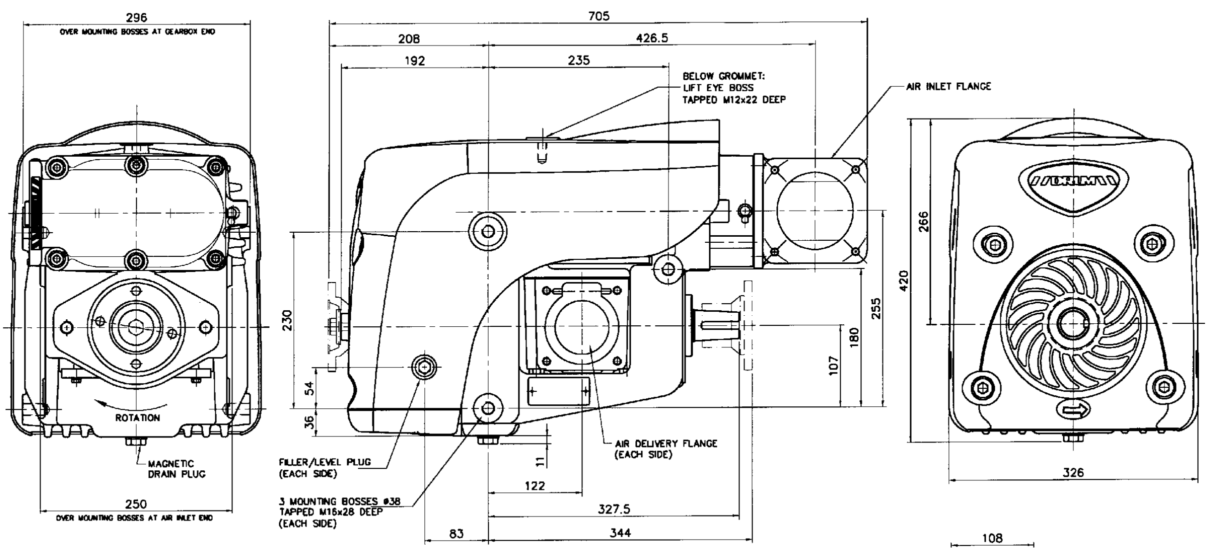


Fig. 3 Outline dimensions of the XK12 compressor

Compressors XK12 and XK18 are designed for air delivery 350-700 m^3/h and 700-1000 m^3/h at 3.5 and 3.2 bars abs respectively. The 'one minute' peak pressure was 3.7 bars and the air temperature rise was limited to 200 ^oC for 3.2 bars.

Both compressors have a gearbox step-up ratio of 4.2:1. This gives an overall step-up ratio of 7:1 when combined with the synchronising gears. The drive shaft speed range is 1000-1800 rpm. Thus the main rotor speed is in the range of 7000-12600 rpm. The gear train and discharge bearings are oil lubricated , while all other bearings are grease lubricated.

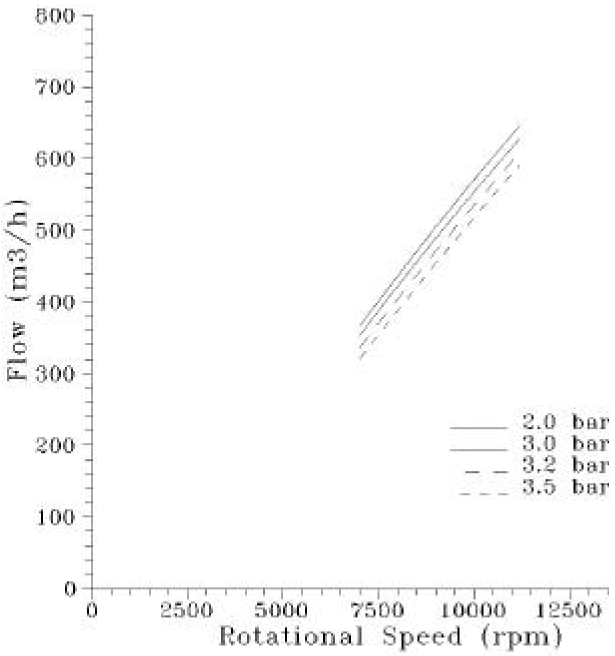
XK12 and XK18 overall dimensions and weight are 617x300x390 mm, 113 kg and 700x300x390 mm, 127 kg respectively. A through shaft gearbox arrangement allows a clockwise or anticlockwise input drive rotation with mounting points on either side of the machine to provide further flexibility. The inlet manifold designs available can accommodate application access to the axial inlet port from either left, right, vertical or the axial direction. The compressor discharge exists from either side of the compressor.

Fig. 4 Photograph of the XK18 compressor

4 TESTING OF XK12 AND XK18 COMPRESSORS

An experimental rig for testing air compressors was designed and constructed at Drum-International to meet criteria of Pneurop/Cagi requirements for screw compressor acceptance tests. High accuracy test equipment was used for the measurement of all relevant parameters. All measurements were recorded and processed via full PC automated control. An inverter driven 90kW electric motor permitted testing of the screw compressors with discharge rates of up to 1000 m^3 /h.

The following parameters were measured directly: Atmospheric pressure, Suction pressure, Discharge pressure, Orifice plate pressure, Orifice plate pressure difference, Suction temperature, Discharge temperature, Shaft torque, Orifice plate temperature and Compressor speed.



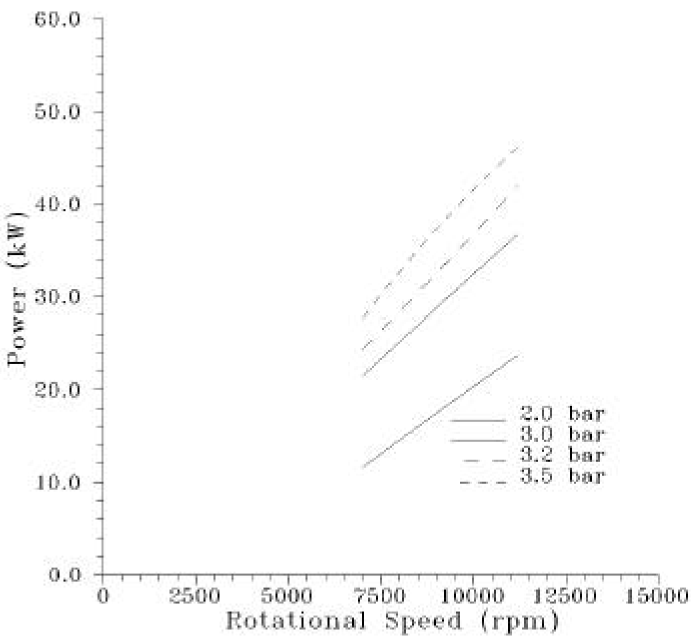
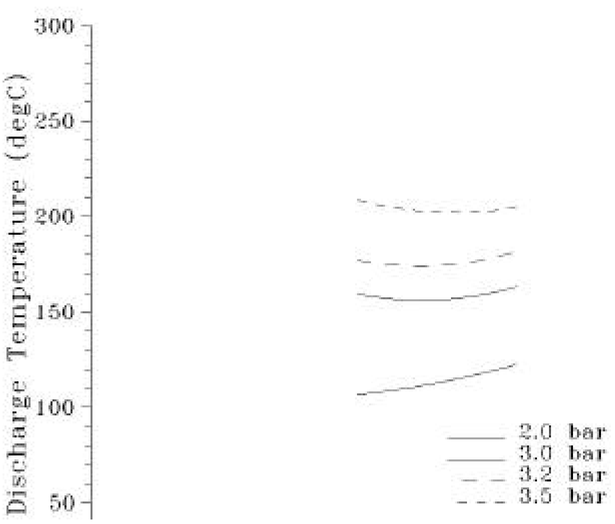


Fig. 5 Compressor flow, XK12

Fig. 6 Compressor power, XK12

Measured values were used to calculate compressor flow, power and specific power and compressor efficiencies. The test results presented are compressor speed characteristics for flow, power and discharge temperature in Figs 5, 6 and 7 and 9, 10 and 11 and flow in function of power in Figs 8 and 12 for XK12 and XK18 compressors respectively. Inlet pressure and temperature were 1 bar and 20°C and discharge pressure varied between 2 and 3.5 bars.



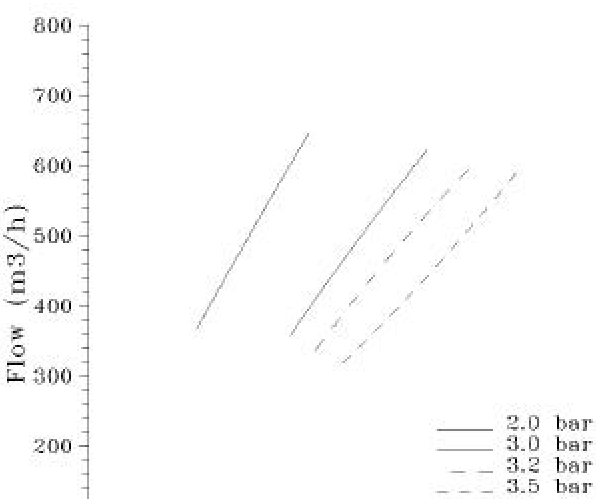
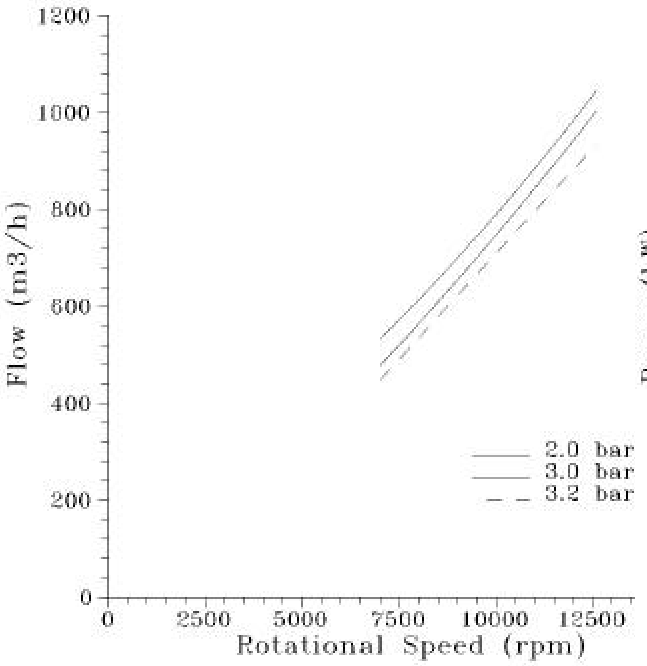


Fig. 7 Discharge temperature, XK12 **Fig. 8 Flow vs power, XK12**



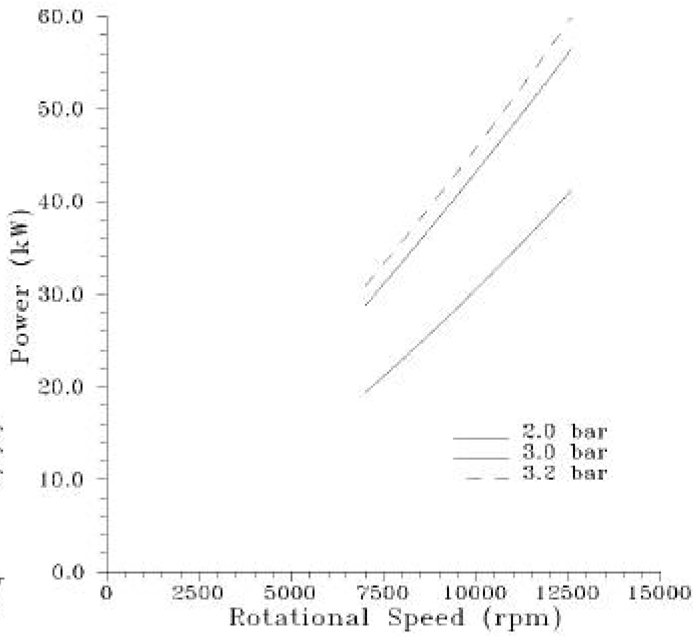
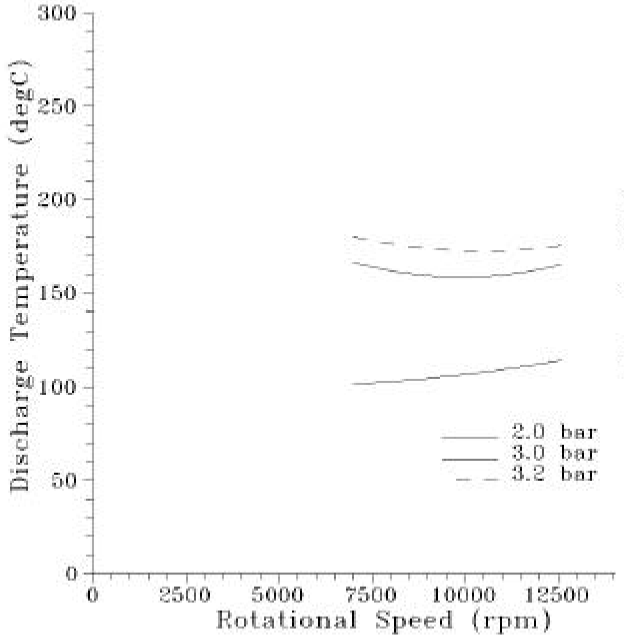


Fig. 9 Compressor flow, XK18 **Fig. 10 Compressor power, XK18**



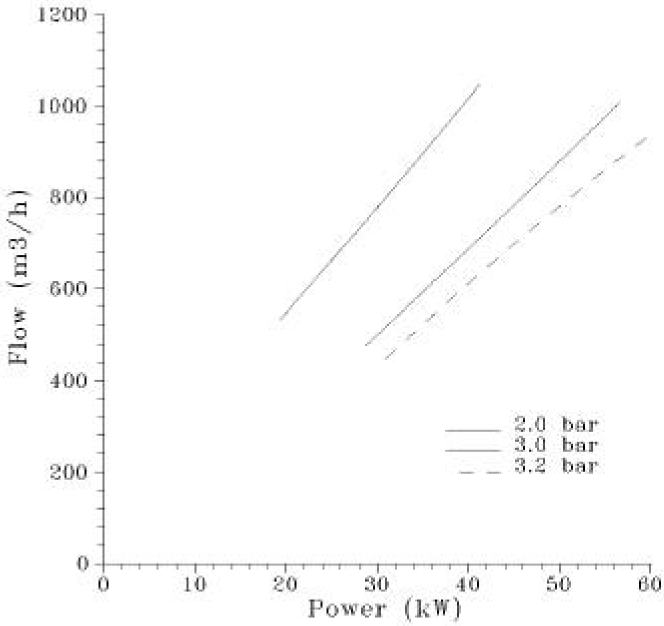


Fig. 11 Discharge temperature, XK18 **Fig. 12 Flow vs power, XK18**

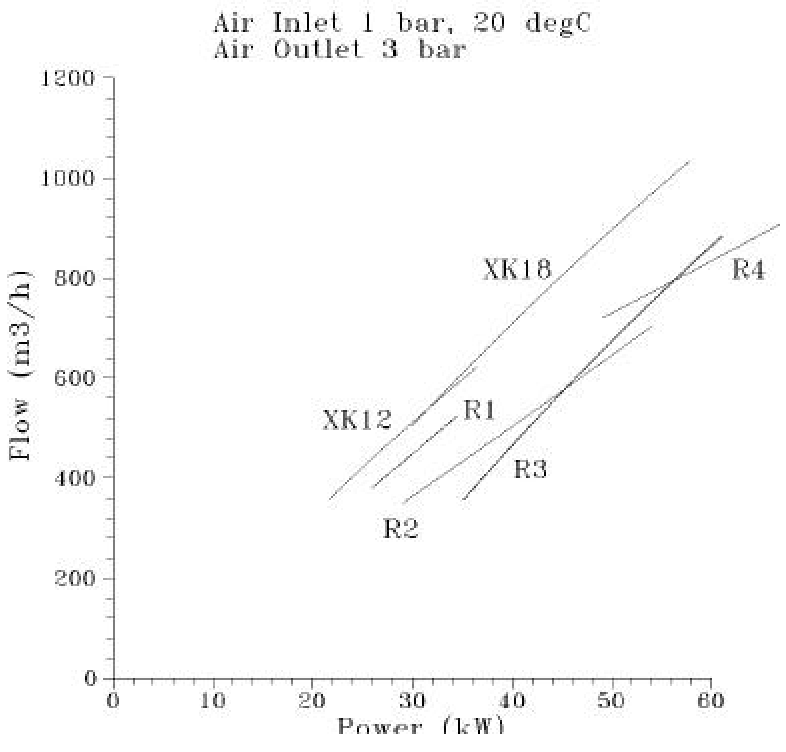


Fig. 13 Flow as a function of power for the XK12 and XK18 compared with reference compressors

Finally, in Fig. 13 the performance of these compressors at discharge pressure of 3 bars was compared with the reference compressor R2, D-9000 of the same manufacturer, R1, C-80 of GHH based on SRM 'A' profile rotors, which despite its age outperformed other reference compressors, for example the compressors R3, Typhoon by Mouvex which is based on modern screw compressor profiles and R4, GHH CS1000, which is again based on SRM 'A' profile.

As can be seen, the flow of XK12 and XK18 compressors is at least 10% higher than of all competitors for the same compressor power, which is actually greater than the predicted value. The measured performance values were found to compare very favourably with published information for equivalent machines at present commercially available.

5 CONCLUSION

A family of two compressors based on "N" profile rotors with a 3/5 configuration has been developed for dry air delivery by Drum-International to cover air delivery in the range of 300-1000m^3/min. Extensive testing has shown that their performance is superior to that of all known compressors of similar application and similar size.

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