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Development and Design of Energy Efficient Oil-Flooded Screw Compressors

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Abstract. It is estimated that about 17% of the world's generated power is used for compression. Thus all, even minor improvement of the efficiency of compressors will substantially reduce CO2 emission. This paper presents development of family of energy efficient oil-flooded screw compressors for Kirloskar Pneumatic Company Ltd. The developmental techniques adopted to improve efficiency such as introduction of superior 'N' rotor profile, rotor clearance management, performance calculation using 3D CCM (Computational Continuum Mechanics), direct parametric interface to CAD (Computer Aided Design), which contains bearing selection for complete 3D solid modelling. Also, contemporary prototyping and experimental investigation is supported by the fully computerised data acquisition and processing. The cumulative improvement of all these elements of the design process resulted in a very efficient machine which guarantees the competitive position of Kirloskar Pneumatic Company Limited in the screw compressor market.

1. Introduction

Oil-Flooded screw compressors have a wide variety of applications such as air compression, oil and gas refrigeration and power utilization from low grade heat sources etc. These compressors have been in application for the past forty years due to their higher efficiency and reliability. There are many literature resources available which describe the operation of the machine and highlight the importance of optimisation of rotor profile [1-6]. Advent of modern mathematical tools have led to the distinguished 'N' rack generated rotor profile which is one of the most popular profile in screw compressor industry [7]. Since, then a number of manufacturers have retrofitted their compressors with 'N' profile [9].

Not only screw compressor technology is popular and sustainable, the market is projected to grow at a compound annual growth rate (CAGR) of 6.62% from 2016-2021, to reach a market size of USD 11.01 billion by 2021 [10]. To add to this, oil flooded screw compressors constitute around 70% of the overall Indian market [11]. Competition to produce screw compressor with improved efficiency is intensive in the market as efficiency will proactively translate to environmental friendliness and most importantly reduced operational costs. It is estimated that the energy cost will outweigh the capital and maintenance cost over the time period of 10 years (Figure 1).

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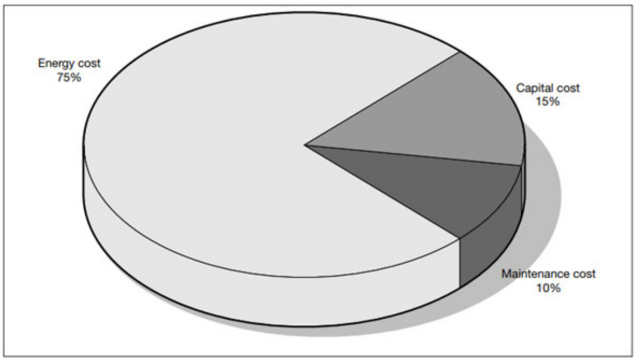

Figure 1. Typical cost of compressed air systems over a ten-year period based on a typical compressor performance of 5 CFM/kW and electricity price of 5 pence/kWh [12]

Alongside the rotor profiling, through continuous research and development various tools have been developed at City, University of London for design and development of screw compressors. The rotor generator and performance calculator suite SCORPATH (Screw Compressor Optimal Rotor Profiling And THermodynamics). This tool is used for generating rotor profiles and preliminary calculation of the thermodynamic performance of screw machines. SCORPATH also allows variations in profile features, oil related parameters, clearances and bearings. The predicted compressor performance is then integrated within software package DISCO (Design Integration for Screw COmpressors) and ScoCAD (Screw Compressor Computer Aided Design) module to produce parametric 3D models in CAD software package Inventor. To further improve performance and check for structural design of the family of compressors, analysis is performed using SCORG (Screw Compressor Rotor Grid). SCORG allows for parametric modelling using standard CFD solvers, such as ANSYS CFX and finite element analysis with ANSYS mechanical.

This paper focuses on the various design criteria in terms of rotors, clearances, bearings and oil injection to design, manufacture and test screw compressor family prototypes. Considering the above design criteria and tools, three sizes were designed and manufactured. Amongst this, two of the prototypes were tested for various operating conditions. The performance values with improved design features are compared with the existing Kirloskar Pneumatic Company Limited's (KPCL) variants. It is seen that with improvement in design procedures overall performance characteristics are improved. This leads us to the fact that, better performing machine can be translated into lower operating costs as well as reduction in CO_2 footprint. It is expected that the last or the third developed oil-injected prototype will follow a similar success as that of first and second prototype when tested.

2. Pre-design Study

As a first step, feasibility study is carried out in order to achieve the balance between the compressor performance expectations and design limitations. Considering the requirement of a range of volumetric flows specified at different discharge pressure values, a pre-design analysis is carried out in SCORPATH. This study results in potential sizes of oil injected air compressors and from this three different sizes with best performance is chosen.

To ensure that the designed compressor will be better in performance, thermodynamic performance is investigated and compared with the existing KPCL compressor. A good screw compressor will have maximum delivery per unit size or weight of the machine. In doing so it should consume minimum power for given operating conditions. Therefore, a compressor with lower specific power consumption becomes an obvious choice for the customer. Figure 2 shows performance map predicted through pre-design study. Based on the male rotor sizes, the oil-injected compressor design is characterised further to achieve full prototypes.

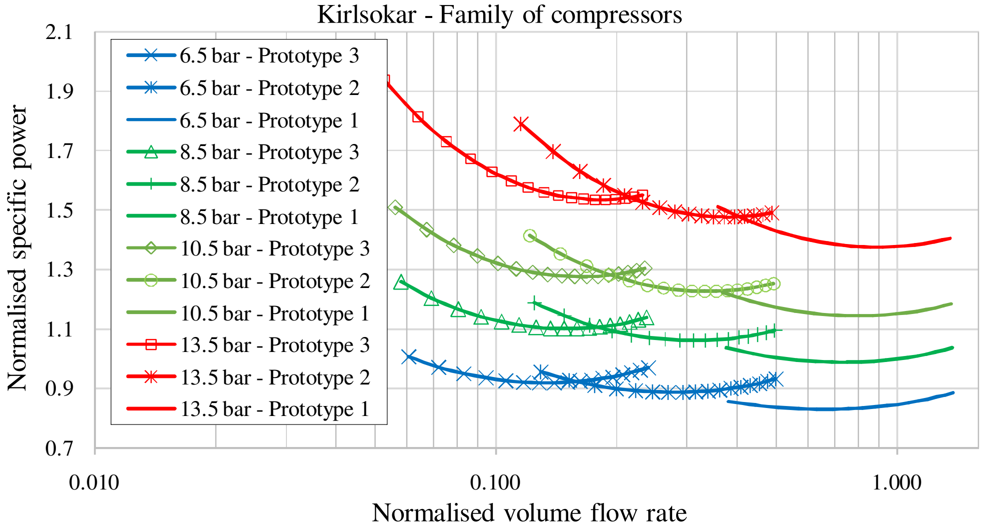

Figure 2. Performance map with predesign study

3. Design features of the screw compressor family

3.1 Rotor Profile

Screw compressor's performance is highly dependent on the rotor profile, number of lobes and clearance between the rotors and the housing. The volume handled by the compressor is defined by the rotor profile. The rotor profile also seals the boundary between successive compression chambers to minimise the leakage through meshing lobes. A good profile will provide higher compression volume and lesser leakage and this will improve the volumetric and adiabatic efficiency of the screw compressor.

Generally, 4/5 or 4/6 configuration is suitable for oil flooded compressors of low and moderate pressure. Centre for Compressor Technology's experience in rotor profiling is agglomerated to 'NSilent' [13] rotors which has demonstrated capacity for high resistance to noise and still maintains high compressor efficiency. This design confers a number of advantages including greater flow area, stronger gate rotor lobes, reduced leakage and lower internal friction than those of alternative types of profile. This means, the performance predicted for this configuration is superior to that of any known type of alternative profile for the same rotor size and clearances. A screw compressor running smoothly without creating excessive noise implies good clearance management.

3.2 Clearance management

Once the profile has been selected for the rotors, the next step in designing a screw compressor is the clearance management. The selection of clearances is very critical, even a small change in clearance of the order of microns can lead to a dramatic change in screw compressor performance. Very tight clearances will produce a good thermodynamic compressor performance because of the reduced leakages. However, it increases the chance of contact between the rotors and the casing. This would result in a noisy compressor and higher specific power consumption. The limitation here is manufacturing constraint to produce very tight clearances. Therefore, it is a trade-off between tight clearances, manufacturing capability and rotor contact, while managing the clearances.

Critical clearances can be categorised according to the assembly of the screw compressor. This includes interlobe clearance which defines clearance distribution between rotors in mesh, radial clearance between rotors and casing and the clearance between discharge face of the rotors and the casing. The clearance between suction face of the rotors and the casing is not controlled in order to allow the accommodation of thermal expansion of the rotors during operation. The latest and the high end rotor manufacturing techniques are capable of producing the rotors with a profile tolerance in the order of single digit micro-meters.

3.3 Selection of bearings
Bearings are the one of the key elements of screw compressor as they transfers rotor load to the housing. However, in doing so, they also contribute considerably to the amount of power loss during power transmission. A typical mechanical power loss in an oil injected screw compressor is about 7-10% of the shaft power. So it is important to optimally select the bearings which will satisfy the required L_{10h} life with minimum frictional losses. A module called as SCOCAD in the program suite DISCO; calculates the loads acting on the rotors for given set of operating conditions. This module provides an interface for selection of the bearings which satisfy the required L_{10h} life.

Comparative analysis of frictional bearing power loss estimated for the developed model (size 1) and equivalent size of KPCL existing model is presented in Figure 3. This analysis is in line with the procedure set through SKF catalogue [14]. Compressors used for analysis are oil injected, air screw compressor with discharge pressure of 8.5 bar absolute. It can be seen from the figure that the existing model bearings shows more frictional power losses compared to the developed model. Theoretically at maximum speed, the frictional power loss in developed model bearings is 37% lower than bearings of the existing model.

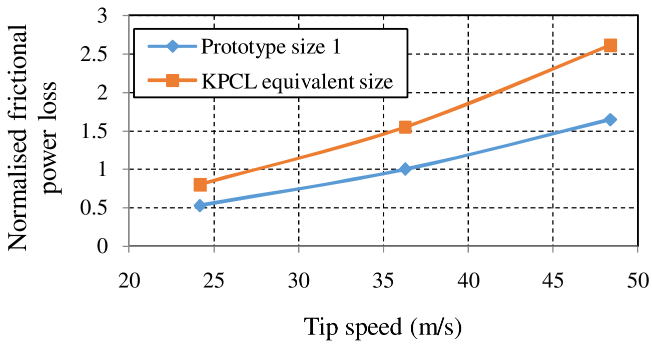

Figure 3. Comparison of bearing frictional power loss

3.4 Parametric Modelling
Parameters required for generating a complete CAD model and related manufacturing drawings are available based on the values from SCORPATH. These values combined with the parameters related to mechanical elements are added to a data interchange between the DISCO interface and commercial CAD package. Once the required selections on bearing, keyway, shaft undercuts are made in the ScoCAD, 3-D models of the airend are generated. This is achieved through writing parameters on to a Microsoft Excel sheet using subroutines and these parameters are picked up by the CAD package for its dimensions. Overall, this enables the design to be modified either from DISCO or Microsoft Excel sheet. The CAD software package used for KPCL is Autodesk Inventor.

Further, for the range of oil-injected compressors with varying sizes, parametric modelling is quite efficient to produce a complete CAD model just by scaling down the rotor sizes to suit flow requirements. This facilitates quick design and saves significant amount of time alongside reduction in errors. Figure 4 represents the 3D model of developed sizes for KPCL.

Size 1 Size 2 Size 3

Figure 4. Parametrically generated CAD models

4. Computer-aided engineering

Generated CAD models are further analysed before the prototypes are built. The whole family of KPCL compressors were analysed with advanced three dimensional Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) tools.

4.1 FEA

Static structural analysis is performed in ANSYS Mechanical for casing of prototype size 1. Analysis is performed for maximum design temperature and pressure. Few iterative operations helped to reduce stress concentration at certain localised areas by modifying design and analysing it again. Finally, the modified housing structure and its analysis showed that the maximum principal stress is well below the endurance limit of the housing material as shown in Figure 5. This confirms that the design is safe for the compressor operating pressure.

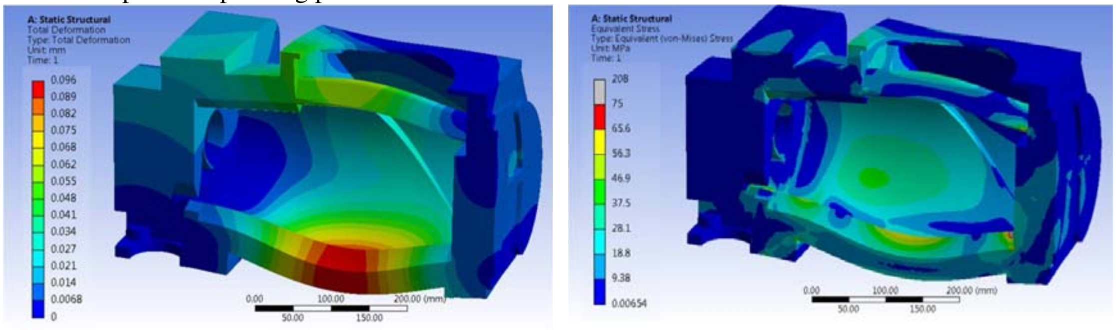

Figure 5. Maximum stress acting on the casing at varying cross sections

4.2 Computational Fluid Dynamics (CFD)

CFD analysis is useful to understand the flow and oil characteristics within a screw compressor [15]. Proprietary software package SCORG developed by City, University of London is capable of generating high quality mesh for complex deforming domains [[16]-[17]. The generated rotor profiles are imported to SCORG in order to generate the relevant grids for prototype of size 1. The multiphase model chosen for this analysis is Eulerian-Eulerian in ANSYS CFX. The mesh generated for below case is rotor-casing conformal mesh (Figure 6a).

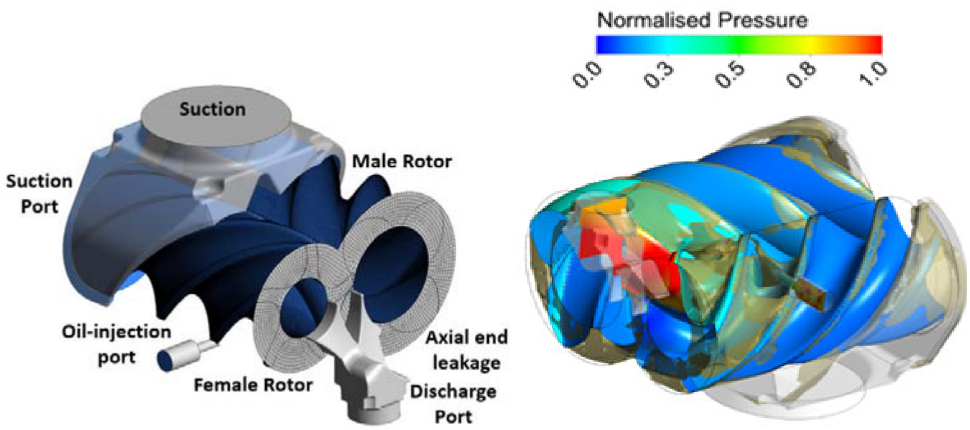

Figure 6. (a) 2D Mesh with rotor grids and ports (b) Pressure contour with oil iso-surface volume fraction of 0.05 for prototype of size 1 when discharge port is open

From the contour plot (Figure 6b), it can be seen that the pressure is gradually built in the rotor lobes leading to the discharge port and discharge port is designed in such a way that there is a minimal pressure drop. Also, oil injection port is positioned in such a way that higher injection pressure also adds to the tangential velocity for running the female rotor thus reducing the total power consumed.

These features of good discharge port and well positioned oil ports improve the performance of the prototype of size 1. Similar analysis is conducted for other prototypes.

5. Experimental Investigation of Screw Compressor Prototypes

Once the prototypes have been manufactured, experiments have been conducted to estimate the performance of the screw compressors. Figure 7 shows prototype size 2 on the test bed. Compressor is driven by a variable speed electric motor through a belt drive. Speed variation is obtained by using frequency inverter and electric motor. Test rig was built to meet CAGI and PNEUROP test standards where the testing procedures are carried out according to ISO 1217:2009.

The inlet duct of the compressor is connected to the air intake filter and intake manifold. It contains the butterfly regulation valve and the non-return valve. Oil is injected into the compressor from through the main oil supply manifold from the water cooled oil cooler. The mixture of hot oil and compressed air is discharged into a two-stage oil separator. In the first stage, with the centrifugal oil separator most of the oil is separated from the compressed air. This oil is filtered, water-cooled and re-injected into the compressor. That air rich/oil lean mixture is then passed into the second stage separator where a filter extracts condensed oil from the air. The oil is collected at the bottom of the separator tank and is not recirculated. The air leaves through a pipeline positioned at the top of the second oil separator and is discharged into a flue. The discharged air flow rate is controlled by the globe valve operated by a stepper motor and thereby regulating the discharge pressure of the compressor. The stepper motor can be controlled either manually or automatically. Measurement data acquisition is carried out using CompactRIO system from National Instruments and LabVIEW software.

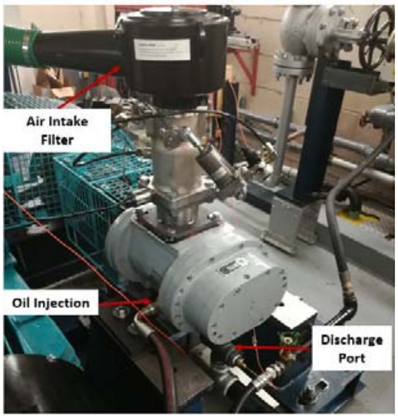

Figure 7. Size 2 prototype on test bed

6. Achieved performance improvement and savings

Test was performed for steady state conditions at specified point allowing the prototype of size 1 and size 2 to fully achieve the required parameters and steady operation. Several test recordings were taken for each steady state condition with time intervals of at least 30 seconds between each recording. The results of airend prototypes are then mapped with existing KPCL airends to look for change in performance. Mapping is done by matching airend pressure ratio for same operating conditions.

Comparison of prototypes and KPCL variants is done by normalisation procedure of flow and specific power to protect confidential information. Since, the individual prototypes will be replacing different KPCL variants, the smallest KPCL variant operating in the same flow range is taken as reference for normalisation. It is seen that for similar flow rate, existing KPCL variants would consume higher power compared to the prototype of size 1 as shown in Figure 8. Similar comparison is done for prototype size 2 with relevant existing KPCL variant (Figure 9).

Also, it is important to understand the environment-friendliness of the prototype; this could be done through understanding the carbon footprint of the compressor. E.On had recently published figures on the amount of CO_2 generated for 1 kWh and it is 0.7 kg [18]. Considering the comparison plot, it can be seen that the current prototype would potentially emit less CO_2 emission compared to the current variant. The developed prototype is cost efficient as well as environment-friendly. The overall manufacturing costs could not be estimated as the required rotors for the prototype were not mass produced and therefore cost for producing per batch is higher and rotors are generally the most expensive parts in an airend. It is anticipated that the rotor manufacture cost will be hugely reduced when mass produced at KPCL.

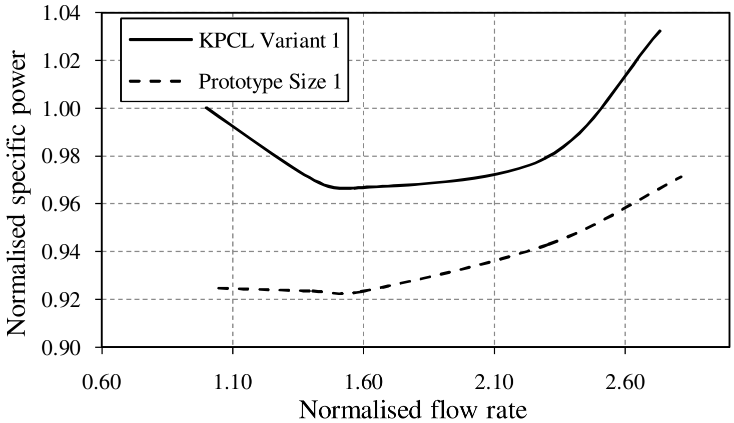

Figure 8. Comparison between KPCL existing compressor and prototype size 1

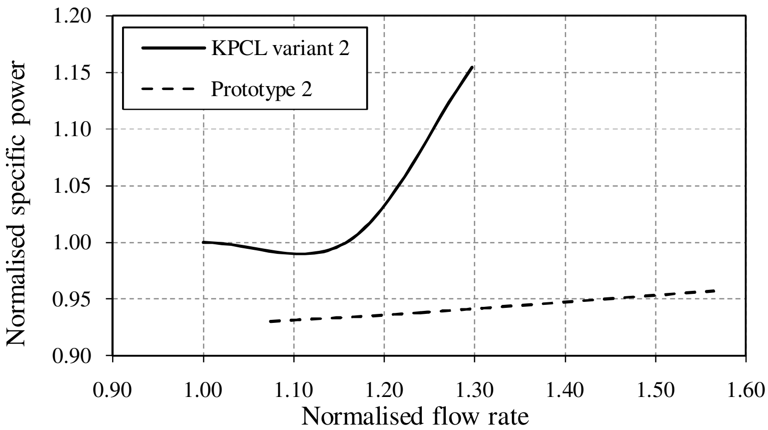

Figure 9. Comparison between KPCL existing compressor and prototype size 2

7. Conclusions

This paper details collaborative design and development of oil-flooded screw compressors performed by Kirloskar Pneumatic Company Ltd. and the Centre for Compressor Technology at City, University of London. This was done by use of proprietary software packages which contains the most contemporary versions of performance calculations, design and experimental tools resulting in an efficient family of screw compressors. The developed prototypes cover a full range of flows and powers common in screw compressor market. The key conclusions are:

- Application of rack generated 'N' rotor profiles with the lowest possible economical clearances led to the highest possible compressor efficiency.
- A well laid out design process was carried which smoothly progressed from pre-design, profile design, clearance selection, calculation of mechanical elements to validation by use of advance 3D CFD and FEA to fully manufactured prototypes.
- Manufactured prototypes of size 1 and size 2 were measured and compared to existing KPCL variants. It was concluded that both prototypes perform better than existing KPCL variants at 8.5 bar pressure ratio.

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