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Advanced Design Environment for Screw Machines

Elvedin Mujic
City University London

Ahmed Kovacevic
City University London

Nikola Stosic
City University London

Ian Smith
City University London

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Elvedin MUJIC*, Ahmed KOVACEVIC, Nikola STOSIC, Ian K SMITH,
Centre for Positive Displacement Compressor Technology
City University, London, SEMS, London, EC1V 0HB, U.K.
Tel: +44 20 7040 8148, Fax: +44 20 7040 8566
e.mujic@city.ac.uk http://www.city-compressors.co.uk

ABSTRACT

This paper describes a set of advanced tools for the design of screw compressors. These have been combined to operate under common environment, called DISCO (Design Integration for Screw Compressors). The number of input parameters required to define the geometry and operating conditions of a compressor is small and all are introduced in one place. Therefore the design process is easily controlled. The software provides fast calculation and evaluation of the main geometry of screw machines. It also directly accesses data on the most frequently used standard mechanical elements in screw machines and routines for their selection. The program can interface with a number of commercial CAD software packages to produce full 3D parametric models and manufacturing drawings of screw machines. From then on, 3D models are used as a base for the generation of numerical grids used later, either in FEM structural analysis or in CFD analysis of internal fluid flow. An established parametric approach enables any changes in the geometry that may be required, to be made easily after evaluation of the design. The program permits any modifications made to the model to be cross referenced through any part of the software. This saves both computer resources and design time when compared with classical design processes. The development of screw machines within this environment has many benefits, including reduced design time, improved quality and reduced machine costs.

1. INTRODUCTION

Screw compressor, as a simple positive displacement rotating machine is today more than ever used throughout the industry for air compression, refrigeration and process gas applications. According to statistical facts about 80% of newly installed industrial compressors are of the screw type. However, these are also heavily used for other applications such as air compression or refrigeration. About 17% of energy generated in developed countries is used for gas compression. The majority of newly installed industrial compressors is of the screw type. Apart from screw compressors, other types of screw machines such as screw expanders and screw pumps are becoming more common.

This clearly indicates increased market demands for quick design and production of such machines, which need be competitive both in efficiency and unit price. Depending upon the machine duty and required capacity of the machine, as well as on manufacturing capabilities, each screw machine design has to be optimised and its development must be conducted individually. This in turn requires flexible and reliable design tools, which accommodates all design phases. A design should, therefore start with generation of a suitable rotor profile, continue with the machine component design by use of a CAD package, and lead to the precise determination of the machine performance through one- and three-dimensional calculations of the screw machine flow and thermodynamics.

Improvements in computer speed and capacity allow today almost everybody to use computer software packages like 3D CAD or Computational Continuum Mechanics (CCM) programs, which have until recently been used only on fast corporate computers and supercomputers and therefore limited to a small number of designer groups. Recent advances in mathematical modelling and computer simulation are used for process analysis and design optimisation. Such models have evolved greatly during the past ten years and, as they are better validated, their value as a design tool has increased. Their use has led to a steady evolution in screw rotor profiles and machine shapes which should continue in future to lead to further improvements in machine performance.

In order to make such computer models more readily accessible to designers and engineers, as well as specialists, the authors have developed a suite of subroutines for the purpose of screw machine design. A number of independent software packages have been developed, each of which aids a different function of the design process. The first phase of the design is mostly performed by use of SCORPATH – Screw Compressor Rotor Profiling and Thermodynamics, for the screw machine analysis and optimization, which enables calculations of the machine performance and its optimisation for a specified duty.

Preliminary mechanical design may then be conducted manually or automatically by use of the SCOCAD (Screw Compressor CAD) module and a CAD system. This software module allows the development of a virtual machine and optimization of its structural elements. Later detailed mechanical design can be conducted by use of a CAD system, which may be different than that used for the first design phase. As a result, manufacturing drawings are produced and a numerical basis is generated for the manufacturing process.

Finally, the screw machine performance is estimated precisely by use of a three dimensional CFD (Computational Fluid Dynamics) code. However, a special program for grid generation of the rotor geometry of screw machines had to be developed by the authors for that purpose. Furthermore the same grid is used for estimation of distortions of the machine elements and its influence to the flow parameters.

2. DESIGN ENVIRONMENT

Despite having all listed programs already available, a great obstacle was to communicate between them. Namely, being iterative, the concurrent design process often requires some phases to be repeated and the information between the software elements has to be interchanged several times. That problem has been solved by development of the design management software DISCO – Design Integration for Screw Compressors, which makes the use of the program components much easier and more efficient.

The DISCO environment requires only a few shared input parameters to describe the geometry and operating conditions. This enables complete control to be retained over the each step of the design process providing that all changes in any phase are returned to all the previous and subsequent design phases. The emphasis is therefore on central parametric control and the reduction in amount of data. This relaxes the computer resource requirements, and significantly reduces the design time.

This approach is very suitable for current market demands since designers and manufacturers of screw machines are expected to achieve the desired performance at low design and manufacturing costs and in a limited time scale. Therefore, the authors decided to develop a program to serve as a computational aid for the complete design process starting from the initial concept all the way up to the manufacturing of the screw machine. The program interface manages all geometrical, thermodynamic, optimization, boundary and operation parameters of the screw machine between all components used for the design of these machines and connects them to the CAD and CFD software.

2.1 Fundamental Design of Screw Machines

The fundamental part of the design is performed within SCORPATH module with its environment shown in Figure 1. SCORPATH established its role as a basic design tool for screw machines, mainly because of its ability to generate rotor profiles and to calculate thermodynamic behaviour of a screw machine quickly and accurately. Rotor profile generation procedure, applied in that software, generates the rotor either from the given curves on other rotor or on the rack using the envelope gearing method introduced earlier by Litvin (2004). Screw machine rotors have parallel axes and a uniform lead angle and together form, effectively, a pair of helical gears. The rotors make line contact and the meshing criterion in the transverse plane perpendicular to their axes is the same as that of spur gears. Although spur gear meshing fully defines helical screw rotors, it is more convenient to use the envelope condition for crossed helical gears to get the required meshing condition as described in. To start the procedure of rotor profiling, the profile point coordinates in the transverse plane of one rotor, and their first derivatives, must be known. This profile can be specified on either the main or gate rotors or in sequence on both. Also the primary profile may be defined as a rack.

Full rotor and compressor geometry, like the rotor throughput cross section, rotor displacement, sealing lines and leakage flow cross section, as well as suction and discharge port coordinates are calculated from the rotor transverse plane coordinates and rotor length and lead. They are later used as input parameters for calculation of the thermodynamic and fluid flow processes within the screw machine as well as for further design tasks, for example the generation of detailed drawings. A transfer of the machine rotor and port geometry to a 3D CAD system out of SCORPATH is also possible. Since SCORPATH also calculates the tool profile, its results form a basis for the Computer Aided Manufacturing. Additionally, SCORPATH provides a calculation of forces on the rotors, which then serve as a basis for further mechanical design of the machine.

Calculation of the screw machine performance based on the thermodynamic model and its ability to optimize the compressor geometry for the required working conditions are SCORPATH advantage compared with other similar packages. The algorithm of the thermodynamic and flow processes used is based on a mathematical model comprising a set of equations which describe the physics of all the processes within the screw compressor. The mathematical model describes an instantaneous operating volume, which changes with rotation angle or time, together with the equations of conservation of mass and energy flow through it, and a number of algebraic equations defining phenomena associated with the flow. These are applied to each process that the fluid is subjected to within the machine; namely, suction, compression and discharge. The set of differential equations thus derived cannot be solved analytically in closed form. In the past, various simplifications have been made to the equations in order to expedite their numerical solution. The present model is more comprehensive and it is possible to observe the consequences of neglecting some of the terms in the equations and to determine the validity of such assumptions. This provision gives more generality to the model and makes it suitable for other applications. More about screw geometry generation and mathematical modeling can be found in Stosic and Hanjalic (1997) and Stosic et al (2005).

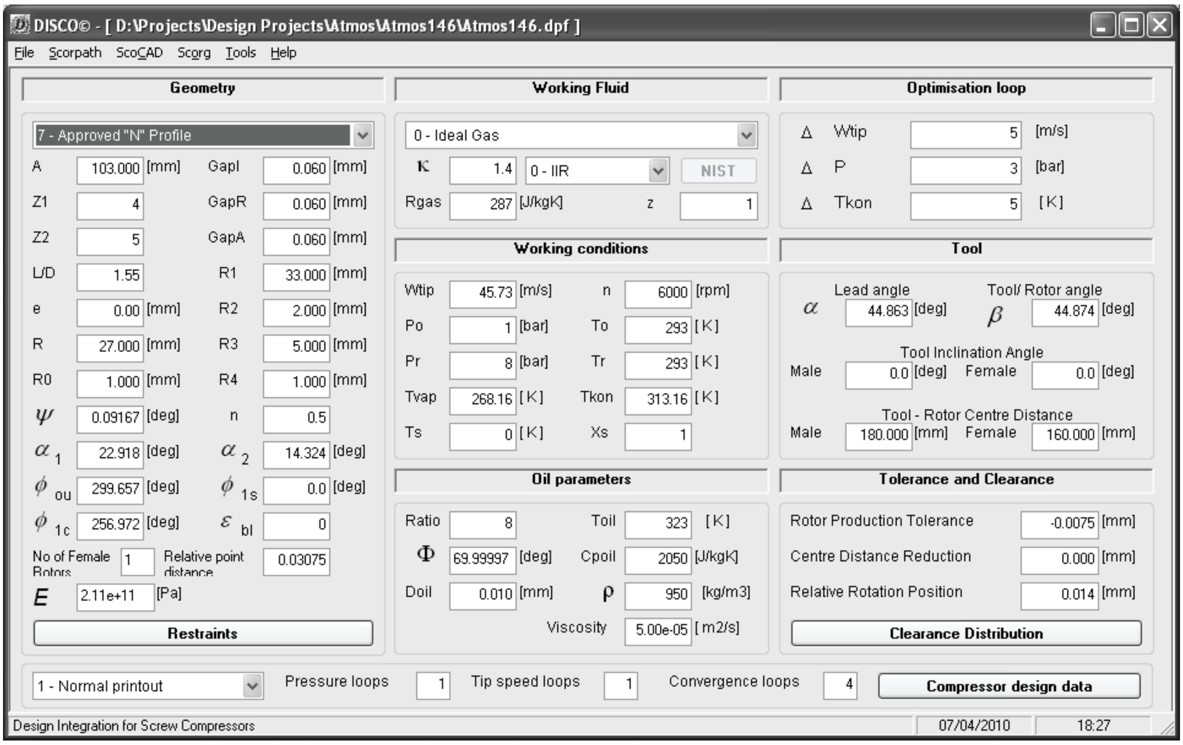

Figure 1 SCORPATH environment within DISCO

The requirements for optimum design of the rotors and other elements of screw machines differ for each application and working fluid. Optimization targets may therefore be different and should be set according to the design requirement. Thus, if high efficiency is required, the specific power or adiabatic and volumetric efficiencies will be targets, if the machine capacity is to be maximized, then its flow will be the optimization target. SCORPATH employs a box constrained simplex method which is used here to find the local minima. One or more optimization variables may be limited by the calculation results in the constrained box method. The optimization results, after being input to an expandable database, finally serve to estimate a global minimum. The database may be used later in conjunction with other results to accelerate the minimization. All features described in this chapter are contained in SCORPATH, a main software package developed by authors, Figure 1.

2.2 Mechanical Design

Although all the parameters required for generating detailed manufacturing drawings are now available, based on the results obtained with SCORPATH, there is still a lot of outstanding design work before the screw machine can be manufactured. This part is managed by SCOCAD as a part of the design software package which transfers the SCORPATH data to an arbitrary CAD system. These data are provided as the 2-D coordinate points of the rotors and 3D coordinate points of the ports. Since these are automatically transferred to the CAD system, a 3-D solid model can be built in a short time. Additionally, parametric organization of the data interchange through an external database, such as MS Excel, enables the design to be easily modified not only from the CAD system itself but also from both the external database and the SCOCAD environment. Being incorporated in DISCO, SCOCAD then enables the design changes to be introduced to other applications integrated in the DISCO environment.

SCOCAD also consists of set of subroutine which represents aids for the mechanical design. An example is the bearing selection routine in which the bearings are chosen from a built-in SKF database of bearings and their life is calculated based on the bearing life theory. Similarly, the locking nuts, shaft keys and keyways, dowel pins, bolts and screws are automatically calculated and selected from a standard database to ensure effective performance of the design. Thickness of the casings is also calculated and recommended here, based on the strength of the material specified by the user. Inlet and outlet terminal points are defined from a database of standard flanges, also incorporated into the SCOCAD module.

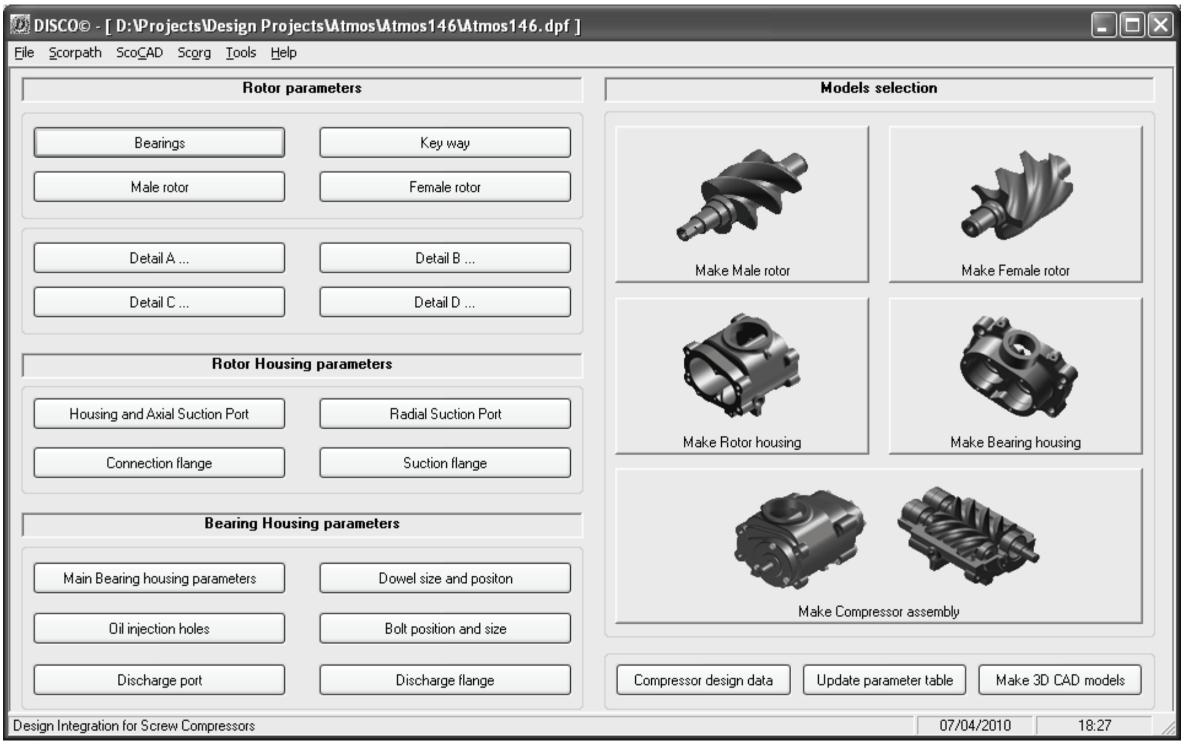

Figure 2 Control module of SCOCAD

The main design screen is shown in Figure 2. Alterations made to general machine parameters as well as to other details of the machine are made through this screen. A graphical user interface generates a set of 2D principal or section views of the screw machine, which are updated in real time, following any change introduced by the user in the current design. This enables the user to visually monitor changes and to evaluate decisions instantly without waiting for the models to be generated in the CAD software. This approach combined with built in databases for selection of standard elements greatly reduces the design time and enables the designer to find an optimum solution for almost any design task. However, if necessary other base elements for the screw compressor calculation and its CAD, as well as spread sheets and data bases, can be used to form and complete the design package instead of the applied ones. The choice depends on availability and customer preference.

A user is able to generate 3D solid models of rotors and casings, as well as a whole machine assembly, in any of the following 3D CAD software packages: Autodesk's Inventor and Mechanical Desktop, SolidWorks and ProEngineer. Since these 3D CAD software accommodate a parametric approach to the design, usually through an MS Excel external database, a spreadsheet is used here as a connection between the 3D models of the compressor components and the DISCO environment. Therefore, all changes introduced or generated by each basic program are automatically updated in all components and a full 3D model of the machine is generated with minimum manual input. DISCO also registers and enables the user to import all changes made independently in CAD software back to the main project. The 3D solid model obtained from the CAD system serves as a basis to generate a numerical grid for structural or fluid flow analysis. From these 3D models, drawings are automatically generated to provide support for conventional manufacturing methods.

2.3 Design improvements and optimization

Having completed the basic and mechanical design of the screw machine it is possible to further analyse its performance by use of commercial CCM software. By this means the influence on the machine performance of rotor and housing deflections, caused by thermal or pressure loads, can be estimated. Also, flow losses or noise generation in the machine ports (Mujic et al, 2007) can be evaluated and necessary changes introduced to reduce them.

These analyses are supported in DISCO by the SCORG (Screw Compressor Rotor Grid generator) module. SCORG is a software package that enables automatic generation of a 3D grid needed for calculation of fluid flow in the screw machine, as described by Kovacevic et al (2001). The numerical mesh is generated by use of a specially developed boundary point distribution and adaptation procedure followed by an analytical internal point generation procedure. A hybrid method based on Hermite transfinite interpolation is used for generation of internal points. By this means SCORG enables the 3D CFD pre-processing to be completed automatically using data generated by SCORPATH. Additionally, only about ten other parameters are required to specify the required grid quality. The authors have developed an automatic numerical mapping method for arbitrary geometry of screw machine, as explained in Kovacevic (2001), which was later used for the analysis of the processes in screw machine, as reported in Kovacevic (2002 and 2004). SCORG also enables a grid, generated by the program, to be directly transferred to a commercial CFD code through its own pre-processor. By this means all previous work on the generation and thermodynamic calculation, as well as the design changes obtained through DISCO, are fully connected into the unique tool for design of screw machines.

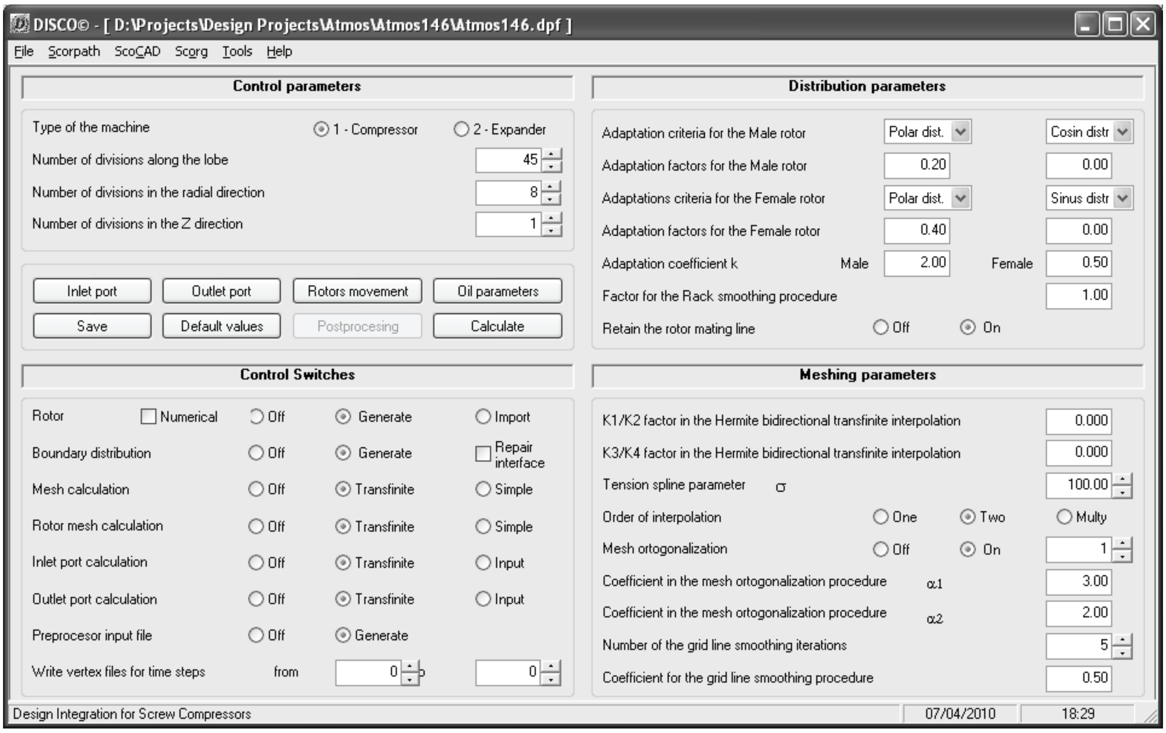

Figure 3 Control module of SCORG

SCOCCM is another part of the design interface which allows fast and accurate introduction of the compressor geometry and working parameters generated by SCORG and CAD system into commercial Computational Continuum Mechanics software. The computational grid of the screw compressor rotors generated by SCORG and the numerical grid of other parts of the machine, the suction or the discharge chambers, which may be generated from either SCORG or CAD system, are imported to CCM software through the pre-processing file. That file also contains working parameters, information of the differencing scheme and other required solver information. A number of commercial computational fluid dynamics, software packages are available on the market. Authors employed COMET and StarCD of cd-Adapco and CFX of Ansys for the screw machine calculations. That code offers a possibility simultaneously to calculate both the fluid flow and solid structure by application of a computational continuum mechanics principle. By this means all previous works on the generation and thermodynamic calculation as well as the design changes obtained through DISCO are fully integrated into an integrated tool for design of screw machines.

3. EXAMPLES OF DESIGNS OF SCREW MACHINES

A few examples of the most recent designs carried out completely within the DISCO environment are presented here. As expected, design and analysis time were reduced significantly. Apart from that, all the later required alterations of the specific design were carried in an easy manner within the DISCO environment.

3.1 Design of Oil Flooded Air Compressor

The first example shown in Figure 4, (courtesy of ATMOS, Czech Republic), shows a 3D model and assembly drawing of the A150 air oil flooded screw compressor. The compressor has been designed for a pressure range of 3-15 bar, delivering up to 800 m^3/h of air.

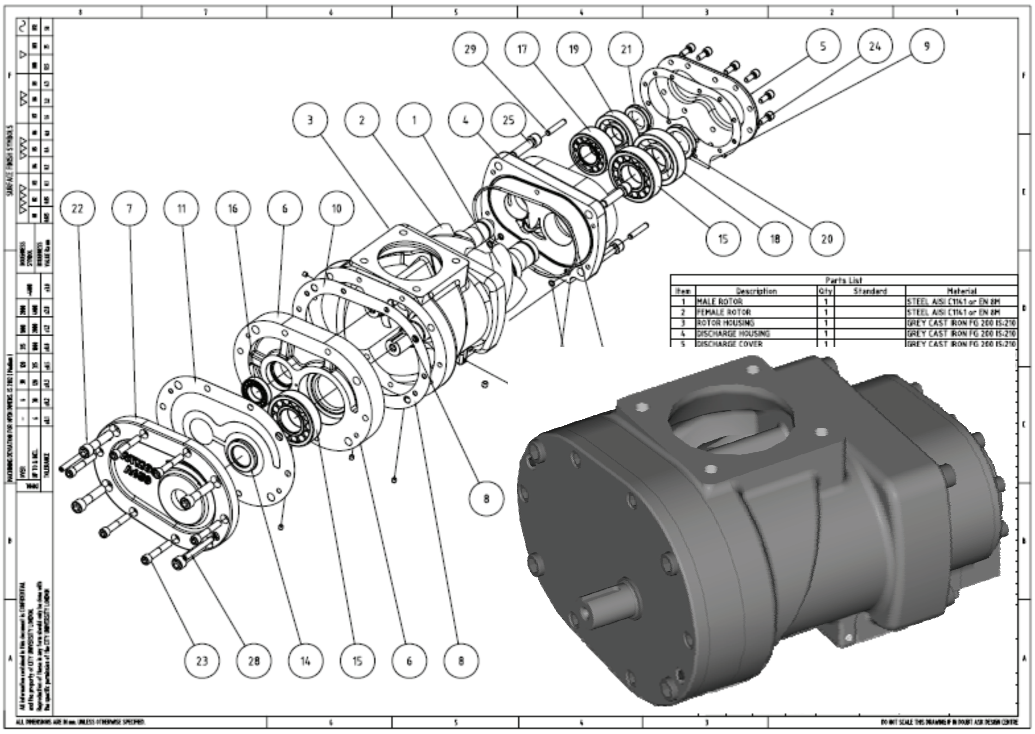

Figure 4 Model and drawings generated by DISCO with Mechanical Desktop

3.2 Design of Screw Expander

In Figure 5 (courtesy of Geodynamics Australia) are shown model and assembly drawing of a screw expander machine. Three dimensional models of the machine generated by DISCO were used extensively for stress analysis of the casings of this machine.

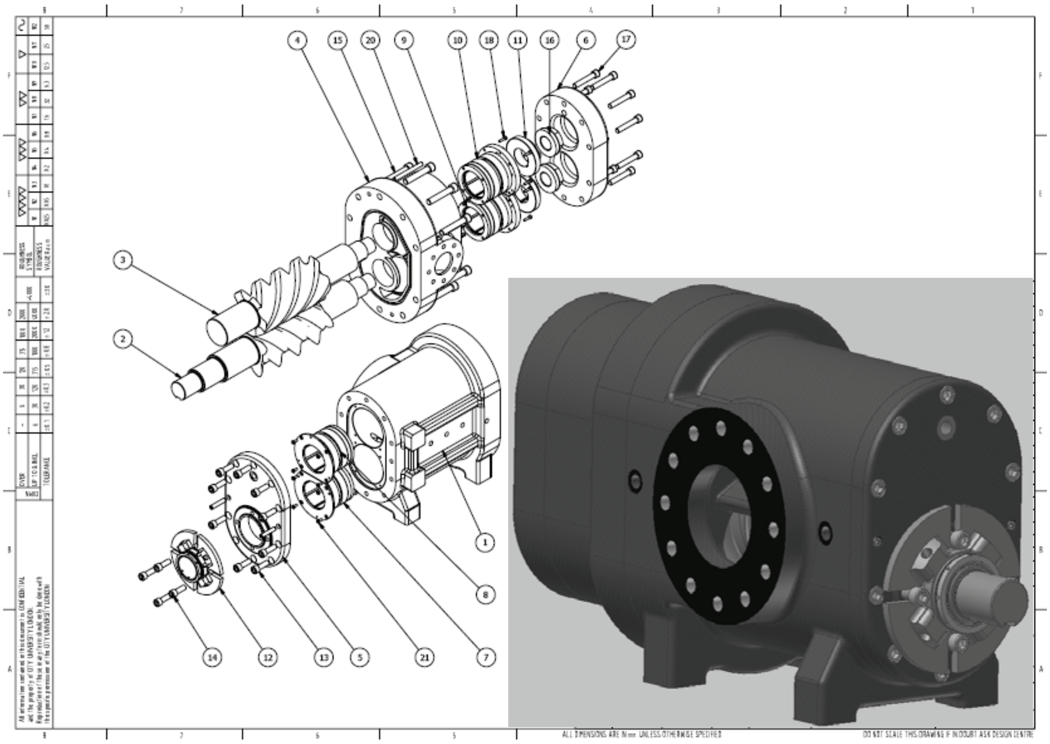

Figure 5 Model and drawings generated by DISCO with Autodesk Inventor

3.3 Design of Compressor-Expander screw machine

Figure 6 (courtesy of Avtovaz Russia) shows a 3D model and the results of CFD analysis of a compressor-expander machine used for a fuel cell application. CFD results give the pressure and temperature distribution on the male rotor of the machine. The machine is used for delivering 100 kg/h of compressed oil free air to a fuel cell stack. The outlet pressure varies between 2 to 3.3bar. The efficiency of the machine and whole system is improved by the expander component which is driven by the fuel cell exhaust products.

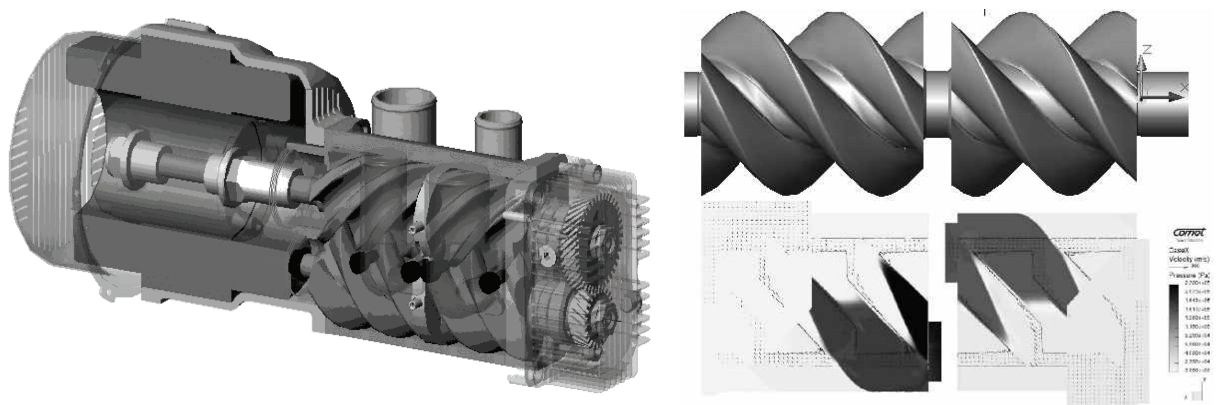

Figure 6 Left - CAD Model of compressor-expander; Right – Pressure distribution obtained by CCM analysis

3.4 Design of Screw pump

A 3D model of a screw pump is shown in Figure 7 (courtesy of PTL UK). The pump is used for pumping a mixture of crude oil and gases. Special design of the rotors enables this pump to work with fluid containing solid particles.

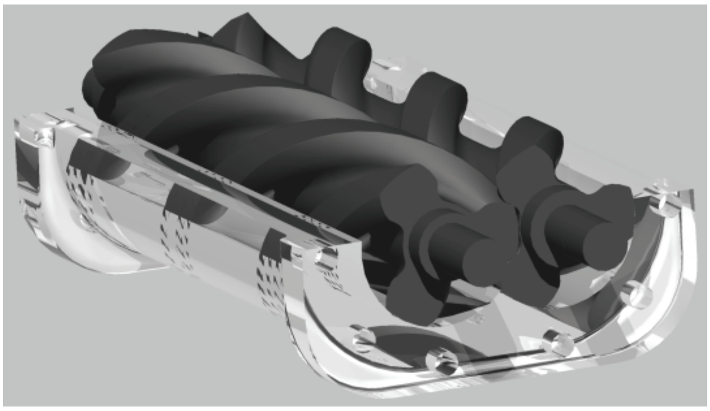

Figure 7 Screw pump rotors

4. CONCLUSIONS

The advanced design environment described in this paper requires only a few input parameters, which specify the geometry and operating conditions of a screw machine. It allows full control of the design process. This means that all changes made in the final 3D model affect previous phases of the process and vice versa. Therefore, the control over the design process is parametrically conducted from only one place, and redundant data and modelling procedures are reduced. This in turn saves both computer resources and design time where, by traditional procedures, any change requires substantial effort to be implemented in all design phases. These and many other software capabilities were proven to be enormous help through a number of designs of different screw machine.

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