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FLUID-SOLID INTERACTION IN THE DESIGN OF MULTIFUNCTIONAL SCREW MACHINES

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1. Introduction

Although the principle of operation of screw machines as compressors or expanders is well established, there is no record of their having been used for simultaneous expansion and compression with only a single pair of rotors. This paper describes how such a novel application of screw machines has been analysed by simultaneous calculation of the fluid flow and rotor deformation.
It is well known that, in a screw compressor, gas is admitted at low pressure through the suction port at one end of the casing, is then compressed between the rotors and discharged through the high pressure port at the opposite end of the casing. If the direction of rotation of the screw compressor rotors is reversed, the gas will flow into the machine through the high pressure port and after expansion between the rotors, it will go out through the low pressure port and it will act as an expander. Moreover, a screw machine will work as an expander when rotating in the same direction as a compressor provided that the suction and discharge ports are positioned on the opposite sides of the casing to those of the compressor, since this is effectively the same as reversing the direction of rotation relative to the ports.

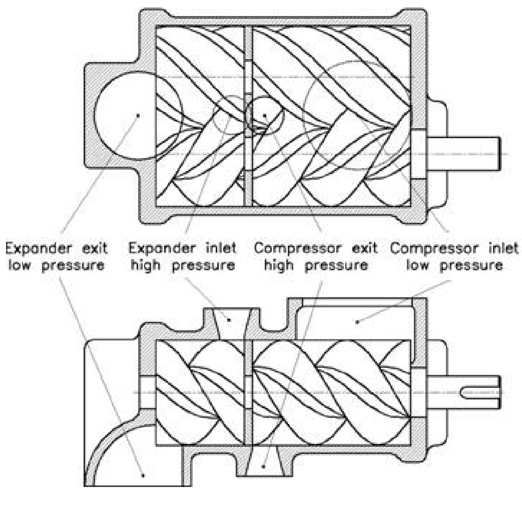

Figure 1. View of the multifunctional rotors acting simultaneously as compressor and expander

Fig. 1 illustrates the arrangement of a screw machine, which both compresses and expands in one pair of rotors. High pressure gas to be expanded enters the expander port at the top of the casing, near the centre, and is expelled from the low pressure port at the bottom of the casing at one end. The expansion process recovers power and causes the rotors to turn. Gas to be compressed enters the low pressure compressor port, at the top of the opposite end of the casing, is compressed within it and expelled from the high pressure discharge port at the bottom of the casing, near the centre.

The same principle may be used for a two stage compressor, by exchanging the positions of the second stage ports. The low pressure suction port of the second stage will then be located on the top of the machine and the high pressure discharge port will be at the machine bottom. This offers the possibility of a compact two stage machine that may be used either in the oil flooded or dry operating mode. A two stage expander can operate in the same manner by reversing the direction of rotation of the rotors.

If the same rotor profile is used for the compression and expansion sections, then the rotors can be manufactured in a single machine operation by designing them to form a full sealing line on both contacting surfaces.

Pressure forces heavily load screw compressor rotors. The bearings on each end of the rotors have to withstand both the radial and axial loads. As a result, some of the power transmitted through the rotors is lost in bearing friction. By combining both functions in one pair of rotors, the axial forces on the rotors can be fully balanced and the radial forces partially balanced. Thus mechanical friction losses will be less than if the compression and expansion processes were performed in two independent units. The machine mechanical efficiency will thereby be increased.

2. Software Suite for Screw Compressor Design

Effective design of screw compressors requires rotor and casing optimisation, 3-D flow and structure analysis and drawing of the mechanical construction to be carried out as a combined interactive procedure. The need for this is even greater when designing more complex machines, like combined screw compressors and expanders.

A number of independent software packages for each of these functions have already been developed at City University and details of them have been published. More recently, it has been realised that the repetitive use of each of them can be minimised if they are all connected through a single user interface. Also, by this means, any modifications to a design can immediately be cross referenced with the design software units used. This results in substantial savings of both computer resources and design time.

To this end, an interface has been developed, as described here, to interconnect the following software packages.

- SCORPATH – Screw Compressor Optimal Rotor Profiling And Thermodynamics, a program for the estimation and optimisation of the compression and expansion processes.
- SCORG – Screw COmpressor Rotor Grid, a compressor/expander grid generation program
- A CFD tool for simultaneous 3-D analysis of the heat and fluid flow and its effect on the solid structure
- An accessories data base
- A CAD system

2.1 Rotor and Compressor Process Calculation and Optimisation

The algorithm used for the analysis of the thermodynamic and flow processes and their optimisation is based on a set of differential equations, which describe the physics of the compressor processes. It comprises the rotor geometry, which gives the instantaneous operating volume changes with shaft rotation angle, and equations of conservation of mass and energy, as well as a number of algebraic equations defining phenomena associated with them.

The rotor and compressor design is obtained in one pass by combining the algorithm with a minimisation function for simultaneous optimisation of a number of key variables. These include the four rotor profile radii and the machine built-in volume ratio, as well as operating parameters, such as the oil flow rate, its temperature and injection position and droplet size.

The optimisation target depends on the design requirement. Thus for high machine efficiency the specific power or adiabatic and volumetric efficiencies are targeted. On the other hand, if the compressor capacity is to be maximized, the aim is to maximise the compressor flow. Any combination of these and other requirements is possible.

A box constrained simplex method was used to find the local minima. It selects the simplex stochastically, as a matrix of independent variables and calculates the optimisation target. This is later compared with those of previous calculations and then their minimisation is performed. The optimised results are then input to an expandable compressor database and finally serve to estimate a global minimum. The database may be used later in conjunction with other results to accelerate the minimisation. All these features are contained in the software package developed in house, known as SCORPATH, details of which can be found in Stosic at al [2003].

2.2 3D Fluid Flow and Structure Analysis

The authors have developed an automatic numerical method for the mapping of any arbitrary screw compressor geometry. This has been used for the analysis of the processes in screw compressors by attaching it to any numerical procedure, which is suitable for the simultaneous solution of fluid flow and structural analysis, as described by Kovacevic et al [2002]. This led to the development of the SCORG software package, which enables the grid, created by the program, to be directly transferred to a commercial Computational Fluid Dynamics code, through its own pre-processor. A number of commercial CFD software packages are currently in use. That used by the authors is the CD-Adapco COMET. This code can calculate both the fluid flow and its effect on the solid structure simultaneously by means of the Computational Continuum Mechanics (CCM) principle.

2.3 The User Interface

In order to produce a compressor of specified performance in the minimum time and at least cost, it is highly advantageous to use a single program suite to serve as a computational aid for the complete from the initial conceptual design to the production of manufacturing drawings and analysis of test results. The authors have developed a program interface, which manages all the program components, which define the geometrical, thermodynamic, optimisation, boundary and operating parameters of a screw compressor and connects them to CAD and CFD software. Since Mechanical Desktop accommodates a parametric approach to the design, Microsoft Excel is used as an external database to connect 3D models of the compressor components. Therefore, all components and a full 3D model of the machine are generated with minimum manual input. The model then serves as a basis both for rapid prototyping and the automatic generation of drawings required for conventional manufacturing methods.

The interface starts with only a few input parameters needed to describe the machine geometry and operating conditions, it enables complete control to be retained over the each step of the design process providing that all changes in any phase, introduced or generated by each basic program are automatically updated and returned to all previous and following design phases. By this means, the design parameters are controlled from one place only, showing full process flexibility and user adaptability and all previous work on the generation and thermodynamic calculation as well as any design changes obtained through the management interface are fully connected in the unique data container. Therefore, redundant elements in the data and modelling procedures are reduced. This, in turn, saves both computer resources and the time wasted in classical design procedures where any change requires substantial effort to be implemented in all design phases.

Other CFD and CAD base elements than those chosen can be used for the screw compressor calculation, as well as spread sheets and data bases, to form and complete the design package. The choice depends on availability and user preference.

3. Application Examples of Multifunctional screw Machines

Three examples of the use of multifunctional rotors are presented here. These are:

I. As a combined compressor-expander to improve the efficiency of fuel cells.
II. As a combined compressor-expander to enhance the prospects for the use of CO_2 as a refrigerant
III. As a two stage air compressor to obtain high compression efficiencies.

All these applications required interactive calculation of the fluid flow and associated structure deformation. The fuel cell example is described in detail. Only an outline description is given of the other two cases.

3.1 Compressor-Expander for Fuel Cells

Hydrogen proton exchange membrane fuel cells require a continuous supply of saturated air at flow rates of 100-300 kg/h at a pressure of approximately 3 bars. The products of the reaction, containing mainly nitrogen and water, are rejected from them at approximately 80-100^{o}C and 2.8 bars. The power input required for compressing the air is currently of the order of 20% of the fuel cell electrical output and this is unacceptably high for the unit to be competitive. Therefore, power recovered from the expansion of the discharged reaction products has to be used to drive the compressor.
A special rotor profile was generated to provide sufficient sealing of the blow hole areas on both sides of rotors. This is the main prerequisite for both the expansion and compression processes to be efficient. The optimisation of the rotors and compressor geometry and operation conditions were performed by SCORPATH. The 3D CAD model, as developed in Mechanical Desktop, using a fully parametric approach, is presented in Fig 2, together with a photograph of all the machine elements.

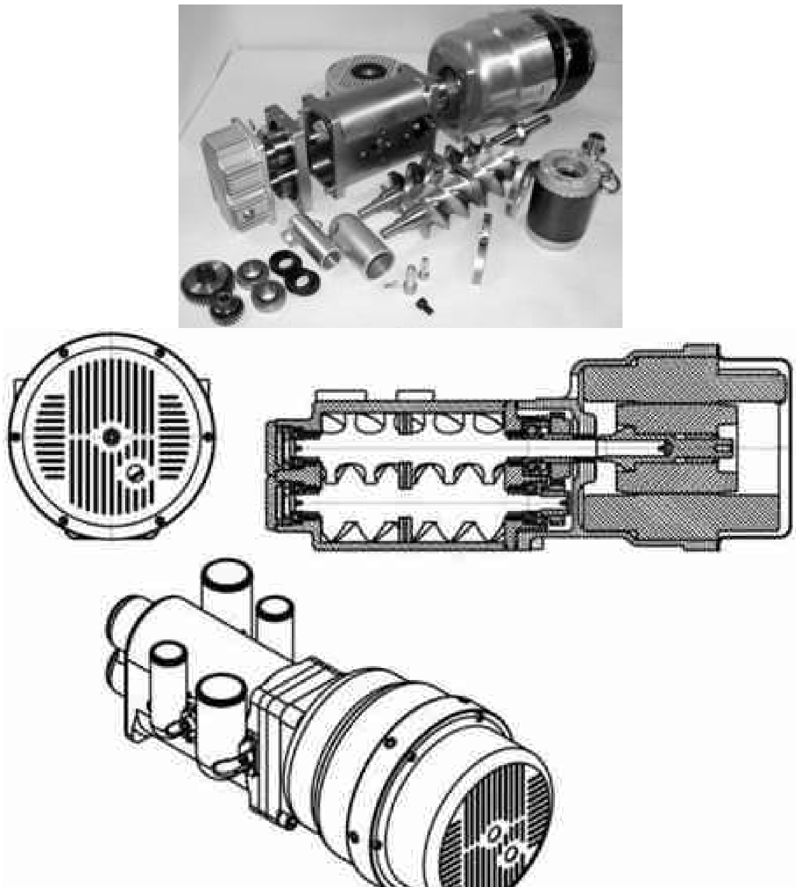

Figure 2. Views of the fuel cell compressor-expander and its elements

The compressor suction pressure and temperature were atmospheric while the discharge pressure exceeded 3 bars with a temperature of up to 80^{o}C. The temperature was kept low by humidifying the air at the compressor suction. The mixture of nitrogen and water vapour at the expander inlet was assumed to be at a pressure of to 2.8 bars and a temperature of 100^{o}C. The optimum male rotor of the machine was found to be 69 mm with an axial distance between the rotors of 48 mm. The compressor length/diameter ratio was 1.2 while that of the expander was 1.0. The rotational speed of the male rotor was assumed to be 9500 rpm.

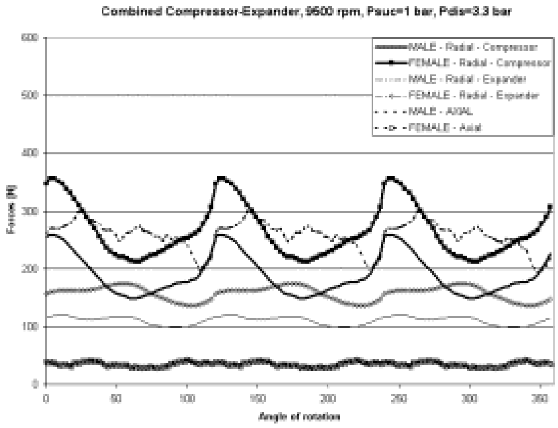

Figure 3. Rotor temperatures given on deformed grid

Figure 4. Axial and radial forces for combined compressor-expander

The calculated temperature and pressure distribution within the machine served as the basis for its mechanical design. Although the air temperature within the machine is relatively high, the temperature of the rotors is not because they rotate at high speed between regions of high and low temperature. Nonetheless the gases at the centre of the machine, where the high pressure air is delivered on one side and the hot products are admitted on the other, cause the rotors to deform in this region. There is no significant distortion at the bearings, which are located in regions of low temperature.

These effects are shown in Fig.3 where the deformation of the rotors is magnified by a factor of 1000 in order for it to be visible. The pressure has little influence on the deformation of the relatively stiff rotors but the changes in temperature cause them to enlarge locally at the centre of the machine and thereby reduce the clearances by 30-40 μm during operation. The effect of this is to reduce the leakage flow in the critical region, where the pressure differences are largest, and hence the volumetric efficiency of the machine is increased. Such an arrangement requires only two pairs of bearings compared with four for a separate compressor and expander. This reduces the overall weight, which is important for automotive applications. In addition, both the radial and axial forces on the bearings are reduced, as shown in Fig. 4. This latter feature hardly affects the rotor deformation but is advantageous if smaller and lighter bearings are required.

3.2 Compressor-Expander for CO_2 Refrigeration Systems

Recent interest in natural refrigerants has resulted in more intensive studies of CO_2 as a working fluid in vapour compression systems for refrigeration and air conditioning. Two major drawbacks to its use are the very high pressure differences required across the compressor and the large efficiency losses associated with the throttling process. To overcome the throttle losses, it is proposed to combine the compressor with an expander to recover work from the expansion process. Furthermore, the combined compressor expander as described in this paper fully balances the axial loads and reduces the radial bearing loads. Design problems associated with high bearing loads in screw compressors for CO_2 systems are thereby reduced.

3.3 Two-Stage Air Screw Compressor

Two stage compression in one pair of rotors reduces leakage losses and hence improves both the volumetric and adiabatic efficiencies compared to single stage machines. One pair of screw rotors can be used for simultaneous compression in both the first and second compressor stages. Such a compressor is presented in Fig. 6. As can be seen, the rotor diameter, as well as the rotor profiles is the same for both stages. The first stage, with the longer rotors, is on the right while the second higher pressure stage is shown on the left. This principle has been known for some time, but, to date, no successful applications of it have been reported. A two stage compressor of this type has now been designed and prototypes of it are being manufactured.

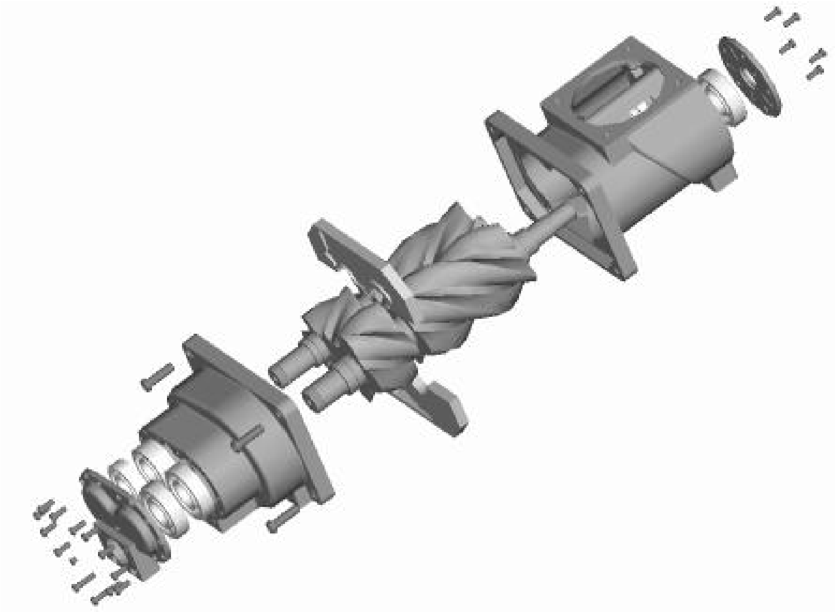

Figure 5. Two-stage compressor on one pair of rotors

4. Conclusions

The program suite described in this paper serves as the managing interface for elementary design software used for the development of screw machines. It requires only a few input parameters to specify the geometry and operating conditions of a screw compressor. It allows full control of the fully parametric design process between profile generation, process calculations, optimisation, 3D CAD modelling and numerical analysis. This enables changes made in any stage of the process to be accounted for in all other phases either earlier or later. Therefore, control of the design process is conducted parametrically from only one place, and redundant data and modelling procedures are reduced. This in turn saves both computer resources and time. An example of the development of a new machine, which comprises both compression and expansion in the working chamber, as well as two additional machine proposals, is presented in the paper.

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