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Systematic engineering design approach for improvement of oil-free twin-screw compressors

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Abstract. Twin-screw compressors are widely used in industry, especially in compressed air, refrigeration, air-conditioning and process gas which consume a significant part of the world's energy. Nowadays, oil-injected compressors represent the majority of twin-screw compressors in the market due to their high efficiency and reliability. The oil-free compressor is potentially a better solution in the context of the net-zero CO2 target in 2050. However, due to its high thermal deformation and small clearances, this technology still suffers from reliability issues. To remedy this problem disruptive innovative solutions are required. In this purpose, the present study uses a systematic engineering design process to develop new concepts for the improvement of the oil-free twin-screw compressor. The paper is focused on the first two phases of the design process which are the definition of problem and the conceptual design. In the problem definition, main objectives are expressed and are divided into sub-objectives and weighed using an objective tree decomposition. Moreover, a thorough functional model of the oil-free compressor is detailed with a focus on the leakage paths and heat transfers. For the conceptual design, engineering characteristics extracted from the functional analysis have been assessed against the most important objectives using Quality Function Deployment matrices (QFD). Based on the developed problem definition, new concepts have been generated and three distinct concept categories have been further explored: Secondary flow; Surface features; Clearance control and monitoring. The evaluation, embodiment and detailed designs of the concepts, using experimental and numerical analyses will follow.

1. Introduction

The main purpose of this study is to present the use of a systematic engineering design method to improve the efficiency and reliability of oil-free twin-screw compressors and thus develop their market among oil-injected ones. This research is part of the project SECRET (Smart Efficient Compression: Reliability and Energy Targets) which is funded by Royal Academy of Engineering and Howden. To understand the relevance and importance of this research, it is therefore essential to recall the context of global warming and compressor market by citing some key figures.

The impact of human activities on climate change and global warming are now known by everyone and it is a major societal preoccupation. Following COP21 in 2015 in Paris and COP26 in 2021 in Glasgow, most countries are in agreement to try to limit the rise in global temperature to 1.5 °C [1]. As a figure of example, the UK developed a strategy of net zero Greenhouse Gas (GHG) emissions by 2050 [2]. Recently the Intergovernmental Panel on Climate Change (IPCC) published its sixth assessment report that shows, among other things, that the increase of GHG since 1750 are caused by human activities, which in turn have raised global temperatures between 1 to 2 °C during the last decade when compared to records of 1850-1900 [3]. Moreover, in 2019, GHG were mainly composed by 64% of CO2 coming from fossil fuel, 18% of CH4 (Methane) and 11% of CO2 coming for land use [4].

Based on BP statistical and IEA (International Energy Agency) it is known that fossil fuel represented, in 2019, 84% of the primary energy consumption in the world, as well as, 60% of the generated electricity [5]. Industry, among all the other sectors, is responsible for more than 40% of the total electricity consumption [6].

Compressor systems are widely used in the world, in every sector (industry, domestic, commercial...) and for a wealth of applications. There are too many applications to list them all but they can be categorised in two main groups: process gas applications (refining, chemical, exploration...) and compressed air applications. Various sources quote that 10% of industrial electricity consumption in European countries is used by compressed air systems [7, 8]. Two reports ordered by the European Commission published in 2014 and 2017, shows that, in 2010 in the EU, 42% of energy consumption in compressed air systems (driven by electric motors) was consumed by oil-injected screw and vane compressors (7-15 bar (g)), 31% by low pressure compressors (all types, 0.05-3.5 bar (g)), 26% by oil-free compressors (all types, 7-15 bar (g)), and to a lesser extent by reciprocating compressors (1%) [9, 10].

Correlation of the figures previously cited gives that around 1.7% of generated electricity is directly consumed by oil-injected screw compressors, 1.3% by low pressure compressors and 1.1% by oil-free compressors[1]. These figures clearly demonstrated that oil-injected twin-screw compressor is the most common and most energy consuming compressor, which can be explained by the maturity of this technology that shows high efficiency and high reliability [11,12]. Figures for oil-free twin-screw compressors are not expressed directly and are included in low pressure compressors (with roots blower, turbo, scroll...) and oil-free compressors (piston, water-injected screw, scroll...).

Although based on the same principle of using helical screws to reduce the chamber volume and increase the pressure of gas, oil-free and oil-injected twin-screw compressors are very different [13]. Oil-injected compressors operate with one driven shaft and direct contact between screws. They use oil as a lubricant to limit wear, to seal the internal clearances, and to limit and carry away the heat generated by the compression process and minimise thermal deformation. Moreover, bearings are usually lubricated with the same oil supply which eliminates the need for mechanical seals between the gas chamber and the bearings. Oil-free compressors are synchronised using a timing gear and operational clearances prevent contact between screws. Clearances are relatively larger than the oil injected ones to accommodate thermal deformation due to compression. To avoid contamination of the process gas by the lubricated bearings, seals are mandatory.

For oil-free twin-screw compressors, it is estimated that a reduction of 20% of internal leakages will lead to a reduction of 2% of energy consumption. This, associated with the needs of reliability and reduction of use of fossil fuel will allow the oil-free screw compressor to expand its market and become the preferred solution in compressed air and process gas sectors.

The project SECRET is born in this context. This five years project awarded to City,

[1] This correlation is based on the assumption than the European Union compressor market is representative of the world market.

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University of London aims to pave the way for the future of compression technology. Thus, it is divided into three phases: I. Understanding the physic of leakage flows and Conjugate Heat Transfer (CHT) in clearance gaps; II. Building and testing an efficient and reliable prototype machine; III. Developing a smart efficient commercial screw machine.

To achieve the first phase, an experiment was developed based on a roots blower specifically modified to integrate an optical access to the radial clearance gap and observe the leakage flow during normal operation. This apparatus allowed the measure of surface and leakage flow field temperatures as well as flow velocity, boundary layer and vortex formation by various techniques. Surface temperatures were measured by high speed infrared thermography [14]. Flow velocity, boundary layer and vortex formation by Particle Image Velocimetry (PIV) [15,16]. Leakage flow field temperatures by Planar Laser-Induced Fluorescence (PLIF) for which the feasibility was demonstrated [17]. These experiments are exploited to validate the development of CFD tools to improve the modelling of CHT in leakage flows [18] which can then be used to model more complex geometries.

The second phase of the project consists of building and performing extensive laboratory tests on an oil-free screw compressor prototype. New concepts developed using the systematic engineering design process and presented here will be tested into the prototype and evaluated based on the performances. In parallel, research on innovative techniques of monitoring and control of clearance gaps applied to positive displacement machines is conducted by a PhD student [19]. This phase of the project will lead to the selection of concepts which demonstrated the best improvements in the prototype. The final phase will be in closer collaboration with Howden Compressors to develop and fully test a new commercial oil-free twin-screw compressor built with the selected concepts, and the monitoring and control system.

Finding innovative disruptive technological solutions to reach the goals of improving efficiency and reliability of oil-free twin-screw compressors is very challenging, especially due to the competitive level of efficiency that corresponds to this high technology readiness level. Thus, to develop new concepts which can be implemented in an oil-free compressor, a systematic approach of engineering design process has been employed. The next sections of this paper will present the systematic engineering design method, and subsequently describe how this method is applied to the oil-free twin-screw compressor design. A discussion will conclude on the use of this method and highlight future developments.

2. Systematic engineering design method

This systematic approach is made to rigorously decompose and fully define a complex problem for which solutions will be generated, compared and refined based on quantitative criteria. Various models defining systematic design process have been proposed in the literature but, the process map defined by G. Pahl et al. [20] is considered as the benchmark for a modern systematic design process [21]. Overall, this process can be divided in four steps, which are: 1) Planning and clarifying the task (or problem definition); 2) Conceptual design; 3) Embodiment design; 4) Detail design. Along this design process decisions are made to progress from step to step and the design is refined using iteration between steps.

This process map is general and can be applied to a wide variety of projects/product designs. In this study, as the initial goal is to define new concepts/solutions for an existing product the focus will be on the first two steps. These two steps can also be seen in the form of the symmetrical problem-solution model presented in Figure 1b. and given by N. Cross in his book [22]. This second model is interesting because it shows the decomposition of a whole problem, which is usually hard to approach, into sub-problems that are easily defined. These sub-problems are used to generated sub-solutions, and sub-solutions are evaluated and combined to form the global solution.

A mix of these two models was adopted to develop the concepts in two distinctive phases: Problem definition and Conceptual design. Problem definition regroup: Identifying opportunities; Clarifying objectives; Establishing functions; Setting requirements and Determining characteristics. Conceptual design is divided into Generating alternatives, Evaluating alternatives, and Improving details. In the problem definition, the identification of opportunities is not addressed in this study as it is related to the wider project SECRET. Conceptual design will be succinctly described in the paper as new concepts developed during this phase cannot be disclosed before the end of the project.

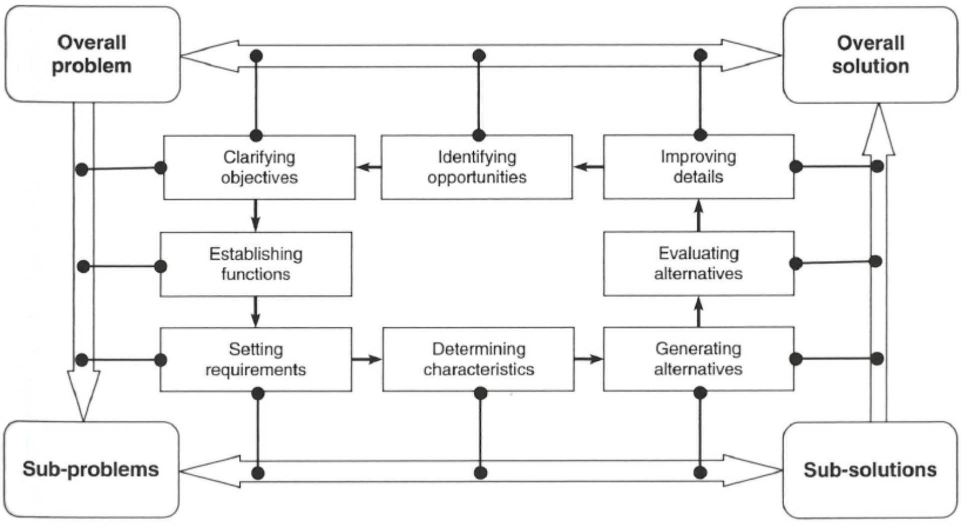

Figure 1. Symmetrical problem/solution model [22].

3. Problem definition applied to the oil-free twin-screw compressor

3.1. Objectives definition

The main objectives of the project SECRET are to improve efficiency and reliability of oil-free twin-screw compressors by keeping a relatively low cost. These objectives are global and hardly achievable directly. To make SMART (Specific, Measurable, Achievable, Realistic, Time-bound) objectives an objective tree was used as a decomposition tool.

Working groups have been formed in the team from City, University of London and Howden Compressors to build the objective tree for all three main objectives: Increase efficiency; Increase reliability; Minimise cost. Due to their large size, these trees are not directly presented in the paper, but results will be shown. In a tree decomposition, the objectives are hierarchical and are expressed in terms of Level, from Level 0 for main objectives to Level 5. Moreover, objectives on a level are rated on a scale from 0 to 1 (percentage scale) respectively to each other under the same objective. A second weight is established by multiplying all hierarchical predecessors with the objective. This second (product) weight is used for the global comparison of objectives on every level.

For example, the objective tree for "Increase efficiency" is presented in the Figure 2 with the relative and global weights for each sub-objective. Level 0 objective (Increase efficiency) is weighted with 0.3 and is divided into three Level 1 objectives: "Increase volumetric efficiency", "Increase adiabatic efficiency" and "Increase isothermal efficiency" with respective weights of 0.6, 0.2 and 0.2 and product weights of 0.18 (0.3*0.6), 0.06 (0.3*0.2) and 0.06 (0.3*0.2).

<table>
<tr><td>Level 0</td><td colspan="22">Increase efficiency</td></tr>
<tr><td>L0 weight</td><td colspan="22">0.3</td></tr>
<tr><td>Level 1</td><td colspan="10">Increase volumetric efficiency</td><td colspan="8">Increase adiabatic efficiency</td><td colspan="4">Increase isothermal efficiency</td></tr>
<tr><td>L1 weight</td><td colspan="10">0.600</td><td colspan="8">0.200</td><td colspan="4">0.200</td></tr>
<tr><td>Product</td><td colspan="10">0.180</td><td colspan="8">0.060</td><td colspan="4">0.060</td></tr>
<tr><td>Level 2</td><td colspan="6">Reduce leakage</td><td>Reduce thermal deformation</td><td colspan="3">Reduce pressure deformation</td><td colspan="4">Reduce power losses</td><td>Match built-in VI</td><td>Reduce suction pressure loss</td><td colspan="2">Reduce discharge pressure loss</td><td colspan="3">Improve cooling</td><td>Reduce frictional losses</td></tr>
<tr><td>L2 weight</td><td colspan="6">0.500</td><td>0.300</td><td colspan="3">0.200</td><td colspan="4">0.500</td><td>0.300</td><td>0.100</td><td colspan="2">0.100</td><td colspan="3">0.700</td><td>0.300</td></tr>
<tr><td>Product</td><td colspan="6">0.090</td><td>0.054</td><td colspan="3">0.036</td><td colspan="4">0.030</td><td>0.018</td><td>0.006</td><td colspan="2">0.006</td><td colspan="3">0.042</td><td>0.018</td></tr>
<tr><td>Level 3</td><td colspan="4">Reduce clearance</td><td>Reduce differential pressure across the gap</td><td>Improve sealing</td><td></td><td>Seals and bearings</td><td>Dynamic deflection from imbalance</td><td>Rotor deflection due to pressure</td><td>Reduce bearing losses</td><td>Reduce flow losses</td><td>Reduce sealing losses</td><td>Reduce drivetrain losses</td><td></td><td></td><td>Throttling loss</td><td>Discharge pressure pulsation</td><td>Cool gas</td><td>Cool rotor</td><td>Cool housing</td><td></td></tr>
<tr><td>L3 weight</td><td colspan="4">0.300</td><td>0.200</td><td>0.500</td><td></td><td>0.3</td><td>0.4</td><td>0.3</td><td>0.1</td><td>0.3</td><td>0.5</td><td>0.1</td><td></td><td></td><td>0.5</td><td>0.5</td><td>0.2</td><td>0.4</td><td>0.4</td><td></td></tr>
<tr><td>Product</td><td colspan="4">0.027</td><td>0.018</td><td>0.045</td><td>0.054</td><td>0.011</td><td>0.014</td><td>0.011</td><td>0.003</td><td>0.009</td><td>0.015</td><td>0.003</td><td>0.018</td><td>0.006</td><td>0.003</td><td>0.003</td><td>0.008</td><td>0.017</td><td>0.017</td><td>0.018</td></tr>
<tr><td>Level 4</td><td>Reduce axial clearance</td><td>Reduce interlobe clearance</td><td>Reduce tip clearance</td><td>Reduce blowhole</td><td colspan="18"></td></tr>
<tr><td>L4 weight</td><td>0.300</td><td>0.300</td><td>0.300</td><td>0.100</td><td colspan="18"></td></tr>
<tr><td>Product</td><td>0.0081</td><td>0.0081</td><td>0.0081</td><td>0.0027</td><td colspan="18"></td></tr>
</table>

Figure 2. Objective tree for "Increase efficiency" with relative weight.

For each level, objectives are ranked using the global weight. Rankings for Level 0 and Level 1 are presented in Figure 3 and Figure 4, respectively. On Level 0, "Increase reliability" is the most important objective as main issues with oil-free compressors are related to reliability. This is followed by efficiency and finally cost. Similarly on Level 1, objectives related to reliability are at the top ("Design for reliable operation", "Optimise reliability metrics", "Facilitate serviceability"). Overall, cost related objectives are less important especially at the early stage of the project, which also serves to initiate a study which is not restricted by cost.

Level 0	Weight
Increase reliability	0.5
Increase efficiency	0.3
Minimise cost	0.2

Figure 3. Ranking of the main (Level 0) objectives.

Level 1	Weight
Design for reliable operation	0.2
Increase volumetric efficiency	0.18
Optimise reliability metrics	0.125
Facilitate serviceability	0.125
Minimise operating costs	0.1
Increase adiabatic efficiency	0.06
Increase isothermal efficiency	0.06
Protect against external environmental conditions	0.05
Minimise capital (purchase) costs	0.04
Minimise maintenance cost	0.03
Minimise sales and admin costs	0.01
Minimise development costs	0.01
Minimise end of life costs	0.01

Figure 4. Ranking of the Level 1 objectives.

Level 3 objectives presented in Figure 5 are very specific and much more measurable and achievable than upper levels. In this list, objectives from Level 2 without descendants are also reported with the Level 3 objectives. This level regroups 78 objectives in total, top objectives are related to reliability like the reduction of thermal deformation, the safe start and stop operation and the safe operation in transient states. Efficiency related objectives are also on top, with the improvement of sealing for internal clearances, the reduction of power consumption or reduction of internal clearances. Level 1 objectives will be used in the definition and selection of functions. Level 3 objectives will be used for the requirements definition and the generation of concepts.

3.2. Functional model

For an oil-free twin-screw compressor, the main function is to compress the gas. The compressor can be defined as a black box with input flows and output flows transformed by this function as presented in the Figure 6. The inputs are the gas flow (at a certain pressure and temperature)

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Level 3 with reported Level 2 alone	Weight
Reduce thermal deformation (Level 2)	0.054
Improve internal sealing	0.045
Reduce power consumption (Level 2)	0.04
Ensure safe start & stop operation	0.04
Safe transient behaviour (speed/load)	0.04
Monitor health in operation (Level 2)	0.03
Personnel damage	0.03
Reduce internal clearances	0.027
Manage thermal loads i.e. cooling requirements	0.025
Minimise cost of failure (Level 2)	0.024
Compressor design for field maintenance (Level 2)	0.02
Simplify / minimise compressor aux. systems (Level 2)	0.02
Conceive easy operation (Level 2)	0.02
Flexible to range of pressure ratio	0.02
Flexible to range of process gases	0.02
Minimise downtime (planned / unplanned)	0.02
Reduce pressure differential across the gap	0.018
Match built-in VI (Level 2)	0.018
Reduce frictional losses (Level 2)	0.018
Cool rotor	0.0168
Cool housing	0.0168
Resist to extreme conditions (Level 2)	0.0165
Adapt to site specific hazards (Level 2)	0.0165
Reduce sealing losses	0.015
High standard of control quality	0.015
Prevent mechanical failure	0.015

Figure 5. Ranking of the Level 3 objectives with reported level 2 objectives - First 26 objectives on a list of 78.

and the mechanical energy. This mechanical energy is used to transform the gas (to reach another pressure and temperature), which implies a transformation of this mechanical energy and generation of losses (gas leaks, heat). In addition, the compressor can receive and transform additional material flows (oil for bearing lubrication, inert gas for sealing, water for cooling...) and signal flows (monitoring and/or control of temperature, pressure, clearances...).

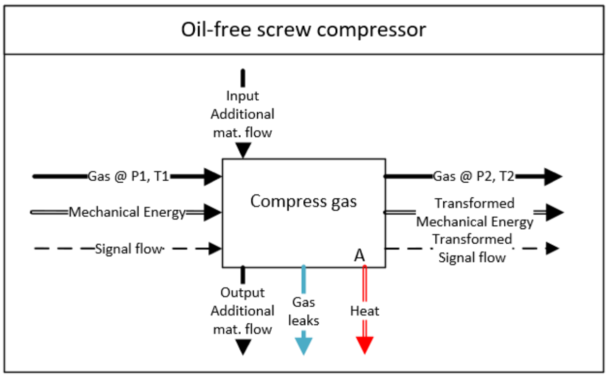

Figure 6. Simplified functional model of an oil-free twin-screw compressor - Main function.

The functional model of the compressor consists of a collection of functions that are completed to achieve the main function. However, as it is difficult to list every functions of a complex system such as the oil-free compressor, it will initially be divided into sub-domains, and functions will be defined for each sub-domain.

The functional model for the whole system (called "Global stream") is presented in the Figure 7. Following the mechanical energy flow (double black arrow on the left of the figure), the functional model starts with the motor shaft (sub-domain #13) which can be considered as an external or an internal part of the compressor. Then it goes to the gearbox (#14) which adapts the mechanical energy for the driving shaft (#15). The driving shaft transfers the mechanical energy to the synchronising gear (#16) and finally to the main (#10) and gate (#11) rotors. Both rotors are guided by bearings (#B) which transfer mechanical energy to the stator (#12). Moreover, bearing seals (#S5) which separate bearing lubricant from the environment and/or from processed gas, also transfer mechanical energy to the stator (#12).

In terms of material flow (top of the figure), which is mainly the processed gas (gas flow), this starts with the gas conditioning at suction (#1) (adjustment of temperature, composition, moisture...) and can be internal or external to the compressor. The gas flow enters the suction domain (#2) where the flow velocities are homogenised, then passes through the suction port (#3) which controls the intake volume and directs the flow into the central chamber (or main gas domain #4) where the compression is achieved by reduction of volume. Flow is released by the discharge port (#5) to the discharge domain (#6) and finally the gas can be conditioned at discharge (#7) (internally or externally).

Mechanical energy coming from the rotors (#10, #11) acts on the main gas domain where it is transferred into internal energy and heat of gas (increase of pressure and temperature), and into heat transferred to solids (#10, #11, #12).

In combination with the gas flow there is a leakage flow which can be defined as a loss of the gas flow and decomposed in several leakage paths. A distinction can be made between external leakage paths going to environment and internal leakage paths opposed to the gas flow and going from a high pressure sub-domain to a low pressure sub-domain. In this way, two external paths have been defined: the low pressure leakage at suction port (#3) and the high pressure leakage at discharge port (#5). These leakages are limited by the use of seals (#S1-S4) on both rotors at suction and discharge and also generate heat and mechanical losses.

Fleming and Tang [23] and more recently Buckney et al. [24] have defined internal leakage paths in twin-screw compressors. Based on that, six internal leakage paths have been identified between sub-domains of the compressor and associated with the existence of the following clearances:

1. Interlobe clearance between main and gate rotor.
2. Radial clearance between rotor tips (both rotors) and housing bores.
3. Blow hole area between rotors and cusps (high pressure side and low pressure side).
4. Axial clearance at discharge between rotors and discharge end plate at the intersection of the rotor shafts.
5. Axial clearance at suction between rotors and suction end plate.
6. Axial clearance at discharge between rotors and discharge end plate at the housing bore side.

The internal leakage paths associated with interlobe, radial and axial discharge clearances are represented in the Figure 8. The blow hole area is not represented in the Figure 8 and corresponds to the area between the two rotors and the housing cusp on the low pressure side (upper side of Figure 8) and on the high pressure side (lower side of Figure 8). The blow hole area is mainly dependant on the rotor profiles and will not be specifically addressed in this paper.

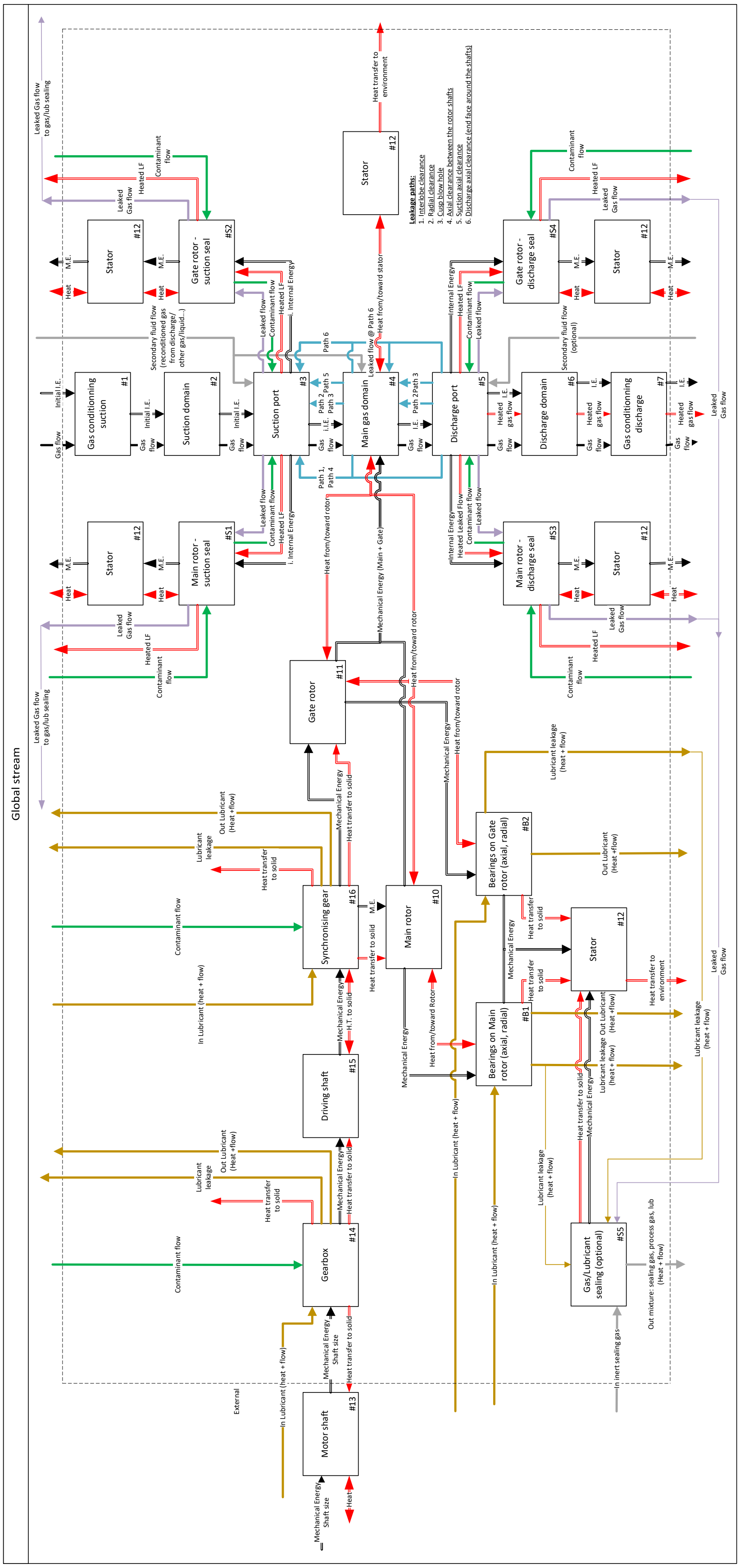

Figure 7. Functional model of the compressor.

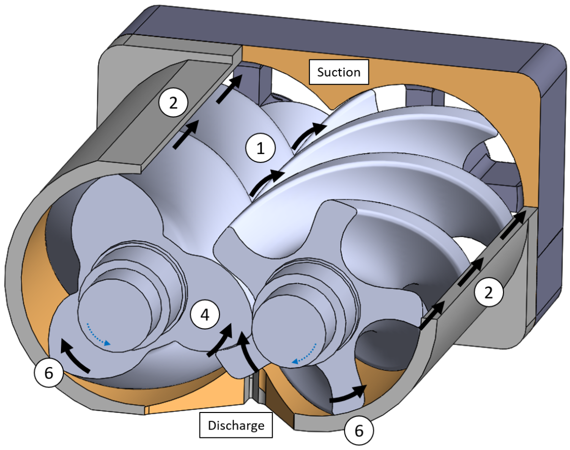

Figure 8. Definition of the internal leakage paths - 1. Interlobe; 2. Radial; 4. Axial discharge between shafts; 6. Axial discharge at the housing bore side. Leakage paths 3. Blow hole area and 5. Axial clearance at suction are not represented.

The domain of the compressor was divided in sub-domains and interactions between sub-domains (flow exchanges). For each sub-domain, functions are established. Overall, the compressor is defined with 22 sub-domains for around 100 sub-functions in total (some sub-functions are identical for several sub-domains). An initial list of 25 functions was drawn up by focusing the functional model to the domains which act on the gas flow. Furthermore, a Quality Function Deployment (QFD) method was used to rate the functions and extract those important functions for the objectives.

Quality Function Deployment 1 (QFD1): In this method, the relationship is evaluated between customer requirements and functional requirements. For this particular case, the customer requirements are the Level 1 objectives (presented in Figure 4) and the functional requirements are the 25 pre-selected functions. As presented in Figure 9, objectives are placed horizontally with their respective weights (defined in the objectives definition) and functions are positioned vertically, forming a matrix. The relationship is evaluated between each objective and function and is defined as: strong relationship (⊝ = 9), moderate relationship (◯ = 3), weak relationship (▲ = 1), or no relationship (empty cell = 0).

All functions are rated based on the sum of products of relationship weight and objective weight. Consequently, functions related to higher importance objectives are likely to be the top rated functions. This QFD1 leads to the selection of functions which are regrouped as follow:

- Ensure functioning clearances.
- Leak through clearances (internal leakages).
- Leak through seals (external leakages).
- Seal the gas domain.
- Restrict radial movements.
- Restrict axial movements.
- Ensure an accurate positioning of rotors (machining, assembling).

As it can be seen, these functions are primarily related to clearances in terms of operation, leakages and sealing. Other functions are related to the main function of bearings and to the general manufacturing accuracy. "Leak through seals" and "Seal the gas domain" are similar but are expressed in opposition to each other. The first one is expressed more in terms of leakages and how a solution will act to reduce or minimise this leakage. The second one expresses the sealing aspect which is more related to 'how to limit exchange between domains, how to avoid contamination of the gas domain'.

Row #	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
			Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	x	x	x	x	▼	x	▲	▼	▼	▼	▼	▼	▼	▲	x	x	x	x	▲	x	▲	▲	▲	▲	▲
			Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	#1 #7 Condition the gas	#2 #6 Homogenise the flow	#3 Controle intake gas volume	#3 Direct the flow to the main domain	#3 #5 Leak through seals	#4 Reduce Chamber volume	#4 Transfer M.E. to I.E. in gas	#4 Transfer M.E. to heat in gas	#4 #5 Leak through path 1	#4 #5 Leak through path 2	#4 #5 Leak through path 3	#4 #5 Leak through path 4	#4 #5 Leak through path 6	#5 Release the compression gas	#5 Direct the flow to the discharge domain	#10 #11 #12 Support M.E.	#10 #11 #12 Support I.E. of gas	#10 #11 #12 Support Thermal energy	#10 #11 #12 #16 Ensure an accurate positioning	#10 #11 #12 #13 #14 #15 #16 Interface with other domains	#B Restrict radial movement	#B Restrict axial movement	#B Support Reverse load	#S Seal the gas domain	#3 #4 #5 #S Ensure functioning clearances
1	20.0	0.20	Design for reliable operation	▲				Θ	O	O	O	Θ	Θ	Θ	Θ	Θ			Θ	Θ	Θ	Θ		Θ	Θ	O		Θ
2	18.0	0.18	Increase volumetric efficiency	O	▲	Θ	O	Θ	▲			Θ	Θ	Θ	Θ	Θ						▲		O	O		Θ	Θ
3	12.5	0.125	Optimise reliability metrics	▲				▲	O	O	O								O	O	O	O	▲			▲	▲	O
4	12.5	0.125	Facilitate serviceability					▲															O	▲	▲	▲	O	▲
5	10.0	0.10	Minimise operating costs	▲				▲	▲	▲	▲	Θ	Θ	Θ	Θ	Θ						O					O	O
6	6.0	0.06	Increase adiabatic efficiency	O				O		Θ		O	O	O	O	O	O	▲						O	O		O	O
7	6.0	0.06	Increase isothermal efficiency	O	O		O	O			Θ	O	O	O	O	O	O	O						O	O		O	O
8	5.0	0.05	Protect against external environmental conditions					▲											▲		▲		▲				O	
9	4.0	0.04	Minimise capital (purchase) costs	▲																		O	▲			O	Θ	O
10	3.0	0.03	Minimise maintenance costs	O		▲		Θ			▲	▲	▲	▲	▲	▲			▲	▲	▲	Θ	O	Θ	Θ	▲	O	Θ
11	1.0	0.01	Minimise sales and admin costs	▲				O				▲	▲	▲	▲	▲							▲			▲	▲	▲
12	1.0	0.01	Minimise development costs	▲	▲	▲	▲	▲	▲								▲	▲				O	▲			▲		
13	1.0	0.01	Minimise end of life costs																				▲			▲		
			Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	3	4	3	3	8	1	1	8	7	8	6	9	7	3	3	4	4	8	7	2	5	5	3	8	7
			Weight / Importance	147.5	37.0	166.0	73.0	**449.0**	126.5	161.5	164.5	**472.0**	**472.0**	**472.0**	**472.0**	**472.0**	37.0	25.0	225.5	220.5	225.5	**307.5**	71.0	**309.5**	**309.5**	103.0	**339.0**	**498.0**
			Relative Weight	2.3	0.6	2.6	1.1	**7.1**	2.0	2.5	2.6	**7.4**	**7.4**	**7.4**	**7.4**	**7.4**	0.6	0.4	3.5	3.5	3.5	**4.8**	1.1	**4.9**	**4.9**	1.6	**5.3**	**7.8**

Figure 9. Quality function deployment 1 for selection of functions.

3.3. Setting requirements

The setting of requirements aims to detail the attributes of the desired product to satisfy the customer needs (objectives) and to define the limits of the range of acceptable concepts. In this study, an existing machine is used as a prototype in which the concepts will be implemented. This will help define attributes and limits.

The prototype machine is an oil-free twin-screw compressor with 3/5 "N" rotors and a 127 mm male rotor diameter designed for a delivered flow of 1000 m^3/h at a maximum discharge pressure of 2.5 bar (g) and a designed radial and interlobe clearance gaps of 180 μm. Rotors are guided by ball and roller bearings to support axial and radial loads, respectively. Sealing of the main gas domain is realised by the use of labyrinth seals at suction and double lip PTFE seals at discharge.

Based on the prototype, some limits are established: It is not considered to change the profile of the rotors and the blow hole area will not be of direct interest in this study. As the bearings and seals are very dependant of the application, they will not be modified in the prototype and will be further explored in the phase III of the project. Furthermore, the manufacturing capabilities will not be explored in terms of machining and assembly tolerances of rotors and casing.

Initial tests were realised for male rotor tip speeds from 50 to 120 m/s and pressure ratio from 1.5 to 2.5. In the worst case (low speed and high pressure ratio) the discharge temperature is maximum at 164 °C for a suction temperature of 30.7 °C. In this case, the specific power was measured at 3.1 $kW.m^{-3}.min$ with 61.9 % and 55.7 % of volumetric and adiabatic efficiencies, respectively. Husak et al. [25] performed a numerical study on this prototype and shows that for a discharge temperature of 180 °C, the radial clearance can decrease from 180 μm up to 100

μm on the male rotor and up to 140 μm on the female rotor. This study also shows that change of clearance is not uniform and is bigger at the position of opening of the discharge port.

These results justify the top rated Level 3 objectives: reduce thermal deformation, improve internal sealing, reduce power consumption, ensure safe start and stop operation, safe transient behaviour and monitor health in operation. Our goal is then to reduce the thermal deformation by reducing the discharge temperature. This will lead to the increase of specific power and thus an increase of volumetric efficiency (directly related to the reduction of internal leakages) and an increase of adiabatic efficiency (related to the thermodynamic behaviour of the machine). Moreover, this will ensure a better reliability (safety of transient operation) by limiting the clearance gaps variation and encouraging the reduction of the designed clearance gaps.

3.4. Determining characteristics

The characteristics, or more specifically the Engineering Characteristics (ECs) of a product are the physical parameters of functions that affect the requirements. In other words, the ECs defined the performance expected by the user of the parameters of a function. These ECs can be common for several functions but with different values. From the selected functions, 48 ECs were defined for the following categories of properties:

- Geometry: Clearance gap and length, surface roughness, machining accuracy...;
- Kinematic: Gradient and average flow velocity, surfaces velocity;
- Energy: Pressure, temperature, flow rate...;
- Forces: Mechanical and thermal deformation, rotor balancing...;
- Material: Viscosity and density of gas, Young modulus and thermal expansion coefficient of solids...

A second QFD was done to rate the ECs based on the relationship with the Level 3 objectives which reflects the setted requirements. This QFD is too extensive to be presented in the paper, but top rated ECs were find to be: Clearance variation, clearance gap, temperature difference of the gas between suction and discharge, heat flux in the gas flow, surfaces temperatures, bearing internal clearance, thermal deformation of rotors and casing, rotor balancing, Leakage mass flow rate, clearance lengths and shape, etc.

To summarise, the top rated ECs have a large influence on the most important customer requirements. Which means that innovative design should focused on the concepts that act on these ECs. The ECs will be important in addition of the customer requirements for the evaluation of concepts.

4. Conceptual design

The conceptual design starts with the generation of concepts followed by the evaluation and the development of concepts. This phase leads to a variety of concepts that appear to be promising and results in the design embodiment. Concept generation will be succinctly presented thereafter, but next steps will not, as outside of the scope of the current paper.

4.1. Generating alternatives

For the concepts generation, the morphological chart method was used. This chart consist of a matrix presenting several concepts for each function found with the QFD1. As presented in the setting requirements section, the functions related to bearings and seals, as well as manufacturing will not be covered. This leads to two main functions: "Ensure functioning clearances" and "Leak through clearances" which are applicable to the three most important clearances: 1. Interlobe clearance; 2. Radial clearances; and 4. & 6. Axial clearances at discharge.

A large number of concept can be generated with a morphological chart. To narrow our study and limit the number of concept variances, three streams for concepts were established based on the customer requirements and are succinctly presented below:

1. Concepts related to surfaces properties and shape, such as:
   - Sacrificial tip seal
   - Grooves/steps on tip
   - Roughness
   - Surface texturing
   - Surface coating
2. Concepts related to the use of a secondary flow in the clearances:
   - Re-injection of cold gas
   - Use of economiser port
   - Impingement through casing
   - Impingement through rotor
3. Concepts related to the monitoring and control of clearances:
   - Monitoring of operating conditions and control in case of unexpected behaviour
   - Active control of position of rotor by the use of hydrodynamic bearings
   - Active control of position of rotor by the use of electromagnetic bearings or actuators.

Three independent morphological charts were build for the three categories of concepts. Concepts coming from these charts are under evaluation using a decision matrix based on the fulfilment of the objectives.

5. Conclusion

This paper discusses the systematic engineering design method applied to the development of innovative concepts for the improvement of the oil-free twin-screw compressor. This method conducts to the expression of the specific objectives describing the requirements in a clear and quantifiable way. This was possible with the use of objective tree decomposition of the three main objectives: "Increase efficiency", "Increase reliability" and "Minimise cost". A functional model of the whole compressor detailing the sub-domains, sub-functions, material and energy flow interactions was built. This model was then focused on the functions on which improvements can be made, mainly related to the internal clearances i.e. ensure functioning clearances, leak through clearances, ensure accurate positioning, restrict movements. The setting of requirement further limit the functions of interest and engineering characteristics help to describe the important parameters. Finally the conceptual design depicted the first step of the development of solutions.

In a future work, the concepts will be evaluated and most promising concepts will be implemented and tested in the compressor prototype at City, University of London. The performances of the prototype with the new concepts will be thoroughly analysed. The best concept will be applied to the commercial prototype in the third phase of the project SECRET.

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