IOP Conf. Series: Materials Science and Engineering **425** (2018) 012005 doi:10.1088/1757-899X/425/1/012005

The workflow of rotor machine development: design phases, steps and tools of the development process

H Österman, A Edrisi and I Lashgari[1]

Svenska Rotor Maskiner (SRM), Fannys Väg 3, 131 54 Nacka, Stockholm, Sweden

[1]Email: iman.lashgari@rotor.se

Abstract. In this work we present an overview of the workflow of rotor machine[§] development, focusing on twin-screw compressors and expanders. The rotor machine development process consists of an orchestrated activity of specification, design and verification where individual phases, steps and tools contribute significantly in developing cutting-edge technology and delivering sustainable solutions. Our goal is to present those phases, steps and tools with relevant examples, highlight the development challenges and argue the inevitable deviations of real-life condition from the original specification. We believe that this contribution will shed light upon the essential elements of the rotor machine development process, something that benefits the entire community from academia and suppliers to end users.

1. Introduction

This report presents an overview of the workflow of rotor machine development, based on SRM's (Svenska Rotor Maskiner) experience, including more than 500 individual machine designs. Most of these designs have been developed all the way from specification to full-scale prototype tests in SRM laboratories. We will discuss the individual design phases, steps and tool packages which are essential in developing forefront technology and viable solutions. We emphasize that state-of-the-art rotor machine development is guaranteed only by considering all these individual elements in the chain of the development process.

Rotor machines are categorized as positive displacement rotary machines which serve in many industrial applications such as refrigeration, air conditioning, process gas, chemical, automobile, airborne and waste heat recovery. These machines are important tools for engineers worldwide to find industrial solutions with low environmental impact. Even though these machines have relatively simple mechanical structure, they can tolerate high rotational speeds, wide range of operating flowrates and pressures and many different fluids and gases. After more than 80 years of continues development, rotor machine technology still has a competitive market because of the substantial improvement potential which depends on many design and manufacturing parameters from rotor and housing to bearing, lubrication, sealing and injection systems. That is why top developing companies invest significantly on optimization procedures to offer competitive high efficiency - reasonable cost products. The two most common products of rotor machines are twin-screw compressor and twin-screw expander which are the focus of the present paper.

Screw compressors are the most developed type of rotor machines which have extensively replaced other types such as reciprocating and centrifugal compressors due to their compact, simple, efficient and reliable design. Opposite to reciprocating compressors, screw compressors do not need suction or discharge valves and timing of filling, compression and discharge processes are imposed by the geometry. To meet the market needs, there exists a large variation of screw compressor designs such as dry-running or liquid-flooded, synchronized or rotor-derived, one or multiple stages, with or without capacity control and many more which reflects the broad application range and development possibilities of these machines.

Screw expander, even though with similar technology core as the screw compressor, has still a relatively low amount of market penetration in most applications. These machines offer an appropriate solution in power generation applications where opposite to the classical turbines they can operate even with phase change of working fluid within the machine. Screw expanders can be integrated in Organic Rankine Cycles (ORC) which are the baseline of decentralized small and medium-scale energy production units from low-grade waste heat sources. In near future, heat recovery thermodynamic cycles with screw expanders are going to serve a wider range of applications such as biomass CHP, geothermal power, solar power and internal combustion engines [1].

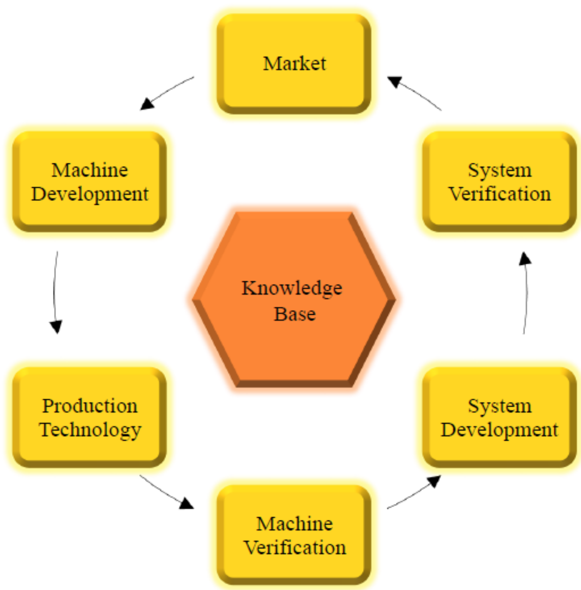

Figure 1. Workflow of rotor machine development.

In this work, following SRM development loop of rotor machines, we will discuss the individual development phases as illustrated in figure 1. These phases are: Market, Machine Development, Production Technology, Machine Verification, System Development and System Verification. The heart of the development process is the knowledge base that contributes decidedly in each phase. The knowledge base is established, over an extended period of developing various machines, facing technical challenges and assessing the final product. Knowledge base is an integrated archive of machine and system database, design and calculation manuals, production and test procedures, internally and externally developed software, patents, technical reports and many more. The arrows indicate the workflow direction of the development process as well as the order of the sections in the present paper. Note however that the connections between individual phases or steps are much more complex in real life, including many crossflow iterations and reevaluations. Despite the intricacy of rotor machine development, the work will be presented in a pedagogical fashion as our goal is to engage the readers of various professional background and interests.

2. Market

The main purpose of rotor machine technology is to meet the market needs, so the development loop should start and end here. Application range, capacity and manufacturing capability of rotor machines have been increased drastically. Commercial machines can now stand operating pressure of more than 60 bar and developing machines well over 100 bar, power consumption of oil injected screw compressors has passed 2 MW and machines can be manufactured conveniently with relatively low costs while meeting the requirement of very small tolerances. The global growth of rotor machine market poses significant opportunities, and at the same time challenges, to the top technology developing companies. The more specific demands on energy- and cost-optimized rotor machines has forced the market to pursue only highly reliable, feasible and tailored technical solutions. Therefore, it is crucial to bind strongly the technology experience, as the main input and output of the development process, with the customer specific requirements.

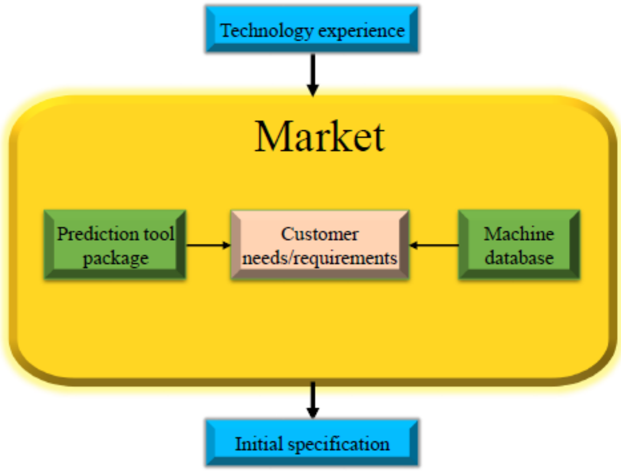

Figure 2. Workflow of market phase

The development process in the market phase is shown in figure 2. In market, technology experience combines with machine database and prediction package to meet customer needs/requirements. Machine database is a documented collection of previously developed machines which helps the market experts in understanding the possibilities and challenges of the upcoming project. The prediction tool package however contains computer programs to estimate the machine performance under different conditions. These programs are based on efficient numerical algorithms with extensive correlation with the laboratory data. We will discuss more the prediction package in connection to the simulation programs in the next section. The outcome of the market phase, initial specification, is not too detailed at the beginning, but it develops gradually through an iterative procedure between market and design experts. The challenge here is to keep the specification alive and relevant while identifying and analyzing the actual customer needs.

3. Machine Development

The machine development phase is the first technical step toward the development of a new machine based on the initial specification, see figure 3. This phase normally consists of two main steps, the initial calculation and layout and detail design. The outcome of the former is the starting point of the latter.

3.1. Initial calculation and layout

In this part the essential machine components such as rotors, ports, bearing, injection and sealing systems are designed and optimized. The heart of the rotor machine, the rotors, are designed based on an often-patented profile. Theses profiles have been constantly developed since 1973 when the first profile with commercial viability, the “A” profile, was introduced by SRM [2]. As shown in figure 3, profile tool package provides designers with necessary routines to compute and optimize the rotor geometrical properties such as lobe shape specifications, sealing line and volume curve. In addition, the desired clearances and manufacturing tolerances are taken into consideration. This task is even more challenging for dry gas compressors and screw expanders because they normally operate at higher temperature range and therefore greater thermal expansion. We note that the choice of rotor profile and other geometrical properties are finalized combining the outcome of profile, simulation and design tool packages.

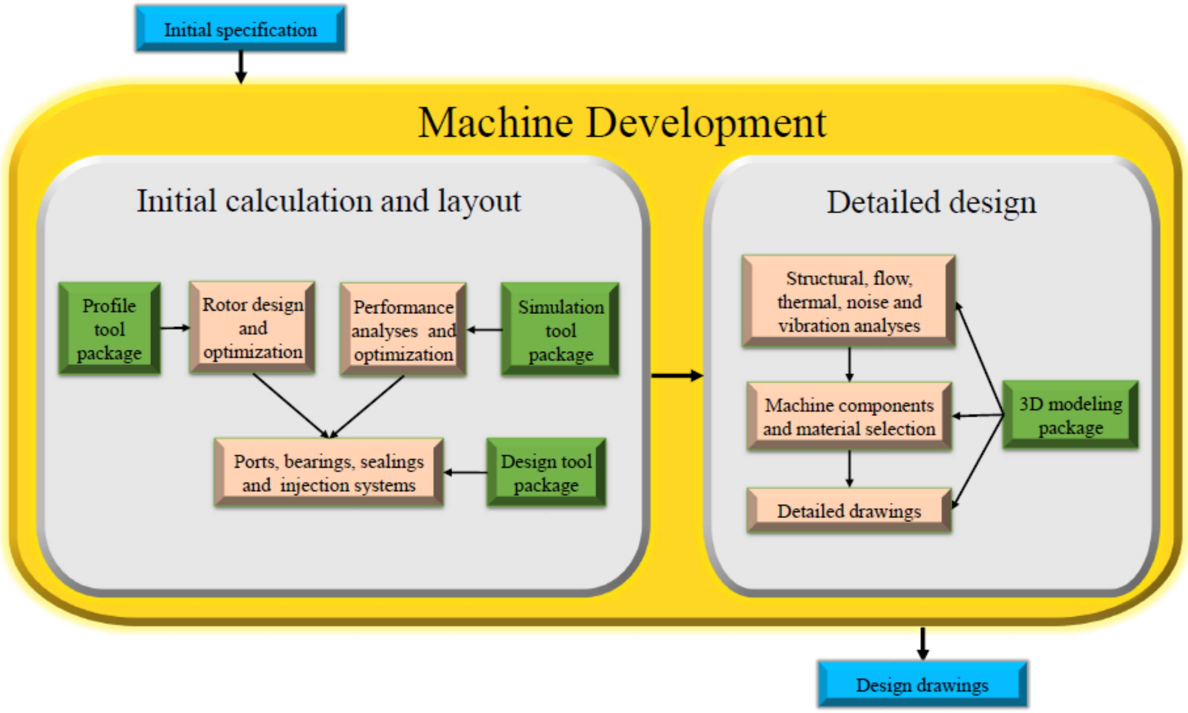

Figure 3. Workflow of machine development

In the next step, but in real life more conducted in parallel, the machine performance is estimated using the simulation tool package. The programs included in the package are developed combining mathematical models, numerical algorithms and experimental correlations. The so-called Thermodynamic Chamber Model (TCM) often is the baseline of the mathematical modeling programs where differential equations of mass and energy conservations together with the equations of states are solved, under quasi-steady assumption, to compute the variation in thermodynamic properties (such as pressure, temperature and phase quality) of working fluid as a function of rotation angle and thereafter machine performance [3]. Mathematical modeling of screw machine has started around 35 years ago where the pioneers are among others Fujiwara et al, 1972 and Sangfors, 1982 [4,5]. Thermodynamic simulation package which covers a wide range of features such as different working fluids and geometries, dry-running or fluid-flooded machine, capacity regulation, economizer and many more, is still among the most important development tool both in industry and academia (see e.g. [6,7,8]).

The initial design calculations are connected directly to the outcome of geometrical and thermodynamic calculations. Designer get assistance from specialized design programs to evaluate various components/systems within the machine (ports, bearing, injections, sealing, gears and so on). This step is fulfilled with the consideration to the experience from former solutions, requirements in specifications and the existing production technology. Calculation of each component/system is usually accompanied with a multi-variable optimization. For example, an efficient oil injection system provides optimal oil flow into rotor and bearing housing under various running conditions to assure proper cooling, sealing, lubrication and noise reduction while avoiding undesired friction losses. Another example is the port design when parameters such as energy losses, mismatch between the internal and external compression/expansion and noise level are optimized simultaneously.

3.2. Detail design

The detailed design step includes a range of 3D modelling and computations which complement the initial calculations and produce the final design drawings. The complexity level of these computations has a direct connection to the machine application. For example, a refrigeration compressor often has much more complex structure in comparison to an air compressor where features like balance piston and slide valves are also included in the design [9].

The rotor machine is a mechanical structure that ought to be analyzed from three main aspects of machine design: structural, fluid flow and vibration. Structural analyses often occur through a series of FEM (Finite Element Method) computations where stress distribution and rotor and casing distortions are among the greatest interest. In addition, FEM analysis is often coupled with a thermal analysis of the entire machine, to estimate the distribution of temperature over machine components under operation (see e.g. [10]). The fluid flow analyses, generally via Computational Fluid Dynamics (CFD), help understanding the details of the fillings, compression or expansion and discharge processes (see e.g. [11]). In addition, force distribution on rotors, friction loses, and injection process are simulated employing reliable flow analyzing tools. This information is also employed to further develop the simulation and prediction tool packages. Finally, noise and vibration analyses are performed to interest both environmental concerns and machine life time. The main noise and vibration sources can be divided into mechanical and fluid sources. The mechanical sources such as rotor rattling, or improper gearing system are the main reason of the machine vibration. The fluid sources such as gas pulsation contribute in noise which is more evident in the filling and discharge processes through the ports (see [12]). The simulation package based on the mathematical modeling of the excitement forces and pressure waves helps the designer with the optimization of, among others, transmission mechanism and port design to reduce the noise level (see [13]).

Next is the selection of machine components depending on the specification, production technology and above-mentioned analyses. Components such as bearings and sealings, also affecting the machine function and performance [14], are often provided by external distributors. These components are verified in the quality control step of the machine verification phase, see section 5. Finally, the choice of material and surface treatment are decided in this step. As regards rotors, improper material selection may lead to strain-hardening and adhesion tendency in the production process while improper surface treatment intensifies wear due to contacts or abrasive particles and therefore results in a reduction of service time especially for the rotor-derived machines (see [15] for more detail). Different rotor coating may be used not only to treat the surface but also to achieve the best possible clearance configuration between the rotors under the operation as the rotor contacts remove partly the coating materials.

The last step in machine development is the production of detailed drawings that often fulfilled employing advanced, but conventional 3D modelling package. The design drawings and technical solutions are the baseline of the machine development process. These solutions will be evaluated in the verification step and compared to the initial specification.

4. Production Technology

This phase reflects the fact that the design should be consistent to the available production technology. It is important to note that this phase may be skipped in the development process if the available production technology is suitable for the technical solution. All the potential steps in this phase are accomplished employing Computer Aided Manufacturing (CAM) systems. Here we focus only on the production technology of rotors, as shown in figure 4, which is both complex and costly. The rotor production technology usually consists of two main steps, special tool development and machining technology. The former deals with the production of grinding wheel and cutters while the latter focuses on rotor production from rounded bars through milling and grinding technology. The main challenge is to generate high quality surfaces within required tolerances in an optimal production time and cost.

In the milling technology, we either deal with special milling machines with disc cutters or relatively modern multi-functional flexible milling machines with bar, torus or finger cutters. The former is more suitable for mass production of small and medium size rotors while the latter is employed in manufacturing large rotors of small numbers or prototyping [16]. The grinding technology, also known as polishing technology, may also be fulfilled using flexible machines when high quality surface is needed. The grinding wheels often show high shape accuracy and wear tolerance which make them an excellent choice for grinding without defects like crack or burn. The outcome of this phase is the production method which is an input to the machine verification phase together with the detailed drawings.

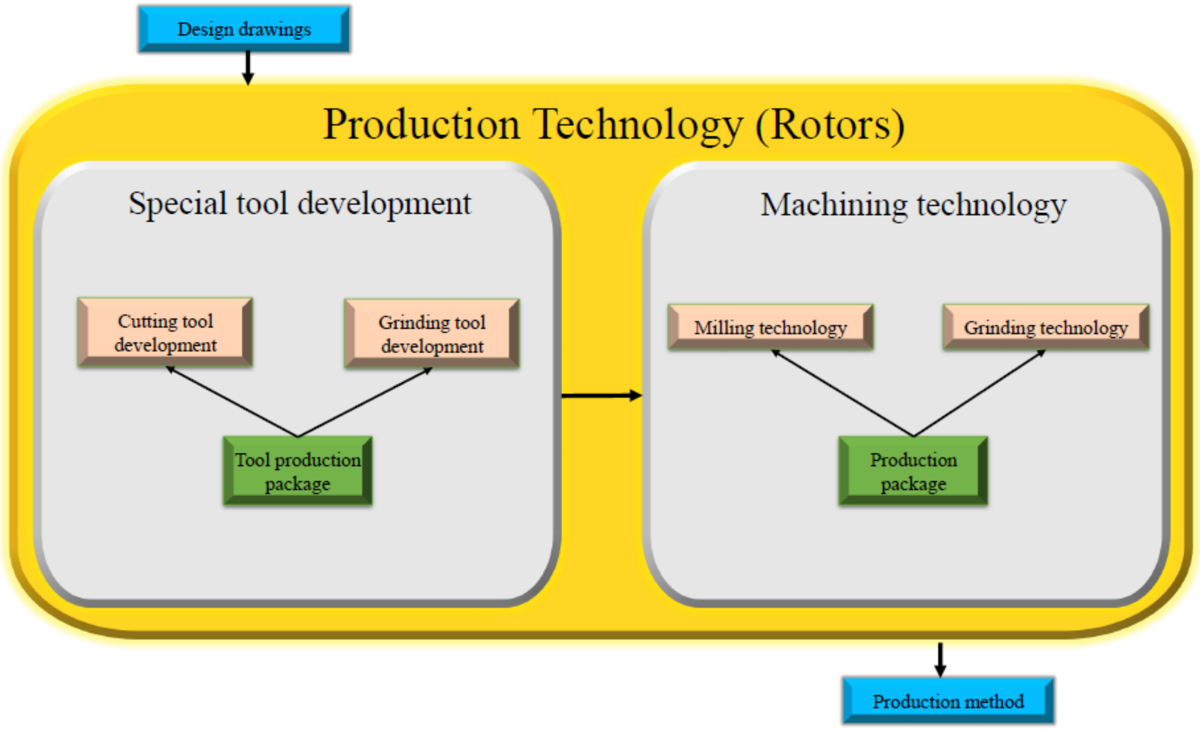

Figure 4. Workflow of production technology

5. Machine verification

The development process of rotor machine cannot be successful without verification. In real life the verification phase is closely connected to the machine development phase. The technical solution suggested in the machine development phase should now be verified and compered to the initial specification. This phase covers quality control of machine components, assembly, and function and performance tests in the laboratories. The workflow of this phase is shown in figure 5.

5.1. Quality control

To be able to verify that the function and performance is according to the specification, one must first verify that all individual machine components are according to the design drawings. The quality control step is more sophisticated for the rotors and housing. The geometrical properties of rotors are usually measured point by point employing Coordinate Measuring Machine (CMM). Rotor inspection is not limited to the individual rotor but also the rotor-pairing when the clearance between the rotors in several points is measured, using rotor-pairing measurement tools, and compared with the design protocol. This step is extremely important as the quality of inter-lobe clearance affects significantly the machine performance, noise level and reliability. Next, dynamic balancing of rotors is accomplished using balancing machines, not shown in figure. All these inspections safeguard the high-speed rotations (sometime up to several tens of thousands RPM) of the rotors with minimum friction, rattling, buzz and distortion [17]. CMM machine is also employed for housing control to ensure all relative dimensions are correct, for example the desired clearance between the rotor tips and the housing. As mentioned before, other machine components, provided by external distributors, are quality checked in this step based on the specifications and design drawings.

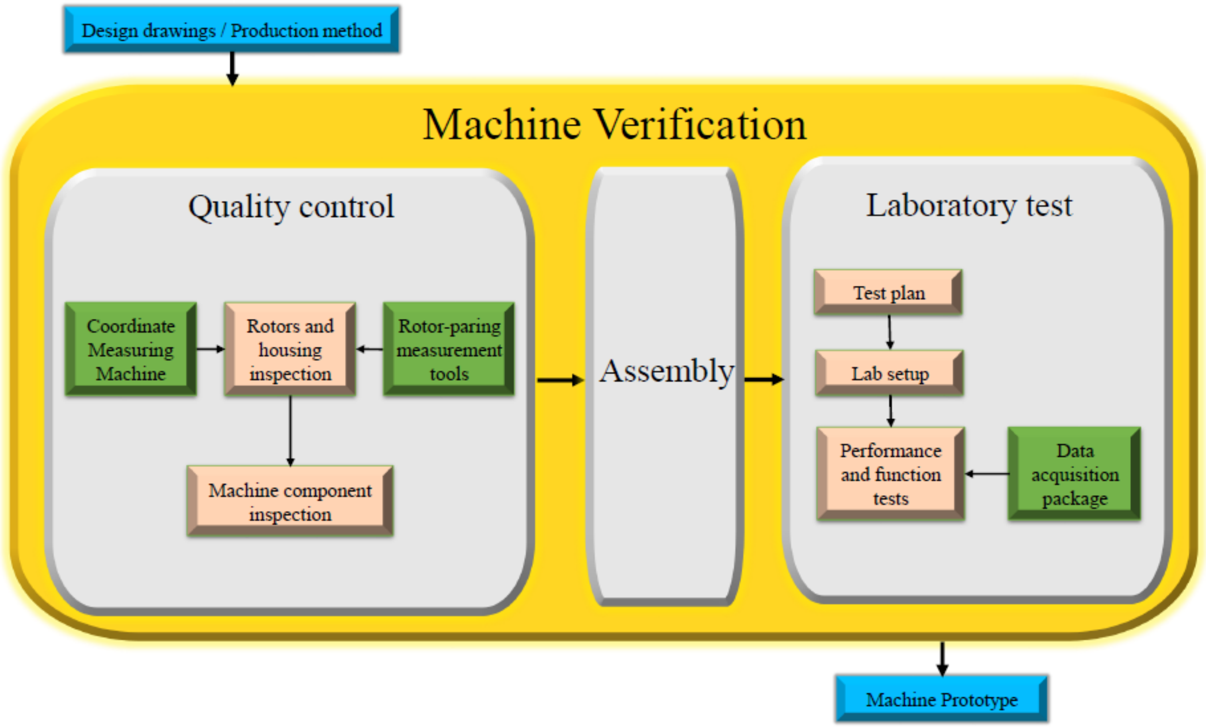

Figure 5. Workflow of machine verification

5.2. Assembly

Before the function of the machine can be verified one must also ensure that it is assembled properly. The assembly of rotor machines is a sensitive task, though is not fully automated. Therefore, the skill of assembly experts directly affects the final product. Assembly of rotor machines is performed step by step following the design drawings and includes many pre-installation procedures such as cleaning, cooling or warming machine components. The actual back-lash and end-plan clearances is reported in this step and compared to the detailed drawings. In real life it is also very common that many deviations are found during the prototype assembly, iterating back to the detail design step of the machine development phase.

5.3. Laboratory tests

The last step in machine verification is laboratory test which generally follows certain ISO standards such as ISO 917, ISO 5167-1 and ISO 1217. Prior to the experimental verification often a test plan is created to indicate a full-scale test range on machine with actual working fluid and over a wide range of running conditions, also taking into account what has previously been tested in the knowledge base. Experimental test rigs are design-specific where the system components, piping, instruments and measurement programs are adjusted to the machine application and working fluid. Data acquisition programs process the signals from the measurement devices, calibrate data and perform thermodynamic calculations such that the operator can monitor the performance of the machine in real time. Accumulated data is then analysed and documented in the final prototype report and also employed to correlate simulation/prediction programs.

6. System development

System development is the next phase in the rotor machine development process. The main concern here is to design a system that exploits the maximum potential of the rotor machine. The integration of the rotor machine in the system is essential to secure the target performance of the final product. In other word, a highly efficient machine may malfunction or poorly function in a system which does not provide the necessary conditions.

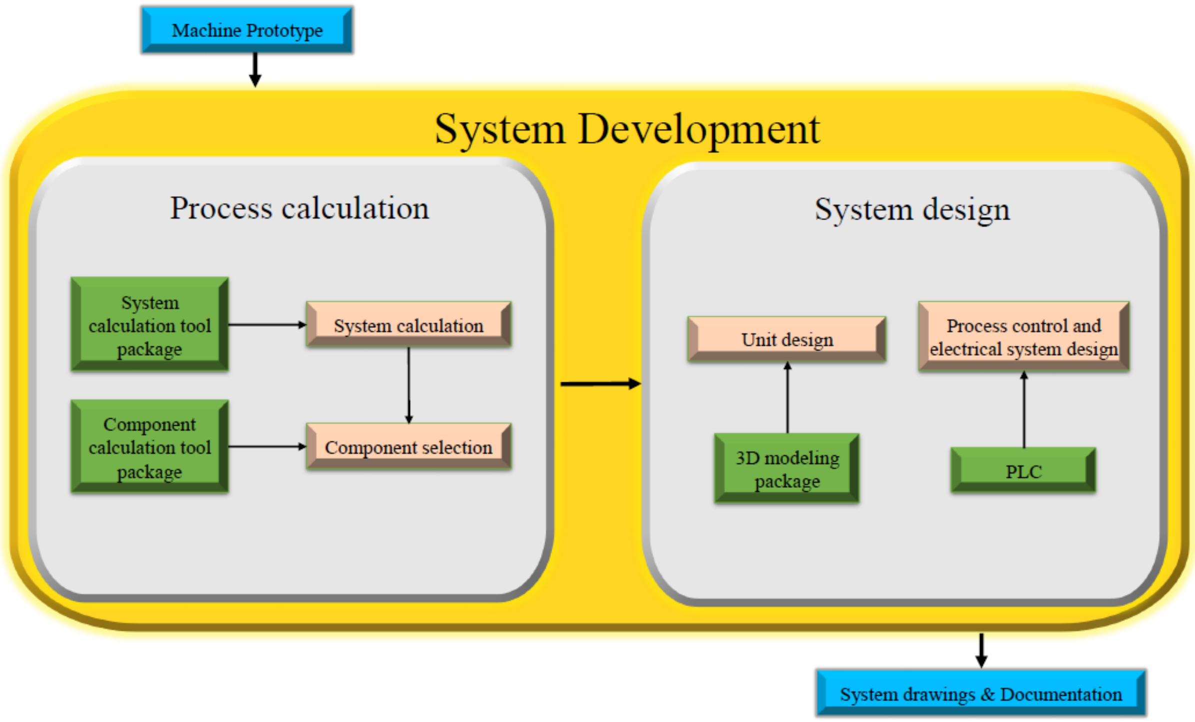

Figure 6. System development phase

Screw compressors and expanders are respectively the main component of refrigeration and waste heat recovery units. This report mainly refers to these two applications while the method and development process is relevant for similar systems. The refrigeration units are often an integrated vapor-compression thermodynamic cycle. In contrast, waste heat recovery units are often Steam Rankine Cycle (SRC), Organic Rankine Cycle (ORC) or a combination of these two. Note that other cycles such as Trilateral Flash Cycle (TFC) and Kalina Cycle (KC) have still negligible global market penetration [18]. System development consists of the process calculation and system design steps as shown in figure 6. The former deals with system calculations and component selection and the latter focuses on unit design and process control and electrical system design.

6.1. Process calculation

Process calculation often starts with conceptual design where simulation tool package is employed to predict the thermodynamic status of specific points on the cycle as well as parameters like power and flowrate under different loads. This information is then employed in basic component design using component calculation tool package. These components can be of the main cycle such as evaporator and condenser or auxiliary cycles such as oil and cooling water pumps. In selecting various components, generally a balance approach is needed to trade-off efficiency, controllability, pressure drop, size, tightness, durability and cost. As an example, heat exchanger should have high heat transfer efficiency, low pressure drops and high resistant against corrosion and leakage while at the same time reasonable price as it affects the total cost considerably. In addition, the process logic is developed in connection with piping calculations, sensor arrangement and controller sequences. Process calculation is usually reported in the form of function specification together with piping and instrumentation diagram (P&ID).

6.2. System design

System design usually occurs after the system calculation. System design can be divided into unit design and process control and electrical design. Unit design starts with the three-dimensional modelling of the entire system with actual component properties such as size, weight, material and positioning. Thereafter, a series of mechanical and structural calculations are performed to ensure the function and performance of the unit under design conditions. In this step, production, maintenance, transport and total cost are some of the main aspects to be considered.

In control system design, the process logic is finalized employing programming logic controller (PLC). CPU controller cards, communication modules and logging units are among the main hardware of PLCs while start-up sequence, power control, trip sequence and shutdown sequence are among the main logics. It is of immense importance to equip PLCs with proper alarm lists which normally divided into three categories, tripping, shutdown and warnings. The control sequences keep the machine working efficient within its window of operation.

Beside system drawings which are normally produced by three-dimensional modelling package, documentation is the main outcome of the system development. Documentation includes a series of descriptions, instructions, manuals, safety regulations and checklists which are necessary in the journey from system design to final operation at the site. The detailed information in every document, although part of development process of rotor machine, is not covered in the present report.

Here we again highlight that the system development is an essential phase in the rotor machine development process because only an appropriate and efficient system can exploit the maximum capacity of an efficient machine. The high-quality machine and system design solutions together result in the best final product.

7. System verification

The last step in the development process is system verification. This is the phase in which we evaluate whether or not the inevitable deviation of the final product from initial specification is within the acceptable range. Ideally, this phase can be done in a laboratory environment, but more often most of the work has to be conducted on the field. Similar to machine verification phase, here we start with the quality control of both internally and externally produced components, see figure 7. In the next step system is produced (assembled) based on the system drawings. The system is now ready for the test based on the protocols which are regarded as Factory Acceptance Test (FAT) and Site Acceptance Test (SAT). The sub steps here are test plan, test setup and performance and function tests which are similar to those of the machine verification. Finally, system is evaluated at the field (site) in two main sub-steps. First, system is quality controlled including regulations and safety checked following documentation. Second, data is logged to monitor system control, stability and performance. Data logging is also important to track flaws if something goes wrong. In this step data mining and analysing package creates a baseline in computing indicator parameters such as machine and system efficiency. The collected data is further employed to develop correlation functions and prediction models and optimize future machines/systems.

We finally note that the most important output of this phase is the technology experience. Rotor machine development from initial specification to system verification has now completed one round where technology and experience are developed and integrated in the knowledge base. At this stage, usually the initial specification has to be updated because the real-life product may have other requirements comparing to what was originally specified.

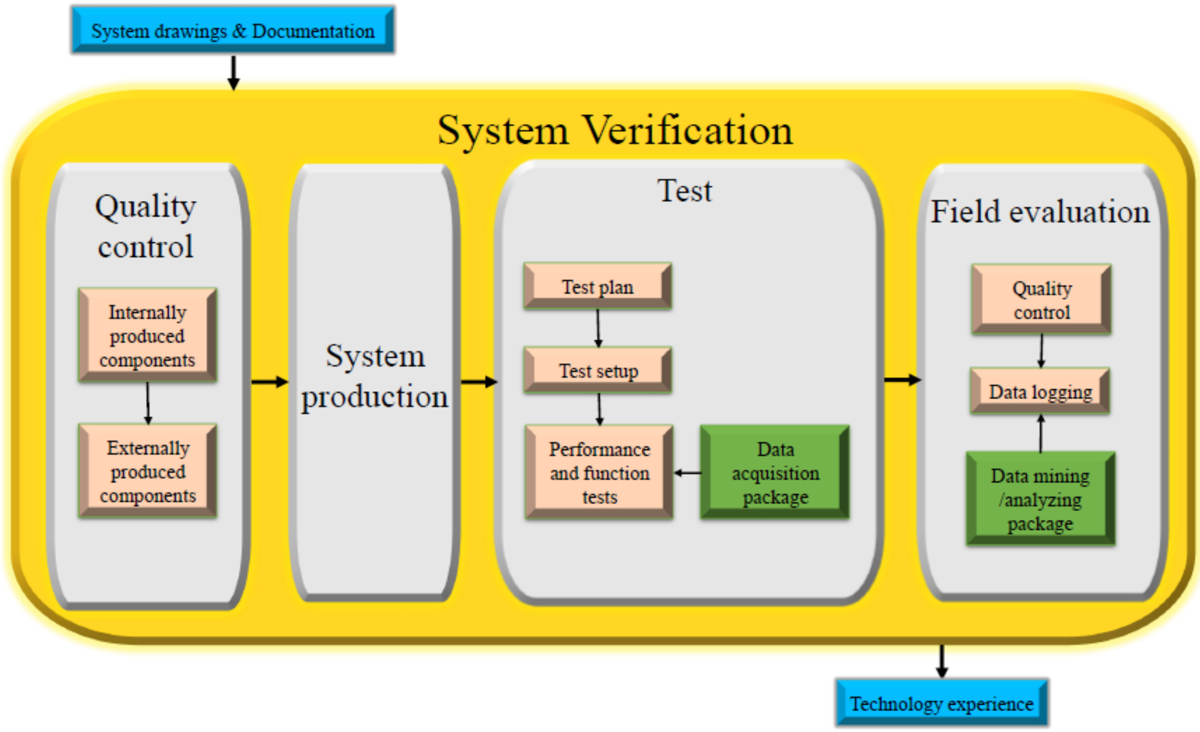

Figure 7. Workflow of system verification

8. Conclusion

The workflow of rotor machine development is an orchestrated activity of many phases and steps where every detail counts; the manipulation of each phase, step or even sub-step may lead to distinctive improvement. Following SRM development loop, the workflow is divided into 6 phases, Market, Machine Development, Production Technology, Machine Verification, System Development and System Verification. In this report, steps and tools under each phase has been discussed thoroughly together with examples and challenges. In figure 8, we show the detailed workflow of rotor machine development by merging all the figures presented in this report. We again note that the production technology may be skipped if the available production method is suitable for the technical solution.

We finally note that even though the connections between individual phases or steps are much more complex in real life, including many crossflow iterations and reevaluations, we pursued a simple method to describe the work for readers of various professional background and interests. We emphasize again that the success in the development process lies on looking up to the individual details, innovations, cross-team collaboration, iterations and optimizations alongside the development loop. The chain of the rotor machine development is of course not stronger than its weakest link.

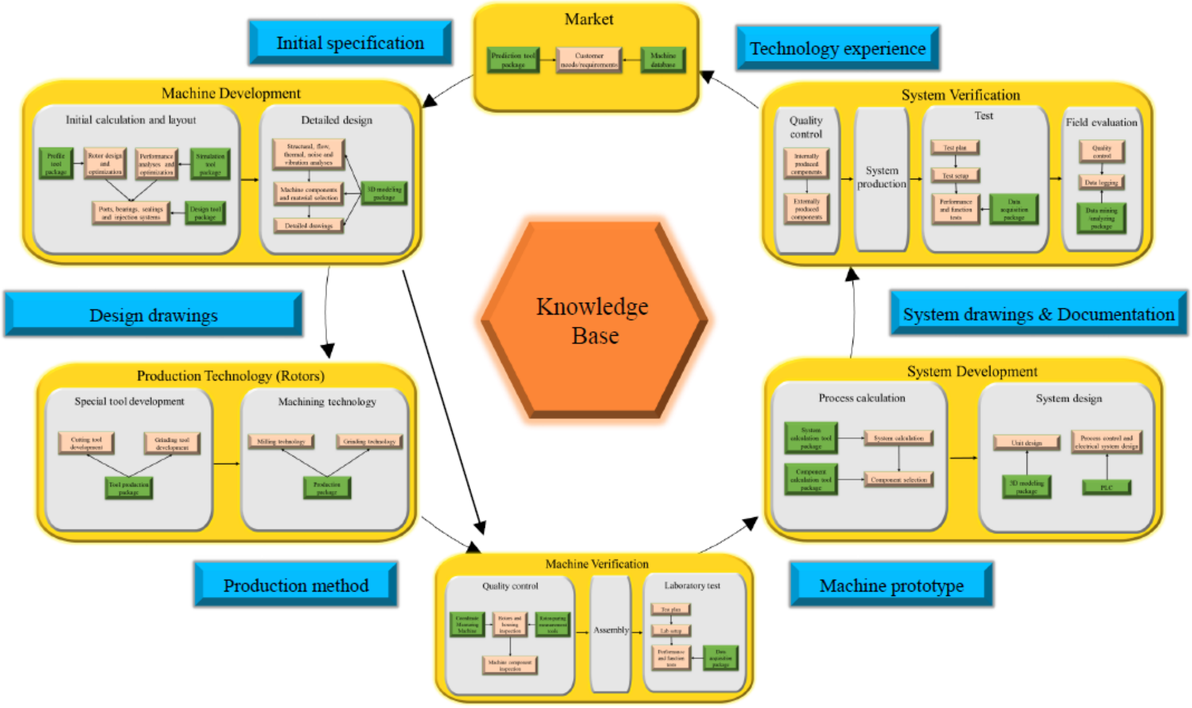

Figure 8. Detailed workflow of rotor machine development

References

[1] Quoilin S, Van Den Broek M, Declaye S, Dewallef P and Lemort V 2013 Techno-economic survey of organic rankine cycle (ORC) systems *Renewable and Sustainable Energy Reviews* **22** 168–186
[2] Shibbie 1979, *US Patent* **4,140,445**.
[3] Stosic N, Smith I K, Kovacevic A and Mujic E 2011 Review of mathematical models in performance calculation of screw compressors *Inter. J. Fluid Machiney and Systems* **4** 2
[4] Fujiwara M, Mori H and Suwama T 1974 Prediction of the oil free screw compressor performance using digital computer *Inter. Compressor Engineering Conf. at Purdue* **186**
[5] Sangfors B 1982 Analytical modeling of helical screw machine for analysis and performance prediction *Inter. Compressor Engineering Conf. at Purdue* **144**
[6] Vasuthevan H and Bruemmer A 2016 Thermodynamic modeling of screw expander in trilateral flash cycle *Inter. Compressor Engineering Conf. at Purdue* **2475**
[7] Bianchi G, Kennedy S, Zaher O, Tassou S A, Miller J and Jouhara H 2017 Two-phase chamber modeling of a twin-screw expander for trilateral flash cycle applications *Energy Procedia* **129** 347–354
[8] Nikolov A, Bruemmer A 2017 Investigating a small oil-flooded twin-screw expander for waste-heat utilisation in organic Rankine cycle systems *Energies* **10** 869
[9] Hou F, Zhao Z, Zhiqiang Y and Xing Z 2017 Experimental study of the axial force on rotors in a twin-screw refrigeration compressor *Inter. J. Refrigeration* **75** 155–163
[10] Powell G, Weathers B and Sauls J 2006 Transient thermal analysis of screw compressors, Part I-III *Inter. Compressor Engineering Conf. at Purdue* **1811-13**
[11] Andres R, Hesse J, Babic H, Salecker U, Spille-Kohoff A, Nikolov A and Brummer A 2016 CFD simulation of a twin screw expander inclusing leakage flows *Inter. Compressor Engineering Conf. at Purdue* **2497**
[12] Mujic E, Kovacevic A, Stosic N and Smith I K 2011 Noise generation and suppression in twin-screw compressors *Proc. of the Inst. of Mech. Eng. Part E* **225** 127–148

[13] Sangfors B 2000 Modeling, measurment and analysis of gas-flow generated noise from twin-screw compressors *Inter. Compressor Engineering Conf. at Purdue* **1487**
[14] Meyers K 1997 Creating the right environment for compressor bearings *Inter. J. Evolution SKF* **4** 21
[15] Muiznieks G, Gerins E, Katasevs A, Ozolins J and Pikurs G 2012 Evaluation of coating material structure of screw type compressor rotor contact surface *Proc. World Congress on Engineering* **III**
[16] Zabel A 2014 Modern machining processes for the manufacturing of screw machine components *Inter. Confrenece on Screw Machines* **2228** 267–278
[17] Holmes C S 2004 Inspection of screw compressor rotors for the prediction of performance, reliability and noise *Inter. Compressor Engineering Conf. at Purdue* **1692**
[18] Öhman H 2015 Low temperature difference power systems and implications of multi-phase screw expanders in organic Rankine cycles *Trita-Pefr Raport 15/02, KTH, Stockholm, Sweden* ISBN 978–91–7595–827–9

§ In this work we decide to use the term “rotor machine” instead of “screw machine” as the former is employed historically in SRM development process. In addition, in the context of development process, we believe that “rotor machine” is the better match.