Automotive Fuel Cell System simulation, component and compressor modelling

Prof. **J.-G. Persson,** Lic.Eng. **C.-J. Sjöstedt** and Dr. **D.-J. Chen**,
Royal Institute of Technology – KTH, Stockholm/S

Abstract

Future fuel cell (FC) systems for automotive applications will significantly depend on the development and realization of efficient and reliable components. The screw compressor for charging of the FC stack constitutes one important component in the system. In the European project NFCCPP (Numerical Fuel Cell Component Performance Prediction tool) within the EC 5th FP, a modular simulation environment has been developed which allows virtual testing of components of fuel cell systems. The objective of this development was to create a useful tool for automotive component suppliers to test their component or subsystem models for performance prediction in a realistic FC system environment, for relevant driving cycles. MATLAB/Simulink, being well established in industry, was chosen as software platform for the modelling. The system model structure, interface definitions and data flows, as well as different approaches to the modelling of screw compressors, will be presented in this paper. Component models of different degree of detail will be possible to plug into the system model. A standard reference model is based on simplified component models. In particular, there have been two main issues for the development of this system:

- **Lumped models** or characteristics approach. Simplified component models will be required to allow for acceptable computing time for system simulation. This is even more important if the system should be used with hardware in the loop, i.e. for real time simulation.
- **Code protection**. Preventing access to confidential information and data of other component suppliers was considered necessary. Even competitors can then test their components together in such an environment. Three different approaches have been taken to this:
    - Centralised simulation with remote user control.
    - Localised simulation with simulation-time model usage control.
    - Parallel distributed simulation.

Compressor models. The complete screw compressor unit, also including electric motor and control system for capacity (speed) control has been modelled in NFCCPP. For a simple compressor model, empirical test data in the form of screw compressor maps for one specific machine type and size could be used. To generalize, screw compressor maps could be transformed by means of similarity laws for scaling. A more detailed screw compressor model should be based on the lumped approach according to the since long well established model structure; a number of compression chambers connected by leakage paths. Building a lumped screw compressor model in Simulink has been tested. Compressor flow field models of CFD element type are however not considered realistic as component models for the complex FC system simulation.
In some FC systems, screw expanders are also used, for energy recovery. The FC system model can be configured to include also an expander. The commercialisation of this program system is being planned for.

1 Fuel Cells, background

After the fuel cell's first appearance in space industry to power satellites and spacecraft, fuel cells for stationary power generation and for automotive application were identified as a potential saviour from the ever increasing debate around reduction of green-house gases and thus protection of the earth's atmosphere. Using fuel cells in the automotive industry for replacing the internal combustion engine as prime mover by a fuel cell system is however quite challenging as far as reliability, cost, safety and Europe-wide operability are concerned.

Fuel cell systems for automotive applications are complex power systems consisting of different component groups as shown in Table 1.

Table 1: Component Group Definition

Group	Components
Air Management	Compressor/expander, humidifier, filter, mass flow sensor, water separator
Auxiliaries	Pumps, piping, valves, pressure regulator
Control	Supervisor, anode, cathode, thermal, power electronics
Driveline Model	Motor, transmission, vehicle
Fuel Processing	Reformer (partial oxidation, steam, autothermal, ammonia cracker), reformate cleaning (shift reactor, preferential oxidation)
Fuel Storage	Liquid fuel tank, compressed H_2, electrolyte storage
Material Properties	Fuels, mixtures, thermodynamic equations and data
Power Management	DC/DC converter/inverter, battery
Stacks	PEM, AFC
Thermal Management	HEX, radiator, start-up burner, off-gas burner, cooling fan

These components interact closely together and influence the entire system behaviour. The general challenges in the development of components for fuel cell systems for different fuel cell applications are:

- Understanding and defining development goals (i.e. component specification)
- Improvement of system efficiencies
- Reduction of production costs
- Improvements of availability and reliability
- Reduction of weight and required space
- Optimisation of dynamic behaviour (incl. start/stop strategies and charging system)
- Further component optimisation (e.g. noise reduction)

2 NFCCPP Simulation program for automotive Fuel Cell systems

In order to develop and optimise single components it is necessary to understand the interaction between the system and the component under development. Thus a "Numerical Fuel Cell Component Performance Prediction Model - NFCCPP" [1] has been developed as a project within the EC 5th FP, to fulfil the particular needs of component manufacturers for a fast and effective simulation tool to evaluate component performance within the fuel cell system. This model is going to be used as a "Reference Model" for fuel cell systems. This reference model contains all known components and sub-systems to date which have been modelled with non-confidential information and modelling know-how, featuring

- High degree of modularisation for fast and easy access to the components
- Standardised I/O signals for the components to enable the use of each simulation block at different positions (if physically possible)
- A graphical user interface to allow a wide range of experts to interact, even if one is not a specialist in the specific software environment
- Easy changes to the system parameters (e.g. model and control parameters)

2.1 Using a visual programming environment

MATLAB/Simulink, being well established in industry, was chosen as a feasible software platform for the modelling. For solving systems of differential equations, using the Simulink visual programming environment is easy compared to conventional programming languages, since the program automatically sorts out the integration order and dependencies. It is easy to get started and to get results quickly. The drawback of using Simulink is that it is not as flexible as an object oriented programming language. For complex models, many function blocks and lines have to be connected in the graphical user interface, and many complex equations have to be entered. The overview can then somehow be lost when too many blocks are interconnected.

2.2 Standardisation of simulation modules and interfaces

To enable ease of component connection and interchange, a standard connection methodology was devised. The basic premise of this was to use generic connections in the form of mechanical, electrical and fluid connections (Table 2). Since Simulink is a casual simulation system the inputs and outputs to each component have to be strictly defined, as opposed to other simulation packages which calculate their own causes and effects from given equations (e.g. Flowmaster, Hopsan) [2]. A component-based approach was used, i.e. the components were modelled the way component manufacturers were used to model them.

The mechanical and electrical connections both work the same way: If the Speed/Voltage is selected as an input, Torque/Current is used as an output and vice versa. In all components the most convenient input and output were selected to guarantee a proper cause and effect action/reaction for the system [3]. For the fluid connection, the Pressure and Mass flow have about the same functions as Torque/Speed. In addition, the Temperature and Mass fractions are included in this connection to calculate the fluid properties, including density, heat capacity, and more, inside each component. The Temperature and Mass flow information are both assumed to always be in the same direction as the main flow direction. The requested mass flow always should be used as an input together with the downstream pressure. Using this method for all the fluid connections, all components will have the same input and output, and can then be connected in any order.

In addition to the Mechanical, Electrical and Fluid connections, there are also control signals, e.g. "requested torque" or "measured mass flow" (electric control signals, e.g. 0-10V, in a real system). They can be used only as input or only as output from the system.

Table 2: Generic Component Connections

Mechanical	Electrical	Fluid 1	Fluid 2
Torque (Nm)/	Current (A)/	Temperature (K)	Pressure (Pa)
Speed (rad/s)	Voltage (V)	Total mass flow (kg/s)	
		Mass fraction , element 1	
		Mass fraction, element 2,	
		….	
		Mass fraction, element n	

Through use of the connection scheme of Table 2, a component may be defined as shown in Figure 1.

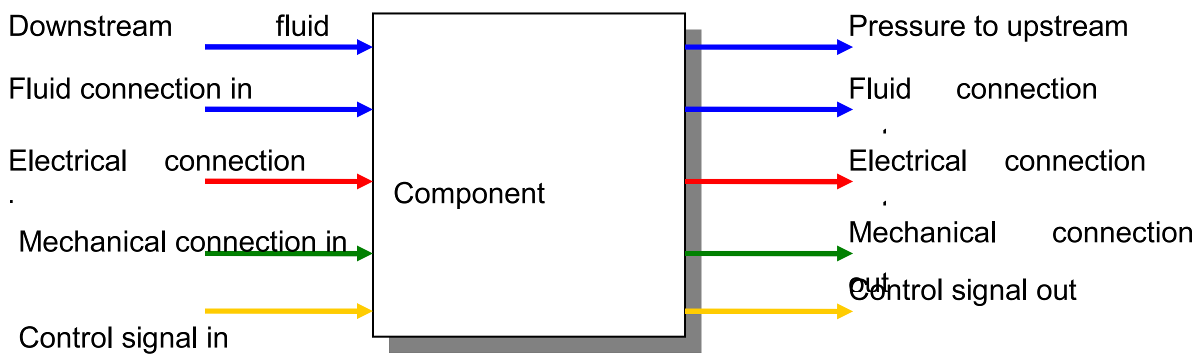

Fig. 1: Component connections

Such a modularised system model enables the user to remove his component module within the existing system model (Reference model), and to put a very detailed, self-developed module into the system model and generate information about the component behaviour in the complete system. There will be a growing acceptance of the results if component manufacturers and their customers use the same reference model for their performance predictions.

It is assumed that especially smaller and medium sized companies will profit from such a standard tool since they presumably have little interest in developing a complete fuel cell system model with their own internal resources, but would profit from the ability to assess the performance of their components in the system.

3 Code protection

The Reference Model can be further improved by exchanging standard modules with enhanced models provided by the different component manufacturers on a voluntary basis. The system model quality will be improved by using detailed component models based on proprietary company information. Such models would thus be provided only if the protection of this confidential information included in the different component modules can be guaranteed.

One objective within the NFCCPP project was then to devise a scheme of IP protection for the NFCCPP model components and a software system to demonstrate concepts for code protection and their feasibility. This was driven by the industrial need of enabling cross-enterprise model exchanges and integrations, which was considered as a key factor for continuous evolution of the NFCCPP reference model and for the maturing of a fuel cell component market.

The task was to identify the potential security risks and basic requirements, and to explore the solution space in a systematic way. The following three possible solution alternatives have been identified:

I. Centralized Simulation with Remote User Control: All simulation and evaluation works are performed at a centralized site run by a neutral “governing body” with remote control interfaces offered to the users for remote control. This follows the concept as in X-terminal architectures.

II. Localized Simulation with Simulation-Time Model Usage Control: All simulations and evaluation works are performed locally by users who obtain or buy external model components of third-parties.

III. Parallel Distributed Simulation: All simulations and evaluation works are performed locally by component users, supported by communication and synchronization services that connect to external model components of third-parties running on their producers' site. This follows the concept of co-simulation.

Based on three conceptual demonstrators built for proof-of-concept, alternative "II" was selected as the most promising one based on the consensus of the NFCCPP partners. Based on the solution concept, this task proposes a cost effective software based component protection approach where some fundamental cryptography mechanisms such as hash and digital signature are employed. To prove the concept of the developed component protection scheme, a demonstrator implementation has been provided.

The protection system is based on C++ S-function and embedded within a standard NFCCPP component by means of code-level integration. Activated at the initialization phase of simulation, the system prevents illegal acts of component interrogation by restricting the component observability and controllability in the simulation environment. The control is performed based on the hash value of a predefined set of configurational information that provides a unique "fingerprint" of the allowed component usage context. The configurational information of concern includes for example how the in/outputs, subsystems, and scopes are connected. To allow component users to combine their own solutions, the protection system distinguishes between the areas of a configuration that are of different concern for component IP-protection in terms of protected area and slots. Settings within the protection area are visible for the component users, but changes will not be allowed. Settings within the slot area are totally open and can be freely tuned or defined by the users. During simulations, the system works transparently without affecting the behavior, performance, or usability of the original components. To hide proprietary component information as well as to prohibit illegal acts of software hacking, a binary encryption technique, referred to as code obfuscation, is adopted. An overview of the adopted protection mechanisms is provided in table 3.

The code protection task was carried out with close collaboration between industrial and academic project participants. The subtasks concerning requirements and evaluations were mainly driven by the industrial participants in order to embrace the end-users' demands and to ensure the industrial significance of solutions. The academic participant (KTH) conducted the systems design work while taking state-of-the-art concepts and technologies into consideration.

Table 3: An overview of adopted component protection mechanisms

Risk	Protection Mechanism	Roles of Protection Mechanism
Direct revealing of sensitive component information	Compilation	Model encryption
	Code Obfuscation	Binary encryption
Illegal acts of component interrogation	Hash Algorithm	Run-time component usage verification.
Unauthorized component usage	Dedicated component usage control key	Usage- and user-authenticity control
Cracking of component usage key	Digital Signature	Encryption and authentication for both hash value and its verification keys.
	Content Shuffling	Encryption of key information
Cracking of component software	Code Obfuscation	Binary encryption

It was shown by the demonstrator, that the component embedded protection mechanisms can effectively detect and prevent illegal acts of component interrogation without affecting the performance, integrity or availability. It is believed that this software-based scheme provides a cost effective solution for promoting cross-enterprise exchanges and integrations of NFCCPP components. On the other hand, no security solution is absolutely secure if the crackers have enough time and resources. Because of the adopted strong cryptography algorithms and binary encryption technique, attacks could be performed by identifying potential vulnerabilities in the simulation and system environments, or in the usage control key. If such vulnerabilities are found in the future, updates of the security solution will be necessary.

4 Screw compressor models

For charging of fuel cells, the helical screw compressor is preferred due to its ability to produce large pressure ratio at low volume flow (compared to the turbo compressor) [4]. Compressed air is supplied at the cathode in PEM (Proton Exchange Membrane, or sometimes called Polymer Electrolyte Membrane) fuel cells, to increase the stack pressure to

reduce stack weight and dimensions. Also, an expander of twin-screw type can be used for recovery of mechanical energy.
Fluid systems, e.g. compressors, can be modeled at different degree of detail. CFD can be used to calculate flow fields, but such detailed flow field calculations are time consuming, in particular for non-stationary and transient behaviour.

4.1 Simulink model of a screw compressor

This paper shows how a one dimensional lumped model of a screw compressor, for non-steady-state operation, can be developed relatively easily using a visual programming environment, allowing for fast analysis/synthesis of concepts. A typical application in system design and product development is when different configurations or layouts are to be examined, as well as parametric studies e.g. for sensitivity analysis and optimisation.

The main difference of a twin-screw compression process, as compared to an ideal isentropic compression process, is internal leakage in clearances between the compressor chambers, and different forms of heat exchange [7]. Kauder et al [5] suggest a generic method on how rotary displacement machines should be modelled in computer software. This is an object-oriented approach where the configuration of the machine easily can be changed and phenomena like heat exchange can be included or excluded at will. Instead of using C++ like [7], Simulink has been used in this project, which has called for slight modifications in the model.

The following assumptions have been made: The state of the fluid inside a chamber is approximated as homogeneous, i.e. state variation over a working chamber volume is neglected. Dry air, where the perfect gas law is valid is used as working medium, is assumed. Two-phase flow for an oil flooded or water injected compressor could be modelled by introducing the corresponding more complex relationships. In order to get the right cause and effect for this system, the compressor model has been systemised using bond graphs [6]. The chambers are idealised as “flow storage” elements, i.e. their compressibility is modelled, but not their pressure drop due to internal viscosity. Between the chambers, so-called flow resistance blocks are modelled, for the leakage flow. Conservation laws have been set up for mass, energy and momentum.

4.1.1 Chamber model

The chambers are, like said above, modelled as compliance objects. The idea of a fluid compliance object is to model the pressure as a function of the net mass flow [6]. In this example perfect gas is assumed. These equations can be expanded or replaced to model real gases or two phase flow, the important thing is to get the pressure as a function of the net mass flow (and other factors like time, phase angle etc.) using conservation laws.
The conservation law for non-stationary systems [7] is used:

$$\begin{aligned}Q = &\int_{\tau I}^{\tau II}\left[\dot{m}(h+\frac{w^2}{2}+gz)\right]_{out} d\tau - \int_{\tau I}^{\tau II}\left[\dot{m}(h+\frac{w^2}{2}+gz)\right]_{in} d\tau + \\ &+\left[m(u+\frac{w^2}{2}+gz)\right]_{II} - \left[m(u+\frac{w^2}{2}+gz)\right]_{I} + E_t\end{aligned} \qquad (1)$$

The process is considered as adiabatic:

$$Q = 0$$

The velocity components and potential energy terms are also neglected in the chambers. When this equation is differentiated, it leads to equation (2):

$$\frac{d(m*u)}{dt} = \Sigma\dot{m}_{in}h_{in} - \Sigma\dot{m}_{out}h_{out} - \dot{E}_t \qquad (2)$$

Since it is a perfect gas, the internal energy and enthalpy are functions of the temperature only. The absolute values of these quantities are not used in these formulas, so T=0 can be chosen as reference point in equation (3) to simplify the expressions.

$$\left\{u = c_v T, h = c_p T, \dot{E}_t = p\frac{dV}{dt}\right\} \qquad (3)$$

$$\left.\begin{aligned}&\frac{mc_v dT}{dt} + \frac{c_v T dm}{dt} = \Sigma\dot{m}_{in}c_{pin}T_{in} - \Sigma\dot{m}_{out}c_{pout}T_{out} - p\frac{dV}{dt} \\ &\frac{dT}{dt} = \frac{1}{mc_v}\left(\Sigma\dot{m}_{in}c_{pin}T_{in} - \Sigma\dot{m}_{out}c_{pout}T_{out} - \frac{c_v T dm}{dt} - p\frac{dV}{dt}\right)\end{aligned}\right\} \qquad (4)$$

The perfect gas law, differentiated by time:

$$\left.\begin{aligned} &pV = mRT \\ &\frac{dp}{dt}V + \frac{dV}{dt}p = R\left(\frac{dm}{dt}T + \frac{dT}{dt}m\right) \end{aligned}\right\} \tag{5}$$

Equations (4) and (5) together give:

$$\begin{aligned} \frac{dp}{dt} &= \frac{R}{V}\left(\frac{dm}{dt}T + \frac{1}{mc_v}\left(\Sigma\dot{m}_{in}c_{pin}T_{in} - \Sigma\dot{m}_{out}c_{pout}T_{out} - \frac{c_v T dm}{dt} - p\frac{dV}{dt}\right)m\right) - \frac{dV}{dt}\frac{p}{V} = \\ &= \frac{R}{V}\left(\frac{1}{c_v}\left(\Sigma\dot{m}_{in}c_{pin}T_{in} - \Sigma\dot{m}_{out}c_{pout}T_{out} - p\frac{dV}{dt}\right) - \frac{dV}{dt}\frac{p}{R}\right) \end{aligned} \tag{6}$$

Since the chamber is assumed to have a uniform temperature, the outgoing temperature equals the temperature in the chamber. It is calculated by equation (4), which can be rewritten as

$$\frac{dT}{dt} = \frac{1}{mc_v}\left(\Sigma\dot{m}_{in}c_{pin}T_{in} - \Sigma\dot{m}_{out}c_{pout}T - \Sigma\dot{m}_{in}c_v T + \Sigma\dot{m}_{out}c_v T - p\frac{dV}{dt}\right) \tag{7}$$

4.1.2 Leakage equations

The leakage paths have been modelled as resistance objects, where the mass flow is a function of the pressure difference. The equation for one dimensional compressible isentropic nozzle flow of a perfect gas has been used [7].

$$\left.\begin{aligned} &\dot{m} = \alpha A \psi \frac{p_0}{\sqrt{RT_0}} \\ &\Pi = \frac{p}{p_0} \\ &\psi(\Pi) = \sqrt{\frac{2\kappa}{\kappa - 1}\Pi^{2/\kappa}\left(1 - \Pi^{\frac{\kappa-1}{\kappa}}\right)} \\ &\Pi_{crit} = \frac{p_{crit}}{p_0} = \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa-1}} \end{aligned}\right\} \tag{8}$$

In this equation α is the flow contraction factor, which depends on the geometry of the clearance. Above the critical pressure ratio, the mass flow is independent of the pressure ratio.

At the inlet and outlet, the pressure drop is estimated from the simplified expression:

$$\left.\begin{aligned}\Delta p &= c_f\frac{\rho v^2}{2} = \left\{v = \frac{\dot m}{\rho A}\right\} = c_f\frac{\rho \dot m^2}{2A^2\rho^2} = \left\{\rho = \frac{p}{RT}\right\} = c_f\frac{RT\dot m^2}{2A^2 p}\\ \dot m &= A\sqrt{\frac{2p\Delta p}{c_f RT}}\end{aligned}\right\}\qquad (9)$$

"c_f" is a friction constant which has to be empirically determined.

4.1.3 Screw compressor model

All geometry data according to Figure 2 should be generated separately and imported to the Simulink model.

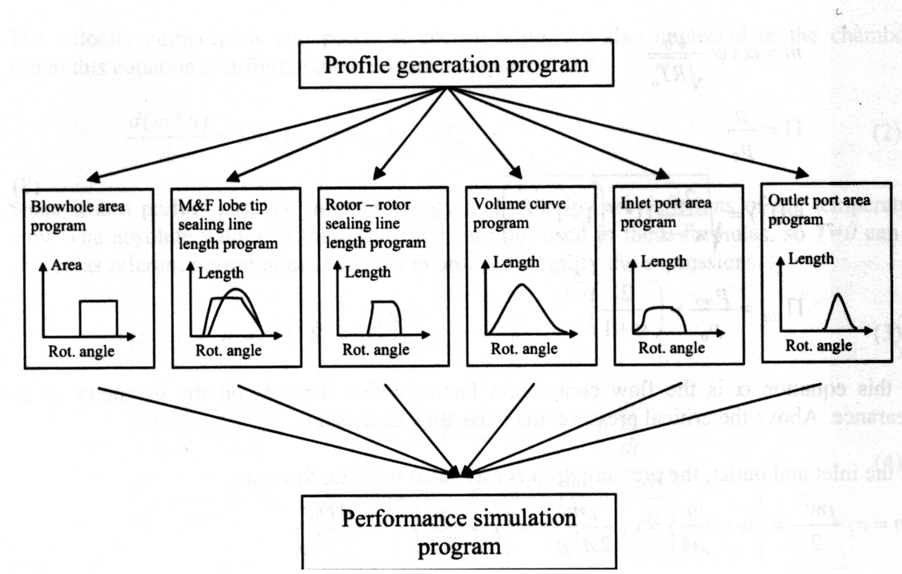

Fig. 2: Geometry input data to the performance simulation program [8]

To describe the modelling approach the volume curve is displayed below together with the leakage between the chambers. Note that there also exists other leakage paths (see Figure 3), but they are not included in these illustrations, in order to make them more readable. They are however modelled in an analogous way.

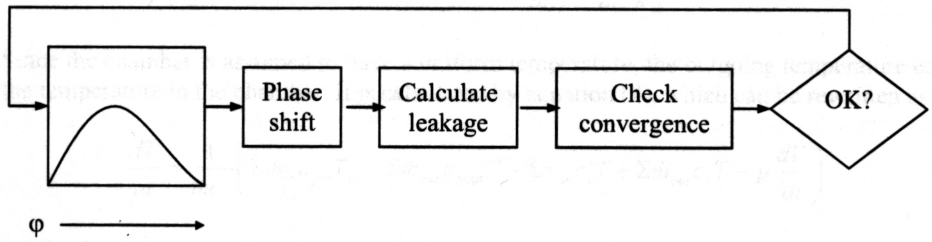

Fig. 3: Leakage calculation according to Jonsson [8] and Platell [9]

In the first generation of calculation software, one chamber is investigated at a time. For leakage between chambers, the curve is phase shifted and an iteration loop is set up [8], [9]. This is illustrated in Figure 4.

Kauder et al [5] suggest setting up the chambers as objects in a queue, with leakage paths in between them. A unified phase angle α is used. α is the angle when a new chamber is created. In the screw compressor case, α equals 360° divided by the male lobe number. The chamber vanishes at a certain angle β, when it has completed one cycle (at the end of the volume curve). If β is not a perfect multiple of α, the number of chambers vary by the closest multiple and one more. Example: If β=700° and α=90°, the number of chambers will be 7 or 8 depending on the rotational angle.

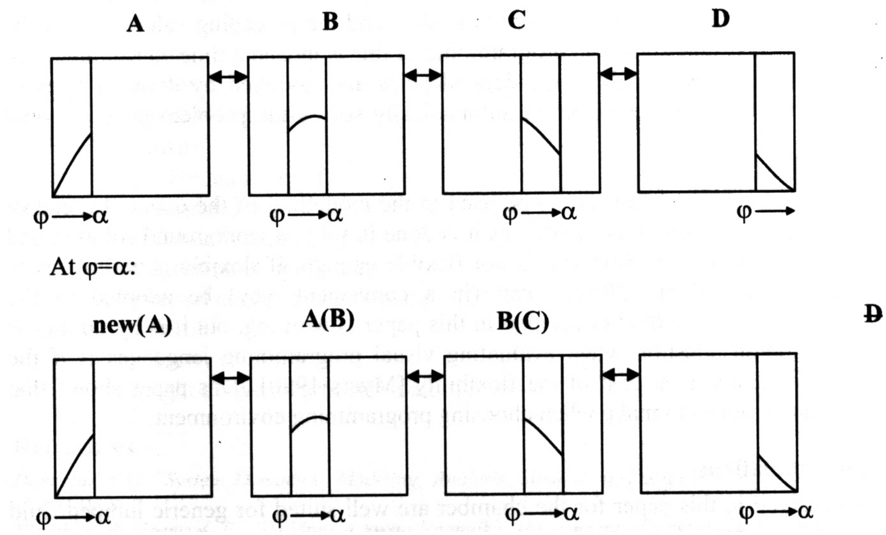

Fig. 4: Leakage calculation according to Kauder et al [5]. This compressor example has only four working chambers

4.1.4 Implementation in Simulink

In Simulink, the maximum possible chambers (8 in the example above) are distributed with leakage paths in between them. At angles that are multiples of α, all thermodynamic data (pressure, temperature and mass) are transferred one cell ahead. In practice, this is used by applying the MOD-function on the rotational angle to create a saw tooth like function with periodicity α. MOD is the standard mathematical modulus function. This signal triggers the external reset on the integration blocks, and the integration starts over, with external initial conditions from the preceding blocks. The phase angle is phase shifted α, 2α, 3α etc. up to the minimum number of chambers (7α in the example above) and used as input to the following block.

In the last cell, all the data is bypassed at angles where it does not exist. A switch and another modulus function are used to achieve this.

4.1.5 Simulink compressor model - results and conclusions

At the time of writing this paper, simulations based on real machine data have not been verified so far, due to lack of proper geometry curves (see Figure 2). The model has however been tested using approximate geometry curves, and checked for energy conservation over the working cycle [10].

One complexity in modelling this kind of problem is to set up the equations, due to couplings and strong interdependencies. The pressure in the volumes is dependent on the leakage between them, which in turn is dependent on the pressure. The dependencies are also mostly non-linear and time dependent. This calculation has to be performed at every time step, and the preceeding values have to be used as input to the next time step. All this is taken care of by Simulink, the dependencies are taken care of by drawing lines in between the objects, and then the program automatically solves the problem using its own solution method. The drawback was the method that had to be used for modelling of the queue. Instead of adding and removing volumes in the model, as it is done in C++, a workaround solution had to be made.

The equations derived in this paper for the chamber are well suited for generic lumped fluid problems with perfect gases and have also been used in the NFCCPP project for modelling of pipe flow and filling/emptying of tanks. This approach is also feasible for modelling of leakage in clearances, other displacement compressor types and more. The Simulink blocks can be reused with a little modification in such types of simulations. In product development, this approach can be used in the concept phase, when the geometry still is unknown, and

quick results are of importance. The queue concept should also be applicable when modelling analogous technical problems in MATLAB/Simulink.
The visual programming environment is well suitable for solving these kinds of problems. The main advantage is the drawing of differential equations with lots of dependencies, and the program itself can sort out the integration order. This is in other words a good implementation of the visual programming concept. The drawback is flexibility; it was by no means obvious how to get the objects to move in a queue.

4.2 Scaling of measured screw compressor characteristics

For the first version of the NFCCPP system model, just the compressor measured capacity – pressure ratio – speed characteristic $\dot{V}(\Pi, n)$ and the isentropic efficiency curves $\eta_s(\Pi, n)$ were used, as look-up tables for a specific compressor size and design, Figure 5.

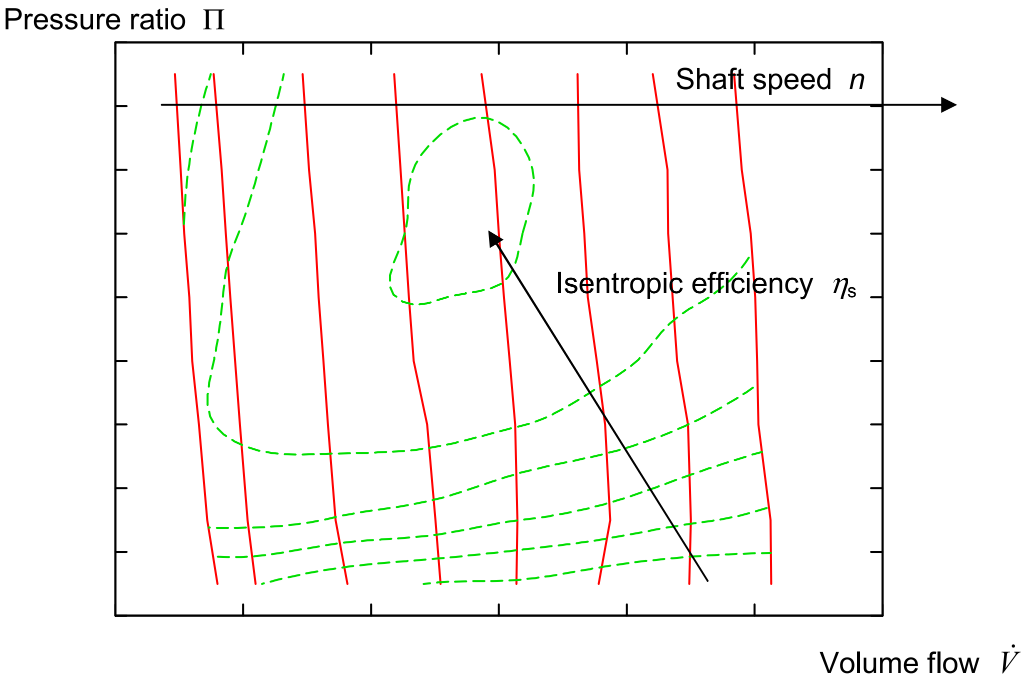

Fig. 5: Compressor characteristic, empirical data

Characteristic curves (tables) for a representative supercharger compressor were used in the reference model. A further development of this very simple approach would be to utilise the laws of similarity for scaling to compressors of different size [11], for parametric studies:

$$\dot{V} = \eta_{vol} \cdot V \cdot n = \frac{1}{\pi} \eta_{vol} \cdot \left(V / D^3\right) \cdot u \cdot D^2 \tag{10}$$

For moderate changes of compressor size D and shaft speed n, assuming a geometrically similar machine, compressor capacity $\dot{V}$ and shaft speed could be approximated as follows, for a rotor size (male diameter D) modification:

$$\dot{V} = \dot{V}_{ref} \cdot \left(\frac{D}{D_{ref}} \right)^2 \tag{11}$$

$$n = \frac{n_{ref}}{\left(D / D_{ref}\right)} \tag{12}$$

with reference parameter values and data taken from look-up tables for the reference machine, and assuming the same rotor profile, L/D ratio, specific displacement V/D^3, built-in pressure ratio Π_i and male rotor peripheral speed u. For minor rotor diameter changes, volumetric efficiency η_{vol} and isentropic efficiency $\eta_s(\Pi, n)$ could be approximated as unchanged from the reference case.

If also the rotor tip speed u is changed, the corresponding expressions will be:

$$\dot{V} = \dot{V}_{ref} \cdot \left(\frac{D}{D_{ref}} \right)^2 \cdot \left(\frac{u}{u_{ref}} \right) \tag{13}$$

$$n = \frac{n_{ref}}{\left(D / D_{ref}\right)} \cdot \left(\frac{u}{u_{ref}} \right) \tag{14}$$

The isentropic efficiency is primarily dependent on the tip speed, so it should then also be modified, based on a polynomial fit to the empirical data $\eta_s(\Pi, u)$, Figure 6, for the reference machine, at the actual operating pressure ratio Π, where the tip speed – shaft speed relation is:

$$u = \pi \cdot D \cdot n \tag{15}$$

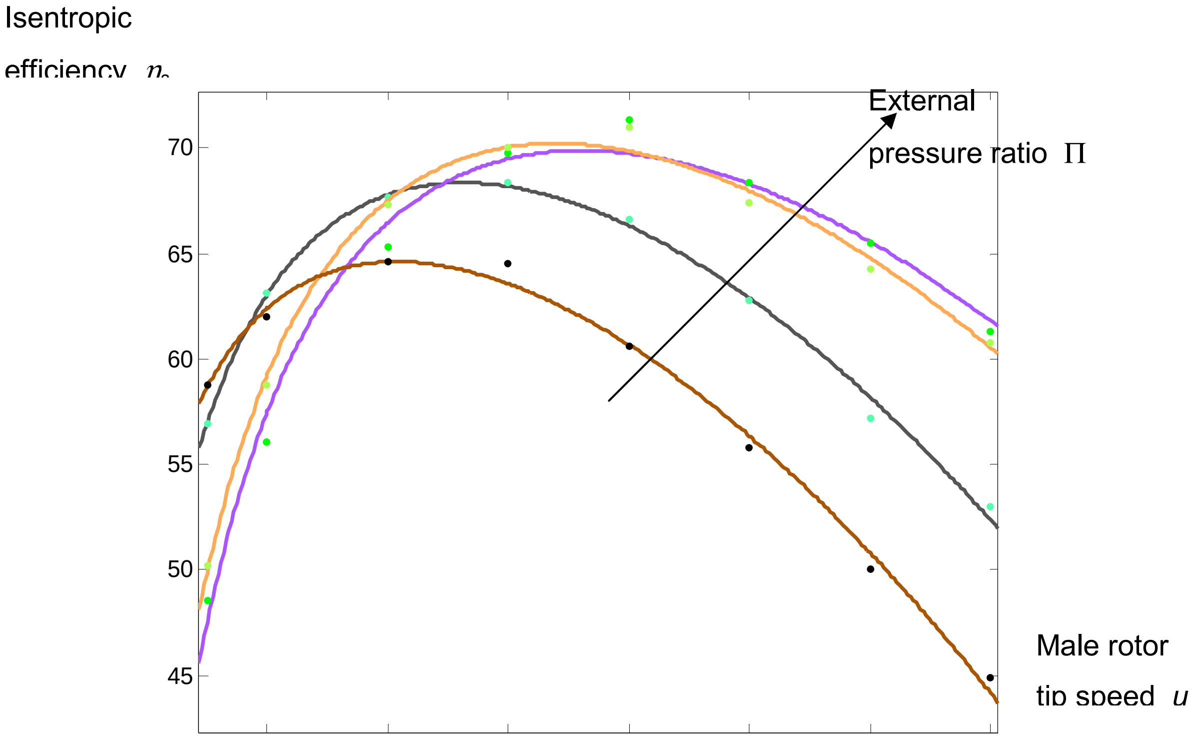

Fig. 6: Isentropic efficiency, empirical data and polynomial fit.

The polynomial fit, at a constant operating pressure ratio Π, could be approximated [11] as:

$$\frac{1}{\eta_s} = k_1 + k_2/u + k_3 \cdot u^2 \tag{16}$$

where $k_1 \geq 1$ accounts for the polytropic exponent deviation from the isentropic exponent (due to heat transfer), the second term (constant k_2) represents the internal leakage loss and the third term (constant k_3) represents the throttling losses in inlet and outlet ports. Coefficients $k_1(\Pi)$, $k_2(\Pi)$, and $k_3(\Pi)$ are determined by polynomial fit to measured efficiencies, for different values of operating pressure ratio Π. However, the polynomial constant k_2 as well as the volumetric efficiency η_{vol} are also dependent on the clearances, hence for more substantial changes of machine size, also the variation in specific clearance δ / D with rotor diameter, should be accounted for [11].

This scaling approach was not implemented in the NFCCPP project and has so far not been tested or verified. However, this approach should represent a faster and simpler way to use a limited set of empirical data (measured compressor characteristics) for extrapolation and parametric studies.

5 Conclusions

Within the European NFCCPP project, it has been demonstrated different approaches to modelling of a screw compressor, included as a major component in an automotive fuel cell system. For such a complex system model, for fuel cell simulation and performance prediction at transient operating conditions, simplified compressor models are needed. Compressor models of three different levels of detail have been demonstrated:

- Machine specific performance map, as look-up table
- Scaling of performance maps, by similarity laws
- Lumped screw compressor model implemented in the visual programming environment MATLAB/Simulink

6 References

[1] Chen, D.-J., Sjöstedt, C.-J, Prenninger, P., Faye, I., Huelshorst, T., Kells, A., Harkness, I. and Schönfelder, C., ”Virtual component testing for PEM fuel cell systems – an efficient, high quality and safe approach for suppliers and OEM´s”, 3rd European PEFC Forum, Lucern, Switzerland, 2005

[2] Larsson, J., Krus, P., and Palmberg, J.-O., “Techniques for Simulation of Multi-Domain Systems”, Proceedings of The Sixth Scandinavian International Conference on Fluid Power, Linköping, Sweden, 1999

[3] Kecman, V., “State-Space Models of Lumped and Distributed Systems”, pp 27-157, Springer-Verlag, Berlin, 1988

[4] Kulp, G., “A Comparison of Two Air Compressors for PEM Fuel Cell Systems”, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 2001

[5] Kauder, K., Janicki, M., Rohe, A., Kliem, B. and Temming, J., ”Thermodynamic Simulation of Rotary Displacement Machines”, Schraubenmaschinen 2002, VDI-Berichte 1715, pp 1-16, Dortmund-Düsseldorf, 2002

[6] Ljung, L. and Glad, T., ”Modellbygge och simulering”, Studentlitteratur, Lund, Sweden, 1991

[7] Ekroth, I. and Granryd, E., ”Tillämpad termodynamiik”, Departement of Energy Technology, Royal Institute of Technology - KTH, Stockholm, Sweden, 1994

[8] Jonsson, S., ”Performance of Twin-Screw Compressors for Refrigeration Purpose”, Schraubenmaschinen ´87, VDI-Berichte 640, pp 187-207, Dortmund-Düsseldorf, 1987

[9] Platell, P., ”Displacement expanders for small scale cogeneration”, Licentiate of Engineering Thesis, Department of Machine Design, Royal Institute of Technology - KTH, Stockholm, Sweden 1993

[10] Sjöstedt, C.-J., ”Modelling of displacement compressors using block model software”, NordDesign 2004, Tampere, Finland, 2004

[11] Persson, J.-G., “Performance mapping vs´ design parameters for screw compressors and other displacement compressor types”, Schraubenmaschinen ´90, VDI-Berichte 859, pp 15-31, Dortmund-Düsseldorf, 1990