Experimental examination of a GASSCREW

Prof. Dr.-Ing. Knut Kauder, Dipl.-Ing. Thomas von Unwerth
Fachgebiet Fluidenergiemaschinen, Fakultät Maschinenbau, Universität Dortmund

ABSTRACT

The hot-gas screw-type engine (GASSCREW), working in a modified Ericson-Joule-Process, is a newly developed drive concept with higher predicted efficiency and usable shaft-work compared to an equivalent gas turbine. It could therefore be suitable for use in plants for decentralised energy supply as well as for automotive or auxiliary drives.

The first prototype design was based on results obtained using a simulation system. In this paper the development from the concept to the realization as well as the comparison of results from the simulation system with the measured data is described.

The target of this development is the verification of operating behaviour and the thermal and mechanical behaviour of the screw-type motor's parts, because the clearances in the motor needed for effective operation have to be very small. Therefore, the first task was to select suitable components with a main focus on the simulation-based design of the thermally high-stressed motor. The necessary calculations were performed using a specifically developed simulation system, of which the authors also give a short outline.

Additionally, the article shows how the essential measurement data was recorded and what techniques were used for the various measurement tasks. Finally the authors provide a conclusion with a discussion of the accuracy of the simulation results and plans for further progress.

1 INTRODUCTION

The development of this new kind of drive concept, intended to convert economically low and medium mass flow at high temperatures into usable shaft-work, began in the mid-80s at the

University of Dortmund. The main aim was to replace the compressor used in a gas-turbine-plant by a screw-compressor and the turbine by a screw-type motor. We named this principle of a hot-gas screw-type engine GASSCREW, just to keep the association with a gas-turbine in mind. **Figure 1** shows the layout:

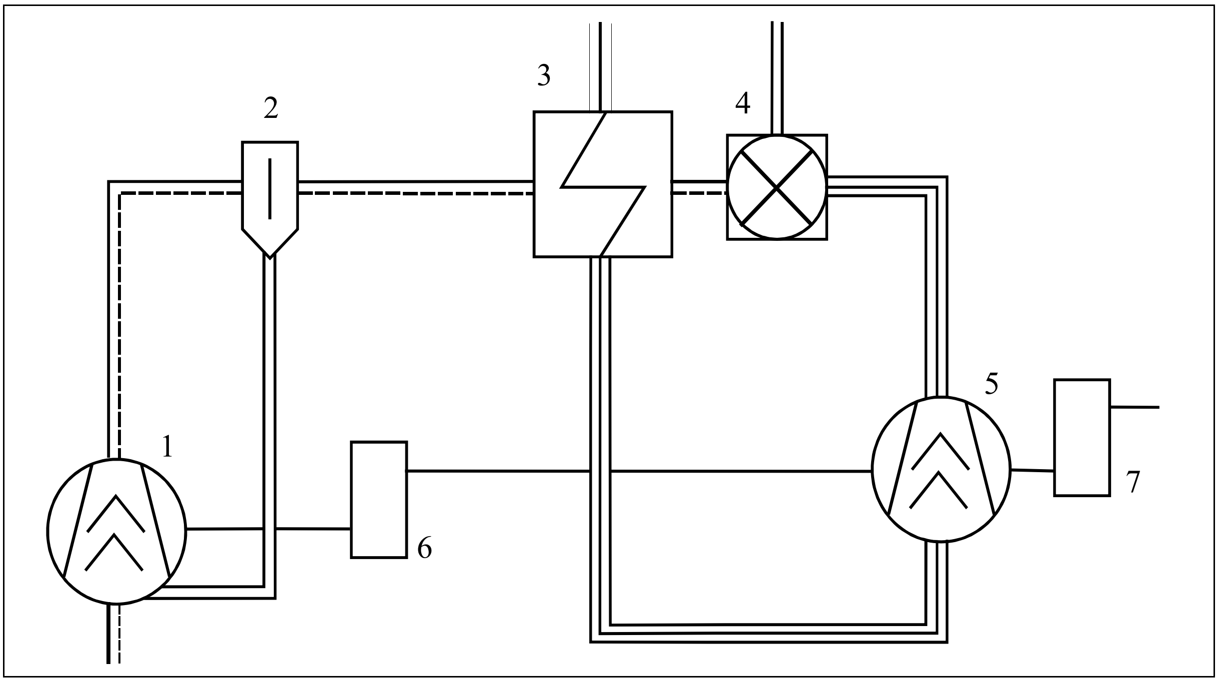

Figure 1: Layout-plan of a GASSCREW

1	**Screw compressor**	**5**	**Screw-type motor**
2	**Oil separator**	**6**	**Gear box**
3	**Heat exchanger**	**7**	**Gear box**
4	**Combustion chamber**		

The main advantages of a GASSCREW in contrast to a comparable gas-turbine are the higher usable shaft-work and higher thermal efficiency. These improvements are the result of improved thermodynamic process management, **Figure 2**. Examining the modified Ericson-Joule reference-process, it becomes obvious that the ideal process management for the compression is isothermal, unlike the isentropic compression in a gas-turbine. The isothermal compression can nearly be achieved by the internal cooling of the oil-injected screw-compressor with an average polytropic exponent of about $\bar{n} \leq 1{,}3$ ($1 \rightarrow 2$), and achieves a higher thermal efficiency because of the enhanced heat exchange (2GA→2HE instead of 2GT→2HE). Also the screw compressor requires lower driving power because of internal cooling, which leads to higher accessible shaft-work than the comparable values of a gas-turbine.

The main focus on the development of this driving concept was hitherto concentrated on the expansion component. As is the case with gas turbines, screw motor efficiencies are higher with high inlet gas temperatures. Considerable analytical work had to be carried out to study this condition. The analyses examined the steady and transient characteristics of the motor and the mechanical behaviour of the individual components. As a result of this work, the Fluid Energy Machinery department at the University of Dortmund has developed an extensive simulation system, allowing for analytical study of the interaction between screw compressors and screw motors. The theoretical research in this sector is intended to lead to the experimental verification of the simulation system described in this paper.

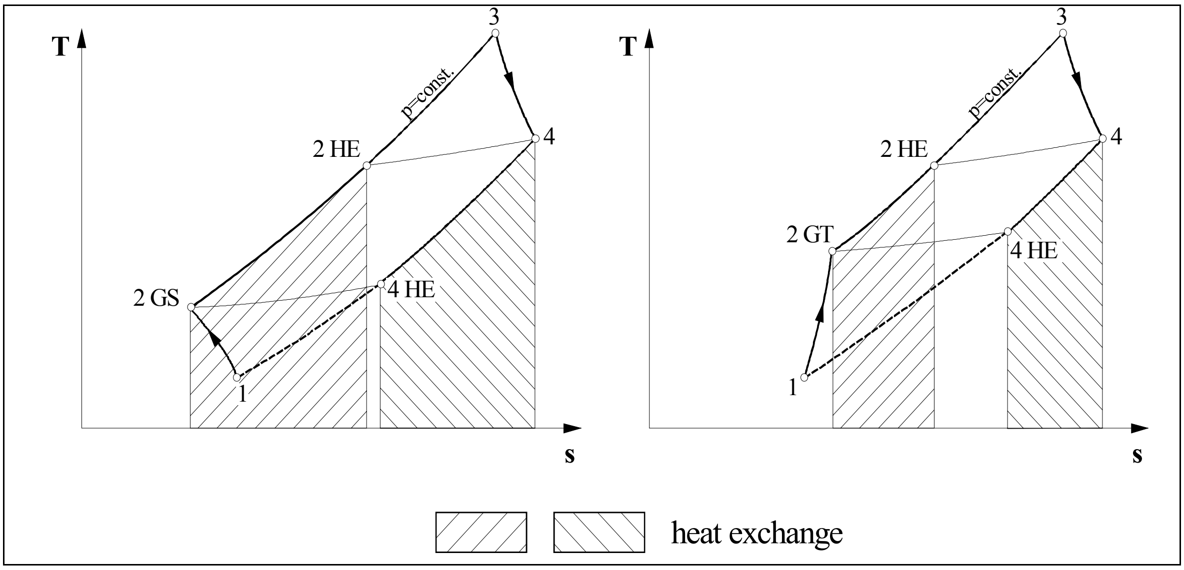

Figure 2: T-s-Diagram of the GASSCREW-process (left) compared to the gas-turbine-process (right)

2 SIMULATION OF THE GASSCREW

The development of a simulation system for the operating behaviour of the GASSCREW has been advanced recently by Kauder and Dosdall (1), Dosdall giving a detailed description in (2). Because the motor of the GASSCREW represents a machine with very small clearances, which must operate reliable at a very high temperature-level, some contributions on the thermal and mechanical behaviour of motor-components by Kauder and Keller (3) follow as a basis for further progress. These are documented in detail by Keller (4) and were used as a basis for simulation-aided construction of the first prototype, described by Kauder and von Unwerth (5).

2.1 Simulation of the operating behaviour

The simulation of the operating behaviour includes both the thermodynamic calculations by means of a suitable chamber model for the screw compressor and the screw motor, and the simplified fluid-mechanical simulation for the cooperation of the regulated, diabatic, oil-injected compressor with the adiabatic, dry-running screw-motor, plus the necessary heat exchanger and the combustion chamber.

Variations in machine and plant parameters were studied with the simulation system. This analytical study provided information on the effect of these parameters on the overall efficiency of the system. This work revealed the considerable potential for development of the GASSCREW with relevant advantages in contrast to an analogous gas turbine. So the GASSCREW as a positive displacement-machine possesses, for example, significantly higher part load efficiencies, and the screw-compressor does not surge.

A more precise examination of the the transient operating behaviour was carried out for use with generators and automotive drives. The analysis of results obtained from these calculations shows that the GASSCREW has much more favourable torque characteristics and similar or shorter acceleration-time than e.g. an automotive gas turbine.

2.2 Simulation of thermal and mechanical behaviour of the components of the GASSCREW-motor

In order to guarantee efficient functioning at the high gas temperatures required, adequate rotor-clearance has to be provided. A simulation program has been developed to enable us to calculate the clearances after warm-up, in particular the rotor intermesh clearance and the radial and axial clearances. This program requires previously determined data relating to component deformation as a result of temperature changes affecting the rotors and the machine housing.

The specialized simulation system consequently begins with a calculation of temperature fields for the components of the screw motor by the Finite-Element method. The parts of the machine are then computer-modelled, after which there is an automatic application of boundary conditions for heat-transfer. The models are shown in **Figure 3**.

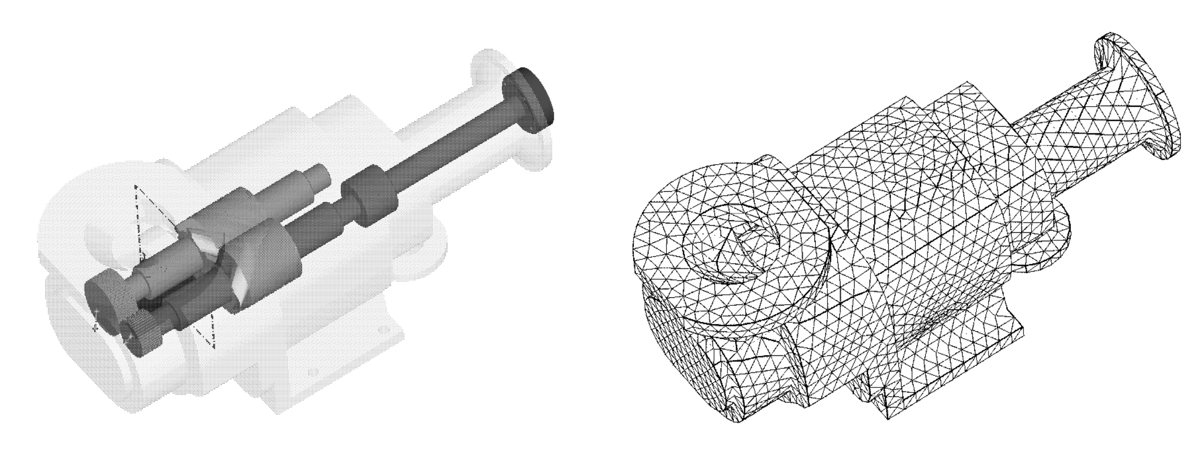

Figure 3: Models of the screw motor components

In the next step thermally related part deformations are computed along with the effects of mechanical loads. These calculations provide the basis for the final calculation of clearances after machine warm-up.

Mathematical modelling of the rotors and housings allows definition of the manufacturing tolerances to allow for the effects of the high temperature levels seen during operation. This approach to specifying the tolerances provides the highest level of machine reliability.

3 STRUCTURE OF THE TEST STAND

The test stand built for verification of the simulation results is shown in **Figure 4**.
The subsequent section describes some construction details for the motor section. The following parameters were considered:

- Cooling of the screw-motor housing through bores, carrying a cooling fluid (➔ a in Figure 4).
- Cooling of the screw-motor rotors through bores, carrying a cooling fluid (➔ b in Figure 4).
- Coating of the screw-motor rotors for realization of a hybridic heat barrier coating with a coeval shrinkage behaviour.

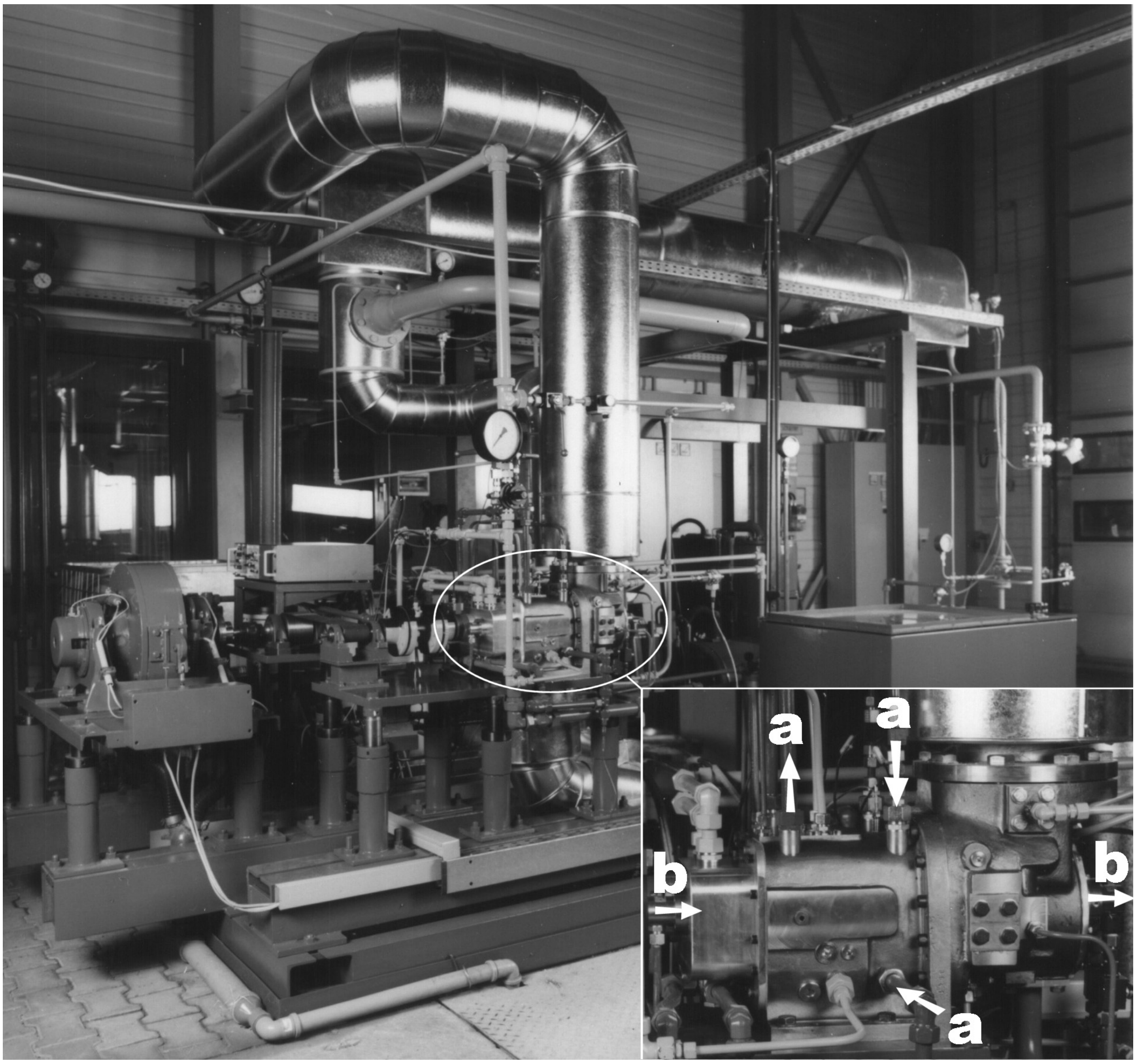

Figure 4: Testing plant for the GASSCREWs motor (see cut-out)

- Manufacturing of undersized screw rotors to compensate for the effects of the coating thickness and thermal deformation to avoid seizure of the rotors during high temperature operation.
- Selection of the housing dimensions to compensate for the thermal deformation of the housing and the effect of bearing displacements to ensure no contact between the rotors and housing during operation.

3.1 Cooling the screw-motor housing

As mentioned in the theoretical examination of the thermal and mechanical behaviour of the GASSCREW motor, economical efficiencies are most easily achieved at higher temperature levels. Because of the resulting thermal loads, cooling of the screw-motor housing is essential. A simplified water cooling is sufficient for a functional temperature behaviour (➔ a in Figure 4).

3.2 Cooling the screw-motor rotors

Analogous to the cooling of the screw-motor housing, the rotors of the screw-motor also require cooling. Water cooling (or water-glycol cooling) represents the most efficient kind of cooling (4). However, because of the dynamic properties of the system rotating at high circumferential speed, the only option at present is to lead the cooling fluid through a concentric bore by means of rotating unions (➔ b in Figure 4).

3.3 Coating the screw-rotors

A special precaution for cooling the rotor material is the laminating of the rotors with a heat barrier coating. The most suitable insulating coating is ytrium-stabilized zirconiumoxide. This material has a very low heat transfer coefficient of about $\lambda \approx 0{,}5\ Wm^{-1}K^{-1}$. In conjunction with a cooling bore through the rotors this provides a highly efficient cooling effect for the GASSCREW motor. For an illustration of the cooling effectiveness, **Figure 5** demonstrates the temperature fields of an uncoated, non-cooled male-rotor in comparison to a coated, cooled male-rotor.

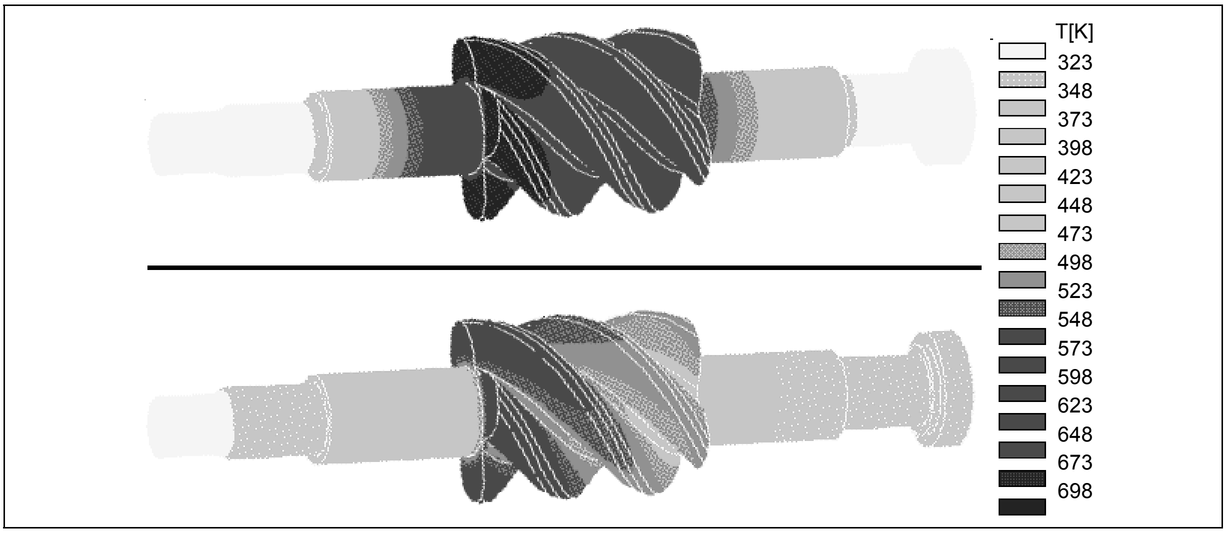

Figure 5: Temperature fields of a) uncoated, non-cooled male rotor and b) coated, cooled male rotor (motor entrance temperature $T_{M,E}$=873K, coating thickness s=0,8mm)

Male and female rotors laminated with a zirconiumoxide coating, as used in the motor, are shown in **Figure 6**.

The ceramic coating gives added safety against damage resulting from contact caused by thermal deformation of the parts. Because of the porosity of the zirconiumoxide coating, rotor-to-rotor and rotor-to-housing contact results in removal of some of the coating. Thus, the parts can "run-in" to an appropriate clearance state, avoiding rotor seizure and housing damage.

Also this abradable coating provides the ability for the rotors to run in the machine for a controlled reduction of the coating thickness. The resulting minimal clearance heights are consequently adjusted within limits automatically because of the thermal component displacements. In conjunction with the precalculated clearance heights, i.e. the calculated manufacuring dimensions, optimal efficiency can be achieved.

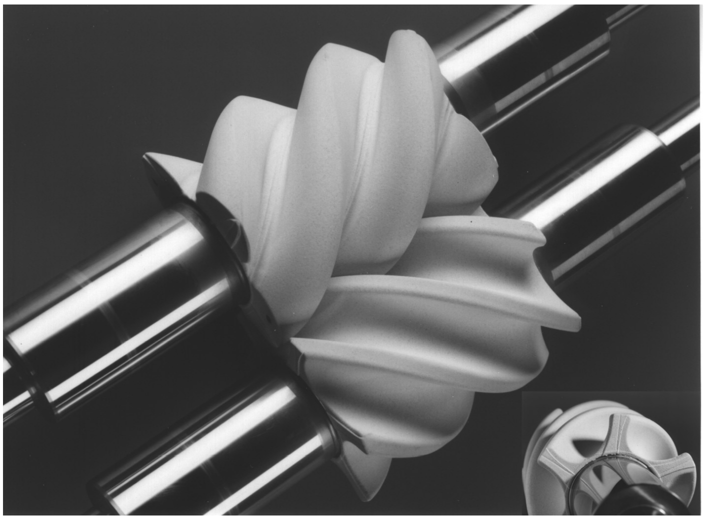

Figure 6: Rotors for the screw-motor coated with zirkoniumoxide

3.4 Calculation of the screw-rotor dimensions

For the reliable dimensioning of the screw motor, knowledge of the chamber's enclosing clearances during machine operation is essential. These are indicated for a given rotor profile by:

- the rotor intermesh clearance,
- the housing clearances (male and female rotor side) and
- the endface clearances (male and female rotor at both high and low pressure ends).

An optimal efficiency of energy conversion within a given machine-geometry will only be achievable if the clearance heights in the running machine, i.e. considering the thermally and mechanically related component deformations, remain as small as possible but as large as necessary for operating reliability.

To achieve this aim, the necessary undersizing of the rotors to obtain such clearances in the rotor intermesh were mathematically predicted. The following paragraph describes the influence of temperature on deformation. First, the temperature and deformation vector-fields of the rotors and the housing have to be quantified.

With the help of the program for calculating the rotor intermesh clearance in screw-machines (6) developed by the Fluid Energy Machinery department at the University of Dortmund, it is possible to specify the necessary undersizing for manufacturing the rotors. Through a mathematical, orthogonal decrease in the profile and the recalculation of the rotor intermesh clearance with the rotors modified this way, a rotor size reduction can be specified iteratively, so that the rotor intermesh clearance under thermal and mechanical loads always shows positive values.

In addition to the rotor deformations the bearing displacements in the housing must be known to be able to calculate the real rotor intermesh clearance at working temperature. These are obtained from the displacements of the housing through an averaging of the displacements at the Finite-Element nodes which lie in the area around the bearings. If we use these bearing displacements for computation of the rotor intermesh clearance, in the end we will get the actual theoretical size reduction for the rotors, (5).

3.5 Calculating the screw-motor housing

To evaluate the screw-motor's operating reliability after calculating the necessary rotor size, i.e. after assuring a positive clearance, we also need to know the working chamber geometries for manufacturing the housing. The housing clearance is the vital factor here, analogous to the rotor intermesh clearance for calculating the rotor dimensions. The rotor and housing displacements are interrelated. Thus, in addition to calculating rotor displacements, the displacements of the inner surfaces of the working chambers must be calculated and evaluated in connection with the results for the rotor displacements.

The rotor geometry and also the clearances in the screw-motor after reaching working temperature adjust themselves, as mentioned, automatically during machine operation due to the coating on the rotors made of zirconiumoxide. But the "preset" working chamber oversize is vital in order to achieve an appropriate minimized housing gap for a minimized rotor intermesh clearance in the warmed-up machine. Determining the axial working chamber dimensions to assure a sufficient face gap height implicates a necessity to calculate the rotor displacements as well as the displacements of the working chamber parallel to the axes. A final overview of the correlations between rotor and housing displacements is shown in **Figure 7.**

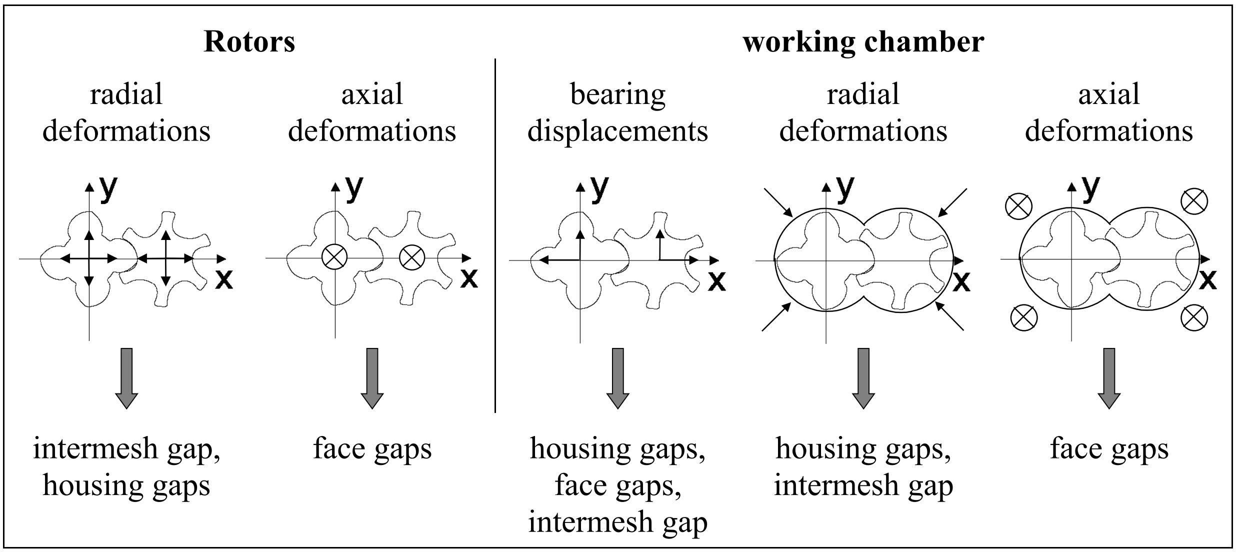

Figure 7: Correlation of gaps in the screw-motor and component displacements

4 VERIFICATION OF SIMULATION

The verification of simulation results always needs a large amount of selected, aquired measurement data. The following paragraph discusses the main measurement points on the test stand for the GASSCREW as well as the measuring techniques employed.

4.1 Verification parameters

4.1.1 Performance data and efficiencies

For a validation of the predicted advantages in performance and efficiency of the GASSCREW, the rotation speed and the screw-motor torque as well as the process variables like pressure, temperature and mass flow of the working gas are measured. A part of the measured characteristics diagram compared with the calculated data is shown in **Figure 8.**

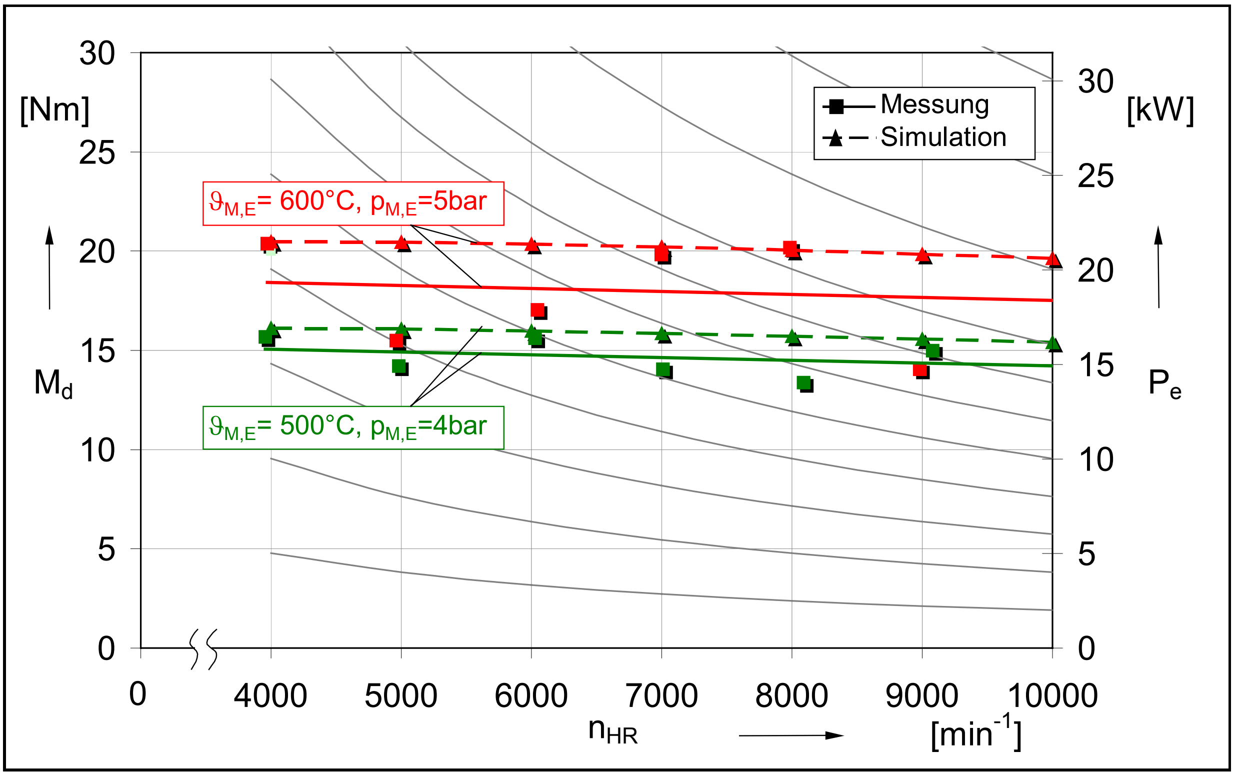

Figure 8: Part of characteristic diagram for the GASSCREW-motor

Additionally the motor is equipped with water-cooled pressure transducers that permit an indication, i.e. a measuring of the indicated work. An obtained indication diagram in comparison to a simulated one is shown in **Figure 9**.

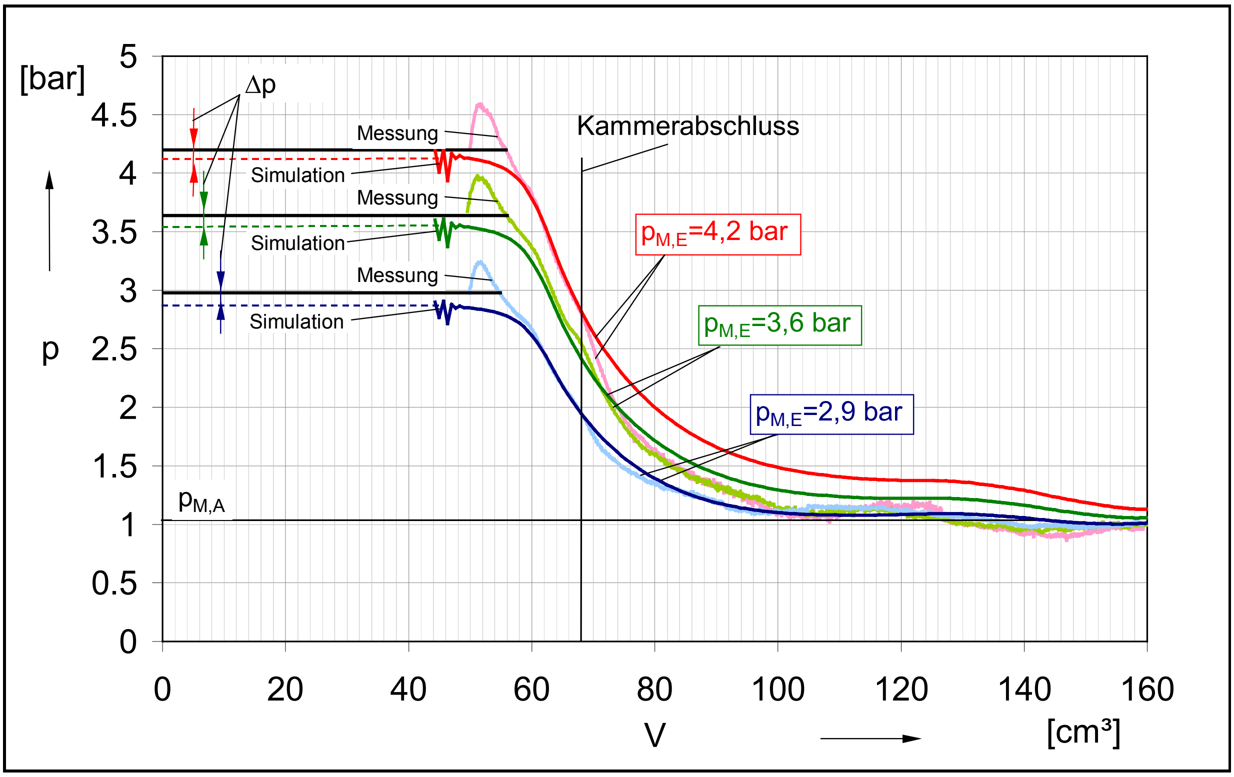

Figure 9: Measured and calculated indicator diagrams for the GASSCREW-motor

4.1.2 Balance of energy

For an energy balance around the system of the screw-motor, the mass flow as well as the temperatures of the entering and leaving fluids for cooling and lubrication are measured. The energy balance also offers, in conjunction with 4.1.3, some predictions about the heat transition models which have been indued. One energy balance for a typical operation point is presented in **Figure 10**.

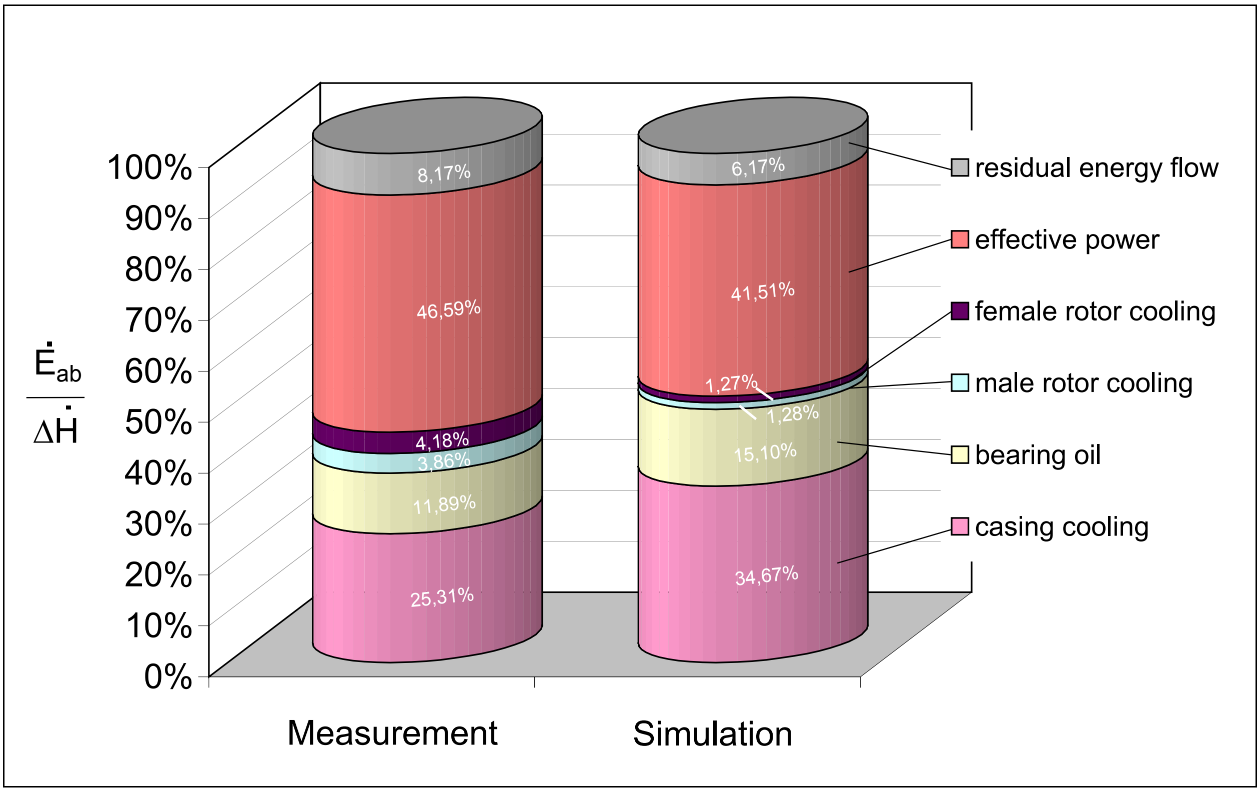

Figure 10: Measured energy balance of the GASSCREW-motor compared with the simulation; Constants: motor inlet temperature $\vartheta_{M,E}$=500°C, motor inlet pressure $p_{M,E}$=6bar, male rotor speed n_{HR}=7000min^{-1}

4.1.3 Thermography

The surface temperatures of the screw-motor housing are measured by a thermography system containing an infrared camera and an interpreter unit. The thermographic pictures obtained in this way are compared with the computed temperature fields and give an integral statement of the quality of the whole simulation system. A sample thermography picture is shown in **Figure 11**.

4.1.4 Rotor telemetry

Because the rotor's inner cooling in the screw-motor, particularly combined with the thermal sprayed coating, should theoretically lead to a dramatic reduction in the thermal load for the core material, thermocouples are placed adjacent to the coating in order to monitor the rotor temperatures. To transmit the data coming from the rotating system, we use telemetry. If then the measured rotor temperatures are compared with the relevant computed node temperatures of the Finite-Element mesh, we arrive at a standard for the quality of the heat transfer models of the rotor coating.

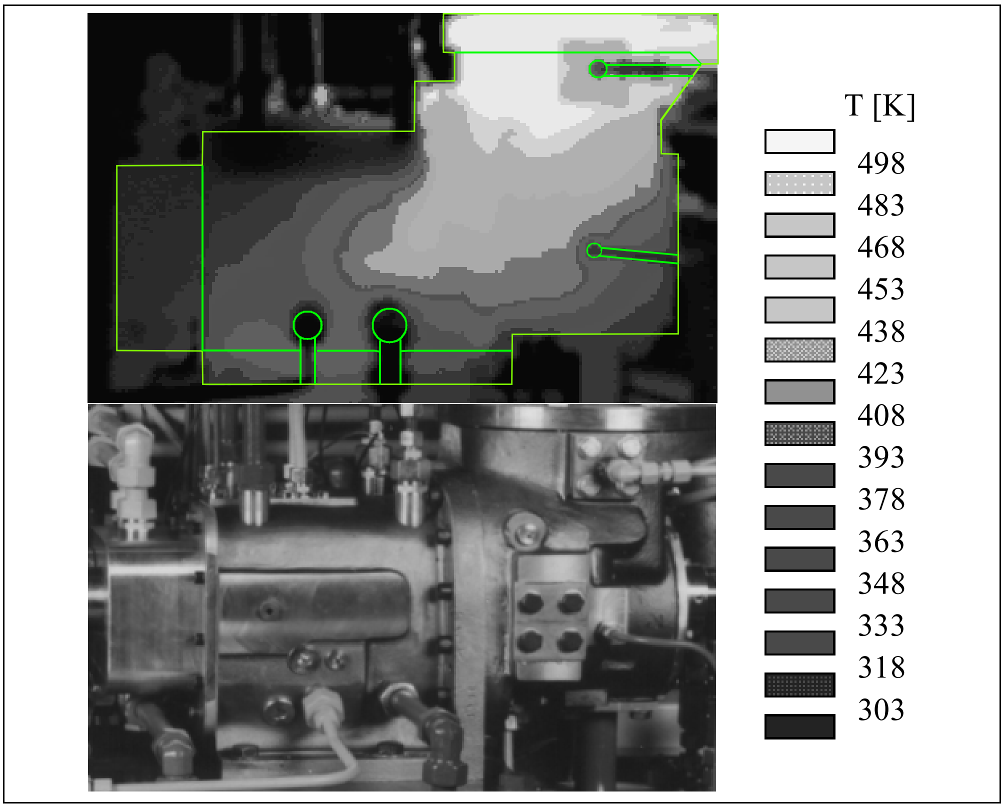

Figure 11: Sample thermography picture of a screw machine

5 OUTLOOK

The measurement results and their comparison with the simulation presented in this paper are only a small extract from the multi-dimensional measurement matrix for the GASSCREW. More results showing a good conformity, will be presented at the conference. They give us a basis for further development with higher motor inlet temperatures and improved cooling management.

With these premisses the GASSCREW will represent an innovative drive concept that can manage decentralised energy supply in many applications and can complement auxiliary-, emergency- and automotive drives or even replace them.

REFERENCES

(1) Kauder, K. Dosdall, H. — Stationäres und instationäres Betriebsverhalten der Heißgas-schraubenmaschine. In: Schraubenmaschinen, Heft 4, S. 10-30, Universitätsdruckerei Dortmund, 1996

(2) Dosdall, H. — Simulation und Untersuchung des stationären und instationären Betriebsverhaltens der Heißgasschraubenmaschine Dissertation, Universität Dortmund, VDI-Fortschrittberichte,

		Reihe 6, Nr. 365, VDI-Verlag, Düsseldorf,. 1997
(3)	Kauder, K. Keller, G.	Die Heißgasschraubenmaschine – Wärmeübergang und Kühlmechanismen im Motorteil. In: Schraubenmaschinen, Heft 5, S. 82-98, Universitätsdruckerei Dortmund, 1997
(4)	Keller, G.	Simulationsgestützte Entwicklung des Motors einer Heißgasschraubenmaschine. Dissertation, Universität Dortmund, VDI-Fortschrittberichte, Reihe 6, Nr. 387, VDI-Verlag, Düsseldorf, 1998
(5)	Kauder, K. v. Unwerth., T.	Die Heißgasschraubenmaschine – Konstruktion und Auslegung, Simulationsrechnungen als Konstruktionsgrundlage. In: VDI-Berichte, Nr. 1391, S. 315-332, VDI-Verlag, Düsseldorf, 1998
(6)	Janicki, M.	Ein Programm zur Profileingriffsspaltberechnung von verformten Schraubenmaschinen. In: Schraubenmaschinen, Heft 5, S. 108-112, Universitätsdruckerei Dortmund, 1996