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International Conference on
SCREW MACHINES 2018
18th - 19th September DORTMUND, GERMANY

Programme
Book of Abstracts

WWW.ICSM.TU-DORTMUND.DE



FOREWORD

Dear friends of the screw machines,

Welcome to the International Conference on Screw Machines 2018 (ICSM 2018). This worldwide unique conference with the exclusive focus on research and development of screw machines is now taking place for the 10th time at the TU Dortmund University. I am particularly pleased that this internationally orientated conference brings together authors and participants from 13 countries around the globe. This is a unique opportunity for the community to grow together, from young engineers to the "old hands".

My highly esteemed colleague Prof. Knut Kauder, who had been doing research in the field of screw machines since 1975, had the idea for the first conference ("Schraubenmaschinen '84"), which took place in 1984. I am particularly pleased that one of the speakers at the first conference and certainly a very well-known scientist in the field of screw machines, Prof. L. Rinder, is faithful to this conference and is present today. Another prominent representative of the developers of screw machines is Jack Sauls, who gave his first presentation at this conference in 1990 and is also present today.

Despite these years of research and development, many scientific questions regarding screw machines are still unanswered today. These include, for example, the modelling or simulation of the multiphase flow, the potentials offered by new manufacturing possibilities of the rotors or the special challenges of designing screw spindle vacuum pumps. The 33 presentations and papers of the 10th ICSM deal with these questions and many other topics. The contributions of all nine previous conferences and the contributions of the 2018 conference are freely available and can be downloaded on the conference website (www. icsm.tu-dortmund.de). Additionally, the papers of the ICSM 2018 are published in the open access IOP (Institute of Physics) conference series.

Finally, I would like to thank everyone involved for their pleasant and constructive cooperation. Firstly, the sponsors of the conference, PTG Holroyd and Kapp Niles, without whom the small conference fee would not have been possible. Furthermore I would like to thank the authors, who have put a lot of time and effort into preparing the papers. The program committee and the reviewers, who ensured the high scientific standard of the conference, are to be mentioned immediately afterwards. My very special thanks to the entire chair of fluidics team, who prepared and organized the conference with a lot of time and effort. From this group I would like to thank Mrs. I. Kokott and Mr. C. Huck personally for their above-average commitment and excellent organizational talent.

Prof. Andreas Brümmer

Conference Chair

technische universität dortmund

ICSM 2018

TUESDAY 18th September

09:00	CONFERENCE REGISTRATION	
10:00	OPENING SESSION Room H.001 p. 3	
12:00	LUNCH BREAK	
13:30	MULTIPHASE FLOW I Room 1.001 p. 4	DESIGN & MANUFACTURING I Room 2.008 p. 5
15:10	COFFEE BREAK	
15:45	MULTIPHASE FLOW II Room 1.001 p. 6	DESIGN & MANUFACTURING II Room 2.008 p. 7
18:15	CONFERENCE DINNER sponsored by PTG Holroyd Machine Tools & Components Storckshof, Ostenbergstr. 111, 44227 Dortmund	

WEDNESDAY 19th September

08:30	CONTACT & LOSS MECHANISMS Room 1.001 p. 8	SIMULATION & EXPERIMENT I Room 2.008 p. 9
09:45	COFFEE BREAK	
10:15	SYSTEM & MACHINE DESIGN Room 1.001 p. 10	SIMULATION & EXPERIMENT II Room 2.008 p. 11
11:30	LUNCH BREAK & LABORATORY TOURS	
14:00	VACUUM Room 1.001 p. 12	SIMULATION (EU MOTOR Project) Room 2.008 p. 13
15:45	CLOSING SESSION Room H.001	
16:00	END OF THE CONFERENCE	

TUESDAY 18th September

OPENING SESSION Room H.001	
10:00	**Welcome address** G. Sadowski, prorector research; M. Stommel, dean of the Faculty of Mechanical Engineering; A. Brümmer, general conference chair TU Dortmund University, DE
10:30	**Advances in modelling of screw machines** A. Kovacevic, Professor in Engineering Design and Compressor Technology City, University of London, GB
11:15	**Potential European ecodesign regulations for compressors – history, status and outlook** H.-U. Fleige, head of research & development Aerzener Maschinenfabrik GmbH, DE

TUESDAY 18th September

MULTIPHASE FLOW I
Room 1.001
Chaired by A. Kovacevic

13:30 **Numerical analysis of oil injection effects in a single screw expander**
S. Randi[1], A. Suman[1], N. Casari[1], M. Pinelli[1], D. Ziviani[2]
[1] University of Ferrara, IT
[2] Purdue University, US
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13:55 **Multiphase-flow simulation of a rotating rectangular profile within a cylinder in terms of hydraulic loss mechanisms**
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14:20 **Mathematical modeling of working processes of variable frequency screw compressor with differentiated oil supply into the working chamber**
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14:45 **Effects of surface condensation in an idealised steam-driven screw expander**
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DESIGN & MANUFACTURING I
Room 2.008
Chaired by C. Holmes

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Svenska Rotor Maskiner (SRM), SE
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13:55 **An analysis of manufacturing factors' influences on the actual screw compressor rotors' profile clearances**
T. Mustafin[1], R. Yakupov[1], M. Khamidullin[1], I. Khisameev[1], V. Alyayev[1], E. Ibragimov[2]
[1] Kazan National Reserch Technological University, RU
[2] V.B. Shneppe NIIturbokompressor, HMS GROUP, RU
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14:20 **An innovative rotor milling method for flexible multi-functional machines**
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Svenska Rotor Maskiner (SRM), SE
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TUESDAY 18th September

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Chaired by L. Rinder

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N. Basha, A. Kovacevic, N. Stosic, I. Smith
City, University of London, GB
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16:35 **Thermal expansion in liquid-injected screw compressors**
U. Dämgen[1], P. Hadamitzky[2], J. Dohmann[3]
[1] Boge Kompressoren, DE
[2] TU Braunschweig, DE
[3] Ostwestfalen-Lippe-University-of-Applied-Sciences, DE
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TUESDAY 18th September

DESIGN & MANUFACTURING II
Room 2.008
Chaired by H.-U. Fleige

15:45 **Novel approach to single-screw compressors and expanders design**
D. Ziviani[1], P. J. Goeghegan[2], E. A. Groll[1]
[1] Purdue University, US
[2] Oak Ridge National Laboratory, US
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A. A. Kotlov[1], I. A. Maksimenko[1], Y. L. Kuznetsov[2]
[1] Peter the Great St.Petersburg Polytechnic University, RU
[2] JSC Compressor, RU
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UTC CCS, Carrier Corporation, US
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[1] City, University of London, GB
[2] Kirloskar Pneumatic Company Ltd, IN
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N. Casari[1], M. Pinelli[1], A. Suman[1], A. Kovacevic[2], S. Rane[2], D. Ziviani[3]

[1] University of Ferrara, IT

[2] City, University of London, GB

[3] Purdue University, US

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R. Andres[1], J. Hesse[1], F. Hetze[1]; D. Low[2]

[1] CFX Berlin Software GmbH, DE

[2] Sullair, a Hitachi Group Company, US

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D. H. Rowinski[1], A. Nikolov[2], A. Brümmer[2]

[1] Convergent Science, Inc., US

[2] TU Dortmund University, DE

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L. de Buhr[1 2], H.-U. Fleige[1], J. Seume[2]
[1] Aerzener Maschinenfabrik GmbH, DE
[2] Leibniz Universität Hannover, DE
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11:05 **A model for the transient pulsation generation at the discharge of a screw compressor by a shock tube analogy**
P. X. Huang
Hi-Bar MC Tech LLC, US
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Y. Lu, A. Kovacevic, M. Read
City, University of London, GB
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10:40 **Numerical and experimental analysis of transient flow in Roots Blower**
S. Sun[1 2], A. Kovacevic[2], C. Bruecker[2], A. Leto[2 3], G. Singh[2], M. Ghavami[2]
[1] Xi'an University of Technology, CN
[2] City, University of London, GB
[3] Džemal Bijedić University of Mostar, BA
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11:05 **Comparison of thermodynamic efficiency between constant, dual and multiple lead rotors for an industrial air screw compressor**
M. Utri[1], A. Brümmer[1], J. Hauser[2]
[1] TU Dortmund University, DE
[2] Compression Technologies and Services, Ingersoll Rand, DE
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WEDNESDAY 19th September

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14:25	**Limits of one dimensional modeling of rarefied Couette Poiseuille clearance flow in vacuum pumps** C. Huck, A. Brümmer TU Dortmund University, DE	p. 53
14:50	**Optimisation of screw spindle vacuum pumps with variable rotor pitch regarding load-lock operation** T. Jünemann, A. Brümmer TU Dortmund University, DE	p. 54
15:15	**Study on the performance prediction of dry twin screw vacuum pump** J. Tuo, B. Guo, R. Wu, X. Chen Xi'an Jiaotong University, CN	p. 55

WEDNESDAY 19th September

SIMULATION (EU MOTOR Project)
Room 2.008
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Delft University of Technology, NL
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14:25 **Isogeometric simulation of thermal expansion for twin screw compressors**
A. Shamanskiy, B. Simeon
TU Kaiserslautern, DE
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14:50 **Isogeometric analysis framework for the numerical simulation of rotary screw machines. I. General concept and early applications**
M. Möller, J. Hinz
Delft University of Technology, NL
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15:15 **Fluid flow through housing clearances of dry running screw machines using dimensionless numbers**
M. Utri, S. Höckenkamp, A. Brümmer
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Multiphase flow I

Numerical analysis of oil injection effects in a single screw expander

S Randi[1], A Suman[1], N Casari[1], M Pinelli[1] and D Ziviani[2]

[1]Dipartimento di Ingegneria, Università degli Studi di Ferrara, ITALY

[2]Ray W. Herrick Laboratories, Purdue University, West Lafayette, IN, USA

E-mail: saverio.randi@unife.it

Abstract. The pursuit of higher efficiency for compression and micro-power generation systems has pushed the researchers to an in-depth analysis of positive displacement machines. Single-screw machines, among the others, are gaining attention in the Organic Rankine Cycle (ORC) systems as expanders, thanks to their extended maintenance intervals and compactness. The performances of such devices are strongly affected by the working conditions, and especially the presence of oil has major effects on the operability. The main advantage of adopting an oil-injected device consists in the lube sealing effect, which permits better performance (greater shaft power for assigned boundary conditions) as well as higher reliability. The choice of whether using an oil-free configuration or not is related to the working fluid cleanness, system complexity (oil separator, filters, recovery pump), flow rate and pressure ratio. In this paper, the full 3D numerical simulation of an oil-injected single-screw expander operating with R245fa refrigerant is presented. Oil is injected together with the working fluid at the inlet of the machine. Oily droplets are tracked over the admission duct to show how the oil droplets reach the inlet ports of the screw machine. Different behaviors related to different oil droplet diameters in the range of (0.5 – 50) μm are studied, for the same operating point. The proper distribution of the oil droplets on the screw inlet ports are directly related to the single screw expander performance. In addition, a particular screw position is analyzed for studying the effects of leakages on the oil injection and oil film evolution over the time.

Multiphase-flow simulation of a rotating rectangular profile within a cylinder in terms of hydraulic loss mechanisms

H Vasuthevan and A Brümmer

TU Dortmund University, Chair of Fluidics Leonhard-Euler-Str. 5, 44227 Dortmund, Germany

E-mail: hanushan.vasuthevan@tu-dortmund.de, andreas.bruemmer@tu-dortmund.de

Abstract. In wet running screw compressors, liquid (oil or water) is injected into the machine. The advantage of liquid injection is cooling of the compressed fluid, sealing of clearances, lubrication of rotors and bearings, and reduced noise and vibration. The disadvantage of wet running machines is the loss in internal mechanical efficiency from the hydraulic loss caused by the liquid. In this paper, multiphase flow simulations are performed using the Volume of Fluid method to investigate hydraulic loss mechanisms. The 2D geometric model consists of a rectangular profile rotating in a cylinder with a clearance height that represents the screw machine housing clearance. In this investigation, the distribution and flow pattern of the liquid are examined with regard to hydraulic losses. Furthermore, the influence of the amount of liquid and the circumferential tip speed is determined through calculation of the torque on the rectangular contour. The hydraulic losses increase with increasing liquid mass in a working chamber and with increasing circumferential tip speed. For the simulations points examined, the tip speed has a greater impact on the hydraulic loss than does the amount of liquid.

Mathematical modeling of working processes of variable frequency screw compressor with differentiated oil supply into the working chamber

V L Yusha, G I Chernov and M A Fedorova

Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia

E-mail: yusha@omgtu.ru

Abstract. Currently, a method of screw compressors regulation by smooth change of rotors spinning frequency, or so-called frequency regulation, is widely used. The operation process of oil-injected screw compressors at frequency regulation modes were examined in this paper in terms of the relationship of a compressor operation modes and its oil system. The calculations based on the operation process mathematical model of oil-injected screw compressor were aimed at defining its integral characteristics when changing the rotor spinning frequency, the quantity of the oil supplied and the discharge pressure.

Effects of surface condensation in an idealised steam-driven screw expander

M Grieb and A Brümmer

TU Dortmund University, Chair of Fluidics Leonhard-Euler-Str. 5, 44227 Dortmund, Germany

E-mail: manuel.grieb@tu-dortmund.de, andreas.bruemmer@tu-dortmund.de

Abstract. Condensation and its effects on turbo machinery operation are well understood and have been widely investigated. However, little scientific work on condensation in rotary positive displacement machines has been published. Since the robustness of screw expanders allows for expansion of slightly superheated vapours or even two-phase fluids, condensation on machine parts needs to be considered during design and simulation of these machines. In this paper the general effects of surface condensation of water on the machine parts of an idealised screw expander are discussed. Diabatic chamber model simulation is used for the thermodynamic simulation of operational behaviour. The effect of surface condensation on energy conversion and the delivered mass flow rate is analysed. Furthermore, a comparison of adiabatic and diabatic simulation of steam expansion in screw expanders is given in order to quantify condensation losses. Typical operating parameters are widely varied in simulation so as to identify influential factors on the condensation process. It is found that surface condensation, which is driven by heat exchange from the working fluid to adjacent machine parts, slightly raises the mass flow rate of the machine. For low expander speeds a reduction in isentropic efficiency can be expected due to a condensation induced pressure drop during the expansion phase.

Design & Manufacturing I

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

H Österman, A Edrisi and I Lashgari

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

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.

An analysis of manufacturing factors' influences on the actual screw compressor rotors' profile clearances

T N Mustafin[1], R R Yakupov[1], M S Khamidullin[1], I G Khisameev[1], V A Alyaev[1] and E R Ibragimov[2]

[1]Kazan National Research Tehnological University, Russian Federation;

[2]HMS Group NIIturbokompressor, Russian Federation

Email: mustimur@rambler.ru

Abstract. One of the most important parameters, which have high influence on screw compressor characteristics, are rotors' profile clearances. They determine in general the smooth of the rotors' gearing and influence on the screw compressor vibration level. Analyse of actual rotor profile clearances depending on the actual rotor temperature fields and on the manufacturing imperfection was done. Specially profiled milling tools were chosen as rotor profile manufacturing tools. Following four types of the manufacturing error, which have the highest influence on the accuracy and quality of rotors' profile surface, were chosen to analyses: the centre distance deviation between the rotor and the milling tool axises (dAi), the departure of the milling tool position from their basic plate (dZf), the milling tool mounting position angle departure (dβ) and the milling tool radii departure (dRf).The actual screw compressor profile coordinates can be obtained by taken into account all factors presented above. They determine the actual rotor profile clearances on "cold" state when screw compressor is on shutdown conditions and can be measured during a compressor assembling or a compressor stripping. However, it should be noted that they are changed depending on the screw compressor working conditions. To correctly determining actual profile clearances depending on working condition also needs to take into account rotors' thermal deformation. The presented multifaceted approach of the screw compressor actual rotor profile clearances calculation improves an accuracy compressor characteristic obtained by their mathematical model. A deep analysis of the obtained results can pointed to the rotors' manufacturing factors, which should be improved firstly during the compressors' mass production.

An innovative rotor milling method for flexible multi-functional machines

A Bergström

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

Email: andre.bergstrom@rotor.se

Abstract. In this work we present an innovative method of rotor milling for flexible multi-functional machines. As an alternative to the disc cutters which are often employed in traditional milling machines, we propose a new tool, a finger cutter, which integrates easily with flexible multi-functional machines. This allows much smoother operation with lower required torque which is in line with the characteristics of flexible machines. This paper describes basic geometrical condition to generate the finger cutter profile from the rotor profile, the mathematical formulation, the basic tool design and grinding procedure of the cutter blades. It also discusses the machining process, productivity and accuracy of the proposed method. We believe that this method opens a new way of manufacturing large rotors with fewer production steps while maintaining required tolerances.

Multiphase flow II

Impact of different clearance heights on the operation of a water-flooded twin-screw expander—experimental investigations based on indicator diagrams

A Nikolov and A Brümmer

TU Dortmund University, Chair of Fluidics Leonhard-Euler-Str. 5, 44227 Dortmund, Germany

E-mail: alexander.nikolov@tu-dortmund.de

Abstract. Twin-screw expanders offer a high potential for energy conversion in the lower and medium power range, for instance in Rankine cycle systems for exhaust heat recovery. With the aim of minimising internal leakages within the expander and lubricating moving machine parts, an auxiliary liquid can be carried with the main flow or liquid working fluid can be fed to the twin-screw expander. Moreover, the operation of twin-screw expanders in Rankine cycle systems at high liquid mass fractions and in trilateral flash cycles is predicted to be a very promising application for expanders in lower power ranges. Thus, a fundamental understanding of the operation of liquid-flooded twin-screw expanders is mandatory. This paper presents results of an experimental investigation into a water-flooded twin-screw expander prototype SE 51.2 designed at the Chair of Fluidics at TU Dortmund University. On the one hand, the aspect of a two-phase working fluid is discussed considering integral characteristic numbers such as mass flow, delivery rate, and effective isentropic efficiency. On the other hand, in order to explain the influence mechanisms of a two-phase working fluid on the operating behaviour of the twin-screw expander, indicator diagrams are recorded by means of high-resolution pressure transmitters to determine indicated power. Hence, mechanical and hydraulic losses, indicated isentropic efficiency, and mechanical efficiency of the twin-screw expander can be calculated. In order to determine the influence of the narrow clearance on the hydraulic losses and the clearance sealing effect in terms of a two-phase working fluid, a systematic variation of the rotor-tip clearance height is carried out. As a result of the investigations, a water surge at the rotor tip is proved to be a significant mechanism affecting hydraulic losses in a water-flooded twin-screw expander.

Effect of oil-injection on twin screw compressor performance

N Basha, A Kovacevic, N Stosic and I Smith

Centre for Compressor Technology, City, University of London, London, UK

E-mail: nausheen.basha@city.ac.uk

Abstract. Oil-injection improves twin-screw compressor performance significantly and its overall effect depends on the working fluid mass flow rate, the shaft speed, the injection position and the injected oil temperature. However, the individual contribution of each of these variables to the machine performance is yet not fully researched. Therefore, tests have been carried out on an air compressor with a male rotor diameter of 98mm, with injection nozzle sizes of 2, 3 and 4mm and with a nozzle of multiple holes. Tests were carried out with discharge pressures of 6.5, 8.5, 10.5 and 12.5 bar and rotor shaft speeds of 3000, 4000 and 5000 RPM. The results from the tests were compared with performance estimates at the same operating conditions as measurements against the standard injection nozzle of 5mm diameter. It was found that there is an optimum quantity of oil injected to obtain the best performance.

Thermal expansion in liquid-injected screw compressors

U Daemgen[1], P Hadamitzky[2] and J Dohmann[3]

[1] Boge Kompressoren, Germany;
[2] Technische Universität Braunschweig, Germany;
[3] Ostwestfalen-Lippe-University-of-Applied-Sciences, Germany

E-mail: u.daemgen@boge.de

Abstract. In screw compressors gaps between rotors and casing have to be small, in the range of 30 to 300 μm. These gaps are influenced by thermal expansion when the screw compressor is in operation. The amount of thermal expansion is about the same size as the gaps, even in oil-injected screw compressors. Especially when starting a cold compressor, there are temperature differences. These temperature differences were measured in a 22 kW oil-injected screw compressor for industrial compressed air as an easily manageable example. Measuring the temperatures in the rotor teeth was done with Pt1000-sensors and transmission with Wireless-LAN. The results showed lower temperature differences than expected. The influence of the oil-injection-temperature is dominant. In bigger screw compressors the temperature differences tend to be larger because of dimensional reasons: A simple numerical model for the temperature differences in a screw compressor with fluid injection allows an extrapolation for larger rotors.

Design & Manufactoring II

Novel approach to single-screw compressors and expanders design

D Ziviani[1], P J Goeghegan[2] and E A. Groll[1]

[1]Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, West Lafayette, 47907-2099, USA
[2]Oak Ridge National Laboratory (ORNL),Oak Ridge, TN, USA

E-mail: dziviani@purdue.edu, geogheganpj@ornl.gov, groll@purdue.edu

Abstract. Single-screw machines are currently employed as both compressors and expanders in vapor compression systems and organic Rankine cycles (ORCs), respectively. The working principle of single-screw machines is based on the simultaneous meshing of two starwheels with one central grooved rotor. The performance of the machine is heavily affected by the wear of the tooth meshing profile after several hours of running. In order to improve the wear resistance of the conventional straight-line profile, multi-column tooth flank designs have been introduced and investigated by several researchers. Cylindrical multi-column envelope profiles are able to distribute the local contact over a larger surface area reducing the wear of the tooth flank profile. Nevertheless, the manufacturability of such profiles is directly linked to the accuracy and limitations of CNC machines. In this work, an attempt is made to overcome the aforementioned limitations. To push the boundaries of possible tooth and rotor profile designs, 3D printing is utilized as manufacturing technique. Such approach allows the investigation of more complex designs that improves the sealing lines during the meshing process. A detailed geometry model based on polygon intersections is utilized to calculate the sealing lines, groove volume curves, and surface areas of the different designs. As a result of this study, a novel rotor design has been manufactured.

The influence of profile geometric parameters on characteristics of rotor-gearing compressor

A A Kotlov[1], I A Maksimenko[1] and Y L Kuznetsov[2]

[1] R&D Laboratory “Gas dynamics of turbo machines” Peter the Great St. Petersburg Polytechnic University, Polytechnical st. 29, St. Petersburg, Russia
[2] JSC «Compressor», Bolshoy Sampsonievskiy prospect, 64, St. Petersburg, Russia.

Email: kotlov_andrej@mail.ru, office@compressor-gaz.ru.

Abstract. Dry (without lubrication) claw compressors have a promising future because they feature both advantages of piston and rotary compressors. The rotor profiles have sophisticated form including several curves of similar type, combined so, that the line of contact is always parallel to the rotor axis. The effect of the main geometric parameters of the profile ($\bar{R}$, α_R and r) on the rotor-swept area value is considered. The research was carried out by the developed computer program intended for selection of the optimum variant of a ratio of profile geometrical parameters. In this paper the results of theoretical studies of influence of profile geometric parameters on integrated characteristics of rotor-geared compressor are given. Optimal relations between parameters are given, defining geometry of gas distribution elements.

Mini Screw: the development of a high-CFM compact compressor for LGWP A1 low pressure refrigerant

M Akei, V Sishtla and S MacBain

UTC Climate Controls & Security (Carrier), Syracuse, New York, USA

E-mail: Masao.Akei@carrier.utc.com

Abstract. Addressing global warming concerns is one of the largest challenges facing the HVAC industry currently. Although A2L refrigerants are important options to consider for certain sizes of HVAC units, there remain many systems that require A1 category refrigerants. Among the several available refrigerants, we looked at DR-12 as one of the attractive refrigerants. Along with it being in the A1 category, its very low GWP value (32) and high cycle performance make it an excellent long-term solution if successfully applied. A significant challenge to overcome with this refrigerant is its low density. DR-12 will require almost 7 times the volumetric flow for the same cooling capacity compared to R410A. The current scroll or rotary technologies are not realistic to be applied in such a low density refrigerant system. The development of a new compact large CFM compressor is key to realize the scope of the project successfully. The authors have explored various types of compression mechanisms and identified screw as one of the most suited technologies for this refrigerant. In order to obtain such large volume flow (19.8L/s, 42CFM), a unique screw rotor design and a high speed PM motor were employed. Innovative bearing design and new compressor layout also enabled the compressor to be compact (□145mm) and cost effective. A prototype compressor was built and tested. This concept delivered 17.6kW (5 ton) capacity at 11,000rpm and 4.4kW (1.25 ton) at 2,500rpm, meeting its target requirements. This paper will introduce details of the compressor concept, along with the test results from a physical prototype.

Contact & Loss mechanisms

Influence of suction port parameters on integral characteristics of screw-type compressor

A A Kotlov

R&D Laboratory “Gas dynamics of turbo machines” Peter the Great St. Petersburg Polytechnic University, Polytechnical st. 29, St. Petersburg, Russia.

Email: kotlov_andrej@mail.ru.

Abstract. At engineering screw-type machines different tasks on search for more effective and reliable design solutions arise connected with: organization of work process; selection of design shapes of the flow channel; strength calculation of machine components and selection of material. Considered in the work is enhancement of suction process efficiency by the use of dynamic head of the suction gas flow. Influence of rotor length to diameter ratio and suction port opening angle on integral characteristics of the compressor is considered. Calculation of work process in the compressor is performed by means of mathematical simulation. According to the work results it was determined that change in performance coefficient may reach 5%. At increase in suction port opening angle the leakage from compression cavities to a suction chamber increases and may reach 20%.

Identification and analysis of screw compressor mechanical losses

S Abdan[1,2], N Stosic[1], A Kovacevic[1], I Smith[1] and P Deore[2]

[1] Centre for Compressor Technology, City, University of London, London, U.K.
[2] Kirloskar Pneumatic Company Limited, Pune, India.

E-mail: suraj.abdan@city.ac.uk

Abstract. Screw compressors are compact machines, used for a wide range of applications where gases or vapours are required to be delivered at moderate pressures with high efficiency and reliability. They are most effective when the compressed medium requires power inputs, approximately in the 10 kW - 1-2 MW range. At lower inputs alternatives such as reciprocating and scroll compressors are preferable and at higher inputs turbo-compressors are more suitable. In industrialised countries, compressors absorb 15-20% of the total electrical power generated. Hence there is a continuing demand to improve their efficiency. This is normally expressed as the specific power consumption, which is the power required to compress unit mass of gas delivered. There already exist mathematical models to assist in the design of such machines and to estimate their performance, which include the estimation of the dynamic loads acting on the rotors and bearings and these loads determine their mechanical efficiency. However, these models do not estimate the magnitude of the mechanical losses, which are only guesstimated as an additional increment to the power required to compress the gas. Such an approximation does not enable the optimum selection of bearings and lubricating oil to minimise the frictional power losses. The aim of the study, described in this paper, was to estimate the effect of the individual parameters responsible for mechanical power loss in oil injected screw compressors and is focussed on the losses incurred in the gear box, bearings and shaft seals. It was found that in the gearbox, meshing, bearing and seal losses all increase both with speed and gear ratio. In the main rotors, it was found that sliding friction losses in the bearings are not significantly affected by the radial load, nor are rolling friction losses significantly dependent on the axial load. However, both axial and radial loads have a significant effect on the total frictional power loss. Lubricant viscosity affects the frictional power losses but the oil level does not.

Raman scattering study of micrometer-sized spots of magnetite and hematite formed at 18CrNiMo7-6 screw rotor surfaces due to liquid-free, unsynchronized operation

H Moldenhauer[1], M Bayer[1], J Debus[1], A Nikolov[2] and A Brümmer[2]

[1]Experimental Physics 2, TU Dortmund University, 44227 Dortmund, Germany
[2] TU Dortmund University, Chair of Fluidics Leonhard-Euler-Str. 5, 44227 Dortmund, Germany

E-mail: joerg.debus@tu-dortmund.de

Abstract. We analyze differently worn surface positions of a screw rotor's contact zone using confocal Raman spectroscopy with 2 μm spatial resolution. The Raman scattering spectra demonstrate signals from magnetite Fe_3O_4 and hematite α-Fe_2O_3 whose intensities and energy shifts are associated with the degree of wear of the surface locations. While magnetite is identified at the worn surface areas studied, excluding a possible white etching domain, scattered light signatures from hematite are only detected at surface positions, at which high temperatures and/or high pressure inputs were proposed to be present during the liquid-free wear process of the screw rotors. The findings may be used to gain a more general understanding of tribological layers and to develop microscopic indicators of wear.

Simulation & Experiment I

Full 3D numerical analysis of a twin screw compressor by employing open-source software

N Casari[1], M Pinelli[1], A Suman[1], A Kovacevic[2], S Rane[2] and D Ziviani[3]

[1]University of Ferrara, via Saragat 1, 44122 Ferrara, ITALY
[2]City, University of London, Northampton Square, EC1V 0HB, London
[3]Ray W. Herrick Laboratories, Purdue University, 177 S Russell Street, West Lafayette, IN, 47907-2099, USA

E-mail: nicola.casari@unife.it

Abstract. The push for having more reliable and efficient positive displacement machines (both compressors and expanders) for vapor compression and power generation (e.g., ORCs) applications has moved researchers to an always more spread employment of computational fluid dynamics (CFD). In particular, twin screw compressors, because of their high efficiency compared to other compressor types, have received interest over the last years. The numerical analysis of such machines is challenging: the deforming working chambers are very difficult to be correctly replicated. The relative motion of the rotors and the variation of the gaps during machine operation are few of the major difficulties in implementing reliable CFD models. A custom mesh generation algorithm is therefore often required for simulating the machine operation. In this work, SCORG-V5.2.2 was used to generate the meshes of the deforming domain around rotating parts of the machines. The open-source software OpenFOAM-v1606+ is then employed to compute the flow field associated with the operation of the twin screw. The coupling of the two tools has been carried out in this work, applying the methodology to a twin screw machine.

CFD simulation of a two stage twin screw compressor including leakage flows and comparison with experimental data

R Andres[1], J Hesse[1], F Hetze[1] and D Low[2]

[1]CFX Berlin Software GmbH, Berlin, Germany
[2]Sullair, A Hitachi Group Company, Michigan City, United States

E-mail: rainer.andres@cfx-berlin.de

Abstract. Computational Fluid Dynamics (CFD) is a common and validated simulation method in research and industry for the analysis of fluid systems. In the past years, it has proven to become more and more applicable for modeling the flow physics inside positive displacement (PD) machines. The working chamber and thus the discretized flow domain of PD machines are changing in time, characterized by complex thermodynamics. Compressible fluids, real-gas properties and leakage flows with trans- or supersonic characteristics are phenomena which have to be accounted for in order to properly model the behavior of the machine. As CFD methods evolve in general, but also for the application of PD machines in particular, the numerical model can replace a prototype during early stages of the product development. The desired simulation approach should be able to deliver sufficient accuracy at a feasible effort in terms of computational time and manpower to create the numerical model. This paper presents the methodology of creating the numerical model for a sample screw compressor provided by Sullair for research purposes. It is a dry running two stage twin screw compressor running with air at a rated power range between 160 and 250 kW. The two stages are gear driven by the main shaft at rotational speeds between 1180 and 2100 rev/min. Each stage features different rotor profiles, where the first stage has a 4-6, the second stage a 5-7 lobe combination. The total pressure ratio of the two stages combined is up to 10:1. To enhance the performance of the compressor, discharged air from the first stage is cooled down before entering the second stage. A specific meshing method is used to model the size-changing working chambers between rotors and casing, where only hexahedral cells are used and mesh topology is constant. The model accounts for radial and axial clearances between rotors and stator, where rotors and stator are connected with interfaces. The transient simulation results are compared to experimental measurements for torque, and flow rate. Also discharge pressure and temperature after first and second stage are compared to the experimental results. In addition, the possibilities of the simulation are exemplified by the gathering of time- and space-resolved monitor points like temperature or pressure at distinct points within the compressor. Apart from direct comparison to the experiment, also a sensitivity study regarding the change of housing clearances is

presented, as leakage flow has severe impact on the compressor performance. These clearances and the resulting leakages are often not exactly known whereas they also vary because of manufacturing tolerances or deformations due to the load on rotors and stator. Here, the numerical simulation can serve as a helpful tool to estimate the sensitivity and change of machine characteristics, which is hard to determine in the scope of experiments.

Modeling a dry running twin-screw expander using a coupled thermal-fluid solver with automatic mesh generation

D Rowinski[1], A Nikolov[2] and A Brümmer[2]

[1] Convergent Science, Inc., Madison, WI, USA
[2] TU Dortmund University, Chair of Fluidics Leonhard-Euler-Str. 5, 44227 Dortmund, Germany

E-mail: david.rowinski@convergecfd.com

Abstract. Understanding the details of the internal flow processes in screw compressors and expanders is very important for their efficient and robust design. Computational fluid dynamics (CFD) provides full access to a modeled three dimensional flow field and its variation in time. However, the application of CFD to screw compressors and expanders can be difficult because of the complicated geometries involved and the need to supply the computational grid on which the modeled equations are solved over a large number of time steps. While the majority of previous research on CFD applications to screw machines features inventive techniques for generating meshes that adequately resolve the flows in the small clearances, an alternate approach is demonstrated in this work. The screw expander SE 51.2 from TU Dortmund University is analyzed here through a CFD model which generates the grid automatically based on a modified Cartesian cut-cell approach. The grid is then adaptively refined based on local gradients of velocity and temperature. At each time step, the grid is regenerated based on the geometry motion. As opposed to resolving the flow in the clearances, a model is applied so that the cells in the clearance can remain relatively large. The detailed measurements of the screw expander are used to validate the model. The operating conditions investigated include the expansion of dry air at a four-to-one pressure ratio for four different rotational speeds. The measured internal chamber pressures are compared to the results from the model, as are the average mass flow rate, indicated power, and outlet temperature. A coupled thermal-fluid approach is used to model the rotor temperatures and corresponding thermal deformation of the rotors and housing. In this approach, the fluid and solid temperatures are solved together; to deal with the problem of the disparate time scales between the fluid and solid heat transfer, the solids are periodically solved to steady state using heat transfer coefficients and near-wall temperatures computed from an energy conserving averaging over several cycles. The effects of the various leakage flow paths in the model, including the rotor-to-rotor, rotor-tip-to-housing, and bearing leakage are demonstrated and quantified. Finally, simulation and experimental results are compared in terms of different rotor-tip-to-housing clearance heights. The model

considering the appropriate thermal deformation of the rotors is shown to yield the best agreement with the measurements, however there is work remaining to reduce the model calculation time, especially at low rotational speeds.

System & Machine design

A Similarity based Efficiency Model of Spindle Screw Pumps

C Schänzle, T Corneli and P F Pelz

Technische Universität Darmstadt, Department of Mechanical Engineering, Chair of Fluid Systems, Otto-Berndt-Str. 2, 64287, Darmstadt, Germany

E-mail: peter.pelz@fst.tu-darmstadt.de

Abstract. Spindle screw pumps are used in numerous different applications and industrial sectors. When selecting a suitable spindle screw pump for a specified application, manufacturers are often confronted with a lack of comparable measurement data for the desired combination of operating conditions and pumping fluid. Consequently, the volumetric and mechanical-hydraulic efficiency of a pump under the operating conditions of the application need to be estimated. In this context, this paper discusses the application of similarity for three-spindle screw pumps and introduces a similarity based efficiency model. The model is validated by means of a measured pump characteristic at different operating conditions varying pressure, rotational speed and the viscosity of the pumping fluid. The validation results prove that a pump characteristic can be represented over a wide operating range based on similarity. An estimation of the volumetric and the mechanical-hydraulic efficiency at a changed viscosity is achieved with high accuracy. Furthermore, a new approach to monitor and to evaluate manufacturing uncertainty based on the model parameter relative gap is presented. Finally, the paper gives an outlook on future experimental investigations at TU Darmstadt on model series of three-spindle screw pumps containing pumps of different displacement volume.

Model tests on the control behaviour of a test air supply system in open or closed-loop operation

L de Buhr[1, 2], H Fleige[2] and J Seume[1]

[1] Institute of Turbomachinery and Fluid Dynamics, Leibniz Universität Hannover
[2] Aerzener Maschinenfabrik GmbH

E-mail: hans.fleige@aerzener.de

Abstract. The Leibniz Universität Hannover is currently establishing a new mechanical engineering campus which includes a new research building "Dynamics of Energy Conversion" (DEW). This building provides a large compressor station for either steady or dynamic (transient) operation of turbomachinery and power plant test rigs (e.g. air turbine, axial compressor, combustion chamber, planar cascade, acoustic wind tunnel). The test air supply system is designed to enable investigations under high load gradients over wide operating ranges with Reynolds and Mach numbers controlled independently in order to fulfil aerodynamic similarity conditions between reality and model experiments. This is achieved by closed loop operation of the test air supply system which allows independent adjustment of pressure, temperature and volume flow rate as well as independence from environmental influences such as temperature or humidity. The compressor station utilizes as first stage two parallel Roots-type PD compressors and as second stage two parallel screw compressors. The test rigs operate at expansion ratios between 1 and 6. Test rig inlet pressures range from 1 bar(abs) to 8 bar(abs) with a maximum mass flow rate of 25 kg/s. At all conditions temperatures can be regulated between 60°C and 200°C. The test air supply system has a maximum electric power input of approximately 6 MW. As stringent demands on stability and reproducibility have to be met and automatic operation was requested, a scaled and simplified but fully functional model of the test air supply system was built, mainly to enable testing of control methods and devices prior to their final implementation on site. The functional model uses DN150 piping and consists of one Roots-type PD compressor as first stage and one screw compressors as second stage. Both compressors are driven by electric motors regulated by frequency converters. A turbine test rig is represented in the model by an adjustable throttle valve. Precise control of the mass flow rate is provided by a cascaded adjustable bypass around the test rig. The paper describes the test air supply system and the scaled model and presents experimental results on the achievable stability of pressure, temperature and mass flow rate at the test rig inlet in steady operation at several operating conditions of the model.

A model for the transient pulsation generation at the discharge of a screw compressor by a shock tube analogy

P X Huang

Hi-Bar MC Technologies, LLC., Fayetteville, GA, USA

E-mail: paulxbh@yahoo.com

Abstract. Although screw compressors (dry and wet) have been widely used in many applications (such as HVAC&R, petrochemical and gas transmission, plant air, etc..) for more than half a century, limited information is available regarding the genesis and mechanism of gas pulsations at pocket passing frequency (PPF) dominating at discharge side of these compressors [1]. The understanding of its physical nature, magnitude and affecting parameters, the location and moment of generation, and the velocity it propagates are all of fundamental, and will help to determine how it will interact with downstream components such as silencers and piping system, especially for accurately predicting downstream pulsation levels and excited vibration and noise at the higher multiples of the PPF. The primary goal of this paper is to apply the shock tube theory [2] to screw compressors during the transient generation phase of gas pulsations at discharge. It will reveal that the nature of gas pulsation is a combination of large amplitude compression waves (CW) and expansion waves (EW) accompanied with an induced fluid flow (IFF). The most dominant gas pulsation at discharge is directly caused by either an over compression (OC) or a under compression (UC) suddenly discharging to compressor outlet. Therefore its exact location and moment of generation, magnitude, travelling directions and velocity can all be predicted based on design parameters and operating conditions of those machines. With this knowledge, its interactions with the compressor cavity and downstream piping and silencer are conducted for a typical UC and case, and results are in good agreement with the test data of previous researchers. The analysis suggests that the shock tube model can provide a pedagogic tool in understanding the physics of the transient phase of pulsation generation and subsequent formation. As such it can provide valuable insight to developers of more precise CFD calculations and a comprehensive algorithm of gas pulsations in the future.

Simulation & Experiment II

Numerical study on screw machines with large helix angles

Y Lu, A Kovacevic and M Read

City, University of London, Centre for Compressor Technology, London, UK

E-mail: yang.lu.4@city.ac.uk

Abstract. Modelling and performance calculation of screw machines with large helix angles such as a single and multiphase screw pumps by use of Computational Fluid Dynamics is challenging. The numerical procedures explained in literature are based on the 3D numerical meshes generated by series of 2D transverse cross sections which allows mesh to either follow the helix or be perpendicular to the rotor axis. This allows generating a conformal mesh. However, if the rotor helix angle is large, the cell skewness becomes prohibitively large which introduces errors in numerical simulation. The paper firstly attempts to generalize the generation method of rotor profiles with emphasis on producing a normal rack and rotors profiles. Then it introduces the method which uses series of 2D numerical meshes in the planes normal to each of the rotors and rack in order to decompose the working domain in two sub-domains. By this means it is possible to achieve 3D numerical mesh with extended capability of mesh refinement in clearances and alignment of the mesh to the main and leakage flows. However, special treatment is required to provide conformal interface between two moving meshes and with the casing. It is expected that it will greatly benefit accuracy and ease of performance calculation using a number of CFD solvers. In addition it is expected that it will allow generation of various different screw machine configurations like single screw machines or machines with conical rotors.

Numerical and experimental analysis of transient flow in Roots Blower

S H Sun[1,2], A Kovacevic[2], C Bruecker[3], A Leto[2,4], G Singh[2] and M Ghavami[2]

[1]Xi'an University of Technology, No.5, South Jinhua Road, 710048, CHINA.
[2]Centre for Compressor Technology, City University London, EC1V0HB, UK.
[3]Sir Richard Oliver Chair in Aeronautical Engineering, City University London, EC1V0HB, UK.
[4]Faculty of Mechanical Engineering, Džemal Bijedić University of Mostar, University Campus, 88104, Bosnia & Herzegovina.

E-mail: sun.shuaihui@city.ac.uk, a.kovacevic@city.ac.uk.

Abstract. The performance of rotary positive displacement machines highly depends on the operational clearances. It is widely believed that computational fluid dynamics (CFD) can help understanding internal leakage flows. Developments of grid generating tools for analysis of leakage flows by CFD in rotary positive displacement machines have not yet been fully validated. Roots blower is a good representative of positive displacement machines and as such is convenient for optical access in order to analyse internal flows. The experimental investigation of flow in optical roots blower by phase-locked PIV (Particle Image Velocimetry) performed in the Centre for Compressor Technology at City, University of London provided the velocity field suitable for validation of the simulation model. This paper shows the results of the three-dimensional CFD transient simulation model of a Roots blower with the dynamic numerical grids generated by SCORG and flow solution solved in ANSYS CFX flow solver to obtain internal flow patterns. The velocity fields obtained by simulation agree qualitatively with the experimental results and show the correct main flow features in the working chamber. There are some differences in the velocity magnitude and vortex distribution. The flow field in roots blower is highly turbulent and three-dimensional. The axial clearances should be included, and the axial grids should be refined in the simulation method. The paper outlines some directions for future simulation and experimental work. The work described in this paper is a part of the large project set to evaluate characteristics of the internal flow in rotary positive displacement machines and to characterize leakage flows.

Comparison of thermodynamic efficiency between constant, dual and multiple lead rotors for an industrial air screw compressor

M Utri[1], A Brümmer[1] and J Hauser[2]

[1]Chair of Fluidics, TU Dortmund University Leonhard-Euler-Str. 5, 44227 Dortmund, Germany
[2]Compression Technologies and Services, Ingersoll Rand Steinbrinkstr. 1, 461485 Oberhausen, Germany

E-mail: matthias.utri@tu-dortmund.de, andreas.bruemmer@tu-dortmund.de, jhauser@irco.com

Abstract. The goal of the European Union funded project "MOTOR" (Multi-ObjecTive design Optimization of fluid eneRgy machines) is the optimisation of fluid energy machines by using isogeometric analysis. This paper deals with the optimisation of the geometry of screw compressors. Screw compressors are usually built using helical rotors with constant lead. However, variable rotor lead holds the promise of higher efficiency due to an optimised progression of chamber volume, clearance, and discharge areas. This is especially true for high pressure applications and for working fluids with low isentropic exponent. This paper describes the optimisation of a variable lead rotor pair for an industrial air screw compressor. The rotors are divided into a discrete number of segments of constant lead, named multiple lead. Using a high number of rotor segments allows a design that approaches a uniformly varying lead. Thermodynamic simulation of the machines is performed using multi-chamber simulation with the simulation tool "KaSim". The thermodynamic simulation is coupled with a Nelder Mead algorithm, which evaluates the efficiency of the machines and optimises the progression of rotor lead. The achievable efficiency of this optimised multiple lead machine is compared with constant and dual lead machine configurations. Results of this study show that the highest efficiency can be achieved by using dual lead rotors.

Vacuum

Analytical and numerical prediction of the flow and performance in a claw vacuum pump

J Willie

Chief Engineer, Innovation and Technology, Industrials Group, Gardner Denver Schopfheim GmbH, Johann-Sutter-Straße 6+8, 79650 Schopfheim, Germany

E-mail: James.Willie@gardnerdenver.com

Abstract. This paper presents the use of a 0-D thermodynamic chamber model and 3D Computational Fluid Dynamics (CFD) to predict the performance of a claw vacuum pump. The 0-D model can be used for pump sizing during the initial design or concept phase. Parameters such as the compression ratio (π), the built-in volume ratio (θ), the volumetric efficiency (η_V), the isentropic efficiency (η_{is}), the volume compression ratio (v_i) and the intermediate pressures (p_z, p_i) are essential to the performance of such machines. To determine these parameters, the volume-curve of the pump is determined as a function of the rotational angle. Using this model, it is possible to enhance the pump performance. For example, by decreasing the carry-over volume and by limiting or preventing over and under compression which can lead to an increase in the power consumption. This paper presents the results of the 0-D thermodynamic chamber model followed by the results of the 3D CFD simulations and validation with measurement data. After the benchmarking, CFD was used to improve the aerodynamic design of the pump discharge tube which led to a decrease in the power consumption of the pump compared to the baseline case. The diffuser angle was decrease to limit the boundary layer size and flow separation and recirculation at the discharge. When left unchecked, it can lead to large pressure drop and to an increase in the power consumption. Using CFD, other phenomenon such as such as pressure jump, which is commonplace in such machines, can be prevented. Otherwise, it can lead to shock wave generation and to noise in the pump.

Limits of one dimensional modeling of rarefied Couette Poiseuille clearance flow in vacuum pumps

C Huck and A Brümmer

Chair of Fluidics, TU Dortmund University, Leonhard-Euler Str. 5, 44227 Dortmund Germany

E-mail: christopher.huck@tu-dortmund.de, andreas.bruemmer@tu-dortmund.de

Abstract. Clearance flows are the main loss mechanism in dry running positive displacement vacuum pumps. In order to calculate the operation of those pumps a detailed knowledge of the clearance mass flow rates is crucial. The dimensions of such pumps and the large pressure range of the operating points require a wide range of gas rarefaction to be taken into account. The clearance flow can be described by a combined Couette Poiseuille flow due to the pressure gradient between two chambers and the rotation of the rotary pistons. A clearance of variable cross section is investigated and in order to determine the mass flow rate, the DSMC (direct simulation Monte Carlo) method is used. Results in the slip and transition flow regime are compared to experimental findings and a good agreement can be found. In addition, a one dimensional theory is presented based on a linear superposition of Poiseuille and Couette flow rates. The aim of the present work is to determine the limits of the one dimensional theory concerning the geometry of such clearances. For this, the boundary conditions circumferential speed, inlet and outlet pressure are varied.

Optimisation of screw spindle vacuum pumps with variable rotor pitch regarding load-lock operation

T Jünemann and A Brümmer

Chair of Fluidics, TU Dortmund University, Leonhard-Euler Str. 5, 44227 Dortmund Germany

E-mail: timo.juenemann@tu-dortmund.de, andreas.bruemmer@tu-dortmund.de

Abstract. Screw spindle vacuum pumps are characterised by high suction speed and the ability to achieve high pressure ratios in a dry running process. If the dimensions of the pump are comparable to the volume of the system's receiver, evacuation only takes a few seconds. For this reason, a typical application for screw spindle vacuum pumps is the evacuation of a load-lock chamber in a predefined time during a clocked production process. In order to reduce power consumption, screw spindle vacuum pumps with an internal change of volume are used almost exclusively. These pumps are commonly with variable pitch rotors. In this article, a new approach for optimisation of variable pitch rotors in consideration of the requirements of the load-lock process is presented. A dimensionless energetic efficiency is defined based on an idealised load-lock process, this parameter is maximised by the optimisation algorithm. The rotor pitch progression, an important factor in pump performance, is approximated by segments of constant pitch at the suction and discharge sides with a linear decrease in between. The overall wrap angle, the minimum rotor pitch, the crown circle diameter, the root circle diameter, and the circumferential speed are constant for the optimisation, during which the rotor length and load-lock pressure are varied. Optimisations are carried out for double-lobed cycloid profiles. The optimisations result in selection of internal volume ratios which are significantly below a theoretical calculated value for the idealised lock-lock process. This is explained by the internal clearances and details of compression process. The studies reveal a positive influence of the rotor length on the load-lock efficiency, this is because the proper rotor length leads to an uniform compression. It is also shown that the wrap angle of the segment on the suction side should be kept low.

Study on the performance prediction of dry twin screw vacuum pump

J Tuo, B Guo, R Wu, Y Zhang and X Chen

Xi'an Jiaotong University, Xi'an, Shaanxi, China

E-mail：guobei@mail.xjtu.edu.cn

Abstract. Dry twin screw vacuum pump, which generates no oil and gas during operation, inherits the advantages of screw machinery, such as high reliability, stable medium conveying, small vibration, simple and compact structure, convenient operation, etc. which has been widely used in petrochemical and new or high-technology industries, like vacuum heat treatment, nuclear research, micro electro mechanical systems, nanotechnology, precision manufacturing and national defense technology. In this paper, the geometric feature of the twin screw vacuum pump such as contact line, meshing line and chamber volume between teeth is analysed, respectively. In order to study the micro working process within the dry twin screw vacuum pump, a test rig has been designed and built and the p-V indicator diagrams of the working process of dry twin screw vacuum pump have been recorded successfully under various working conditions. Based on the indicator diagrams, the working process within the dry twin screw vacuum pump is analysed in more detail, and especially, the effects of the suction pressure as well as rotational speed on the performance of dry twin screw vacuum pump, such as pumping speed and ultimate pressure, is thus investigated. The results presented in this paper are helpful to deepen understanding of the working process inside dry twin screw vacuum pump and offers a good reference for to improve design and optimize such machines.

Simulation (EU MOTOR Project)

Spline-based parameterization techniques for twin-screw machine geometries

J Hinz, M Möller and C Vuik

Delft University of Technology, Faculty of Electrical Engineering, Mathematics and Computer Science, Delft Institute of Applied Mathematics, Van Mourik Broekmanweg 6, 2628 XE Delft, The Netherlands

E-mail: J.P.Hinz@tudelft.nl, M.Moller@tudelft.nl, C.Vuik@tudelft.nl

Abstract. The fully automated generation of computational meshes for twin-screw machine geometries constitutes a mandatory aspect for the numerical simulation (and shape-optimization) of these devices but proves to be a challenging task in practice. Therefore, the successful generation of computational meshes requires sophisticated mathematical tools. Commercially available classical mesh generators can produce high quality meshes from no more than a description of the rotor contours. However, since we are particularly interested in numerical simulations using the principles of Isogeometric Analysis, a spline-based geometry description rather than a classical mesh is needed. In this paper, we propose a practical approach for the automated generation of spline-based twin-screw machine geometry parameterizations in two dimensions. For this purpose, we adopt the principles of Elliptic Grid Generation and present a parameterization algorithm that is compatible with an automated simulation pipeline based on the principles of isogeometric analysis. To demonstrate the proposed techniques, we apply them to an example geometry and present the resulting parameterizations. Finally, we give a qualitative explanation of how the discussed techniques can be utilized to generate geometry parameterizations in three dimensions and their applications to shape-optimization on a variable rotor-pitch.

Isogeometric simulation of thermal expansion for twin screw compressors

A Shamanskiy and B Simeon

Department of Mathematics, TU Kaiserslautern, Paul-Ehrlich-Str. 31, Kaiserslautern, Germany

E-mail: shamansk@mathematik.uni-kl.de, simeon@mathematik.uni-kl.de

Abstract. Isogeometric Analysis (IGA) is a recently introduced computational approach intended to breach the gap between the Finite Element Analysis and the Computer Aided Design worlds. In this work, we apply it to numerically simulate thermal expansion of oil free twin screw compressors in operation. High global smoothness of IGA leads to a more accurate representation of the compressor geometry. We utilize standard tri-variate B-splines to parametrize the rotors, while the casing is modeled exactly by using NURBS. We employ the Galerkin version of IGA to solve the thermal expansion problem in the stationary case. The results allow to estimate the contraction of the clearance space between the casing and the rotors. The implementation is based on the open source C++ library G+Smo.

Isogeometric analysis framework for the numerical simulation of rotary screw machines. I. General concept and early applications

M Möller and J Hinz

Delft University of Technology, Faculty of Electrical Engineering, Mathematics and Computer Science, Department of Applied Mathematics, Van Mourik Broekmanweg 6, 2628XE Delft, The Netherlands

E-mail: m.moller@tudelft.nl, j.p.hinz@tudelft.nl

Abstract. This paper reports on the current status of an isogeometric modeling and analysis framework for rotary twin-screw machines that is being developed by an international consortium of academic partners within the EU-funded MOTOR project. The approach aims at combining accurate geometry modeling capabilities with modern high-performance computing techniques to enable efficient multi-physics simulations. The paper discusses the overall design philosophy of our isogeometric modeling and simulation pipeline and presents an isogeometric grid generator that makes it possible to integrate ANSYS CFX. Preliminary computational results for Sod's shock tube problem and an asymmetric SRM profile are shown.

Fluid flow through male rotor housing clearances of dry running screw machines using dimensionless numbers

M Utri, S Höckenkamp and A Brümmer

Chair of Fluidics, TU Dortmund University Leonhard-Euler-Str. 5, 44227 Dortmund, Germany

E-mail: matthias.utri@tu-dortmund.de, simon.hoeckenkamp@tu-dortmund.de, andreas.bruemmer@tu-dortmund.de

Abstract. The efficiency of positive displacement machines is strongly influenced by clearance flows. The prediction of the mass flow rate is a challenging task since it depends on thermodynamic and operating boundary conditions as well as the shape of the clearance path. When simulating positive displacement machines using chamber models, clearance flow is commonly estimated by using simplified approaches, such as equations for isentropic nozzle flow combined with a flow coefficient. Knowledge of these flow coefficients is important for an accurate simulation of the machine. For this reason one of the goals of the European Union funded project “MOTOR” (Multi-ObjecTive design Optimization of fluid eneRgy machines) is the determination of the flow coefficient for different clearance shapes. This paper deals with the simulation of the two-dimensional fluid flow in the housing clearance of twin-screw machines using the finite volume method for air as ideal gas. Dimensionless numbers are varied to show their individual influence on the mass flow. Results are compared with experimental data from reports in the literature and show good accordance. The primary factors affecting the results are Reynolds number and the moving boundary in the low Reynolds number region.

PROGRAMME COMMITEE

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Ahmed Kovacevic, City, University of London, GB

Johann Lenz, KÖTTER Consulting Engineers, DE

Laurenz Rinder (retired), TU Wien, AT

Jack Sauls (retired), Trane, US

CONTACT

icsm2018@ft.mb.tu-dortmund.de

Chair of Fluidics
Faculty of Mechanical Engineering
TU Dortmund University
Leonhard-Euler-Str. 5
44227 Dortmund
Germany

Phone: +49 (0)231 755 5721
Fax: +49 (0)231 755 5722

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