Fachtagung “Experimentelle Strömungsmechanik”
3. – 5. September 2019, Erlangen

Untersuchung von Erosionsschäden in einem radialen Gebläse mittels gekoppelten CFD-Erosionssimulationen und Experiment

STUDY OF HEAVY EROSION DAMAGE IN A RADIAL AIR-COMPRESSOR WITH MEANS OF COUPLED CFD-EROSION SIMULATION AND EXPERIMENT

Riadh Omri
Institute of Fluid Dynamics, Friedrich-Alexander-Universität
Erlangen/Nürnberg, Bavaria, Germany
Schöneberger Bastian **Antonio Delgado**
Institute of Fluid Dynamics, Friedrich-Alexander-Universität
Erlangen/Nürnberg, Bavaria, Germany
Hans J.Russwurm
Russwurm Ventilatoren GmbH
Meitingen-Ostendorf, Bavaria, Germany

Numerische Simulation, radiales Gebläse, Modellierung von Erosion, Druck Messung
numerical Simulation, Centrifugal fan, erosion modelling, pressure measurement

Abstract

In a pyrolysis plant, a mounted centrifugal fan takes heavy damage because of erosion originating from metal particles mixed with the inlet air flow impacting its blades and volute walls. In a previous study a new design strategy has been undertaken to specifically overcome the excessive erosion damage on the blades resulting in a new design for the fan which has been investigated by means of CFD simulations coupled with a Finnie erosion model to assess the damage via ANSYS CFX.
This study focuses on further qualitatively assessing the erosion model adopted previously. An available air-compressor in laboratory scale is investigated experimentally in similar conditions. Two layers of paint in different colors cover the walls of the rotor and the inside walls of the volute to better locate the damaged areas. The introduction of the metal particles is regulated via a rotary feeder installed for this purpose into the test setup.
The experiments show the effect of the first impact of the particles and severe damages only to the pressure side of the rotor, the suction side is not affected. These results have been observed via CFD in beforehand.
The analysis is conducted in the same chosen stage operating point, defined at a predefined volume flow VF [kg/m³] and total-to-static pressure Δp[Pa]. Simulations are conducted in steady state with compressible air at high static temperature going to 530°C. For CFD calculations the software in use is CFX of the ANSYS Group. All mesh used is structured and produced by TurboGrid and Icem for the different setup parts.

Introduction

Turbomachines have long maintained an important role in the energy conversion process in many forms including power plants, aircraft, pyrolysis and many others. Thus, the wide range of use imposes multiple constraints and extreme working conditions such as high temperatures and in some cases an impure inlet fluid. This is a common problem in pyrolysis plants

GALA e.V., Karlsruhe, Germany, ISBN 978-3-9816764-6-4

where waste is transformed into disposable substances. Parts of these substances escape previous processing and mix with hot air transported into an air compressor which may have catastrophic effects on the performance of the latter namely damage to the blade walls and volute as a result of the impact. This process is better known as erosion, which has been the topic for numerous studies mostly focusing on sand erosion in pipes by means of simulation and experiment.

Some studies in the literature produced erosion models based on selected parameters considered to be the most influencing on the magnitude and the form of erosion. One of the best known is Finnie et al. [1] who divided these parameters into flow-related and abrasive-related and set a general form for the erosion equation

$$ER=K.\ Fs.\ Upn\ .F(\theta) \quad (1)$$

where K is a factor related to the abrasive Brinell Hardness, Fs the sharpness factor, Up the particle speed, n an empirical factor to correct the amount of the impact energy and F(θ) the impact angle function. In his work, Finnie did not conclude any influence as for the particle size due to the small variation spectrum during his experiment and was as a result not included in the model equation. This model for erosion is used for all simulations throughout this study.

Erosion is a known problem in turbomachinery as it manifests for example in centrifugal slurry pumps in submarine applications, Roco, M.C., et al [4]. Minemura and Uchiyama [5] simulated particle trajectory entrained by an inviscid and incompressible flow in a slurry pump. The results showed that the particle trajectories coincide with the fluid streamlines until the first impact with the hub as the particles change their trajectory to a radial direction with an excessive radial velocity at the blade passage allowing them to leave the impeller before impacting the shroud. As a result, the erosion rate is found to be concentrated on the pressure side of the blades and at the hub near the LE.

This study focuses on a better understanding of the erosion phenomena in Turbomachinery. The main purpose is to ensure the reliability of the erosion model through simulation and experiment and to give an overview about the design effect on reducing the abrasive damage.

NOMENCLATURE

Δp_t	Total pressure rise [Pa]
Δp_{t-s}	Total to static pressure rise [Pa]
Z	Blade number [-]
Θ	Particle impact angle [degree]
d_p	Particle diameter [m]
Ω	Impeller rotational speed [$rev.min^{-1}$]
MF	Abrasive mass flow rate [$kg.s^{-1}$]
ER	Erosion rate density [$kg.m^{-2}.s^{-1}$]
C	Particulates loading [$mg.m^{-3}$]
$\dot{V_0}$	Volume flow rate at design point [kg/h^3]
$\dot{V_{max}}$	Maximum volume flow rate [kg/h^3]

Previous study

The previously conducted study serves as a starting point for the results reported in this paper. The latter focused on understanding erosion but treated it under the aspect of geometry. The main purpose was in the first place to be able to simulate the erosion in the compressor then – and by acting on the compressor design – to understand how the design parameters influence the former with the bigger purpose to have an erosion-free design. This has been to some extent achieved by the new design of the compressor where the erosion rate on the blades has been reduced by over 50% compared to the original compressor-design.

The mentioned compressor is part of a pyrolysis plant and is used to drive the air out of the combustion chamber to introduce it to the next treatment phase. Its intake air is heated through

the combustion to reach temperatures ranging from 500°C to 700°C at a given volume flow $\dot{V_{max}}$[m³/h] recommended by the plant operators.
The numerical investigation of the compressor performance as well as the erosion damage inflicted to the blades and the volute walls have been conducted via coupled CFD simulation in the steady state with erosion modeling using the Finnie model suggested by Finnie et al. 1960.
For more details about the plant conditions, the simulation setup and the numerical modeling for the erosion and compressor aerodynamics refer to R.Omri et al. 2017.
The original setup could only last for about three days operation-time and heavy damage to the blades and volute walls were to appear to the naked eye. The extent of this damage is shown in fig. 1 via the dimensionless erosion rate.

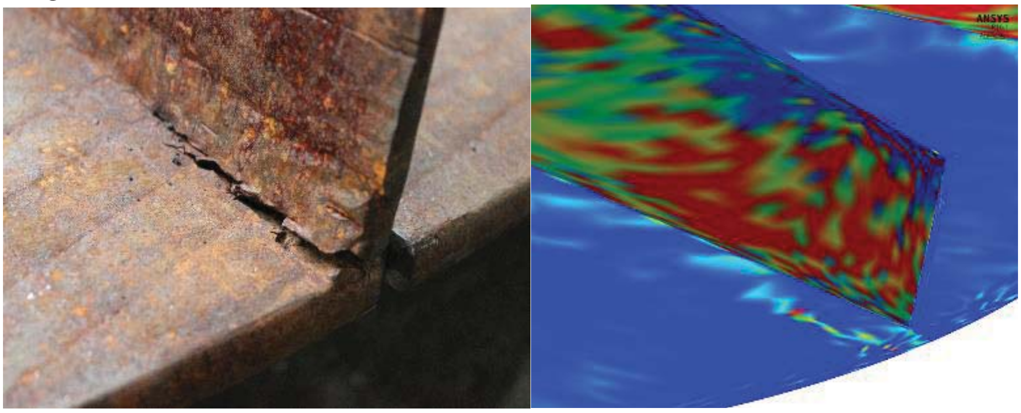


Fig. 1: Eroded blades of the original setup, reality and simulation

After close investigation of the particle impact behavior inside the compressor (refer to R.Omri et.al 2017), a strategy of an optimized design is formulated by inducing the first particle impact on a bladeless flat hub instead of impacting the blades. Two facts may be achieved in this scenario: First, the first particle impact is responsible for the highest damage as the particle is still at full speed and thus can be avoided. Secondly, when impacting a bladeless flat hub, the particle rebound after the impact can be more easily predicted numerically using the discretized form of the force balance which dictates the trajectory in a Lagrangian frame of reference as is shown in fig. 2a.
Accounting for rotational frame and drag forces, the law of motion of the particles in the relative frame of reference is as follows:

$$\frac{du_{px}}{dt} = -2 * \Omega * u_{py} + \Omega^2 * \mathrm{x} + 0.5 * C_d * A * \frac{\rho_f}{\rho_p} * \left\| \overrightarrow{u} - \overrightarrow{u_p} \right\| * (u - u_p) \qquad (1)$$

$$\frac{du_{py}}{dt} = -2 * \Omega * u_{px} + \Omega^2 * \mathrm{y} + 0.5 * C_d * A * \frac{\rho_f}{\rho_p} * \left\| \overrightarrow{u} - \overrightarrow{u_p} \right\| * (u - u_p) \qquad (2)$$

where Ω is the rotational speed, C_d is the drag coefficient, A is the particle projected area and u is the fluid flow relative velocity. ρ_f and ρ_p are respectively the fluid flow and the particle densities.
The right-hand side of equation (1), respectively (2), is a function of only the particle coordinate and velocity. They can be solved as an initial value problem by using the initial location and velocity of a particle. In the following, equations (1) and (2) are numerically integrated by Runge-Kutta fourth and fifth order method at every time interval Δt.
Velocities of particles entering the blade passage after the first impact serve as initial conditions for the velocity terms along with their positions.

The design idea is to base the blade camber-line design on the particle trajectory. Fig. 2a shows particles with 0 $m.s^{-1}$ initial velocity in radial direction entering the blade passage at close locations. The particles are deviated by the rotational forces and the trajectories are presented along with the blades' camber-line of the final compressor design.
For further details about the design strategy and the intermediate designs as well as the final design characteristics refer to R.Omri et.al 2017.

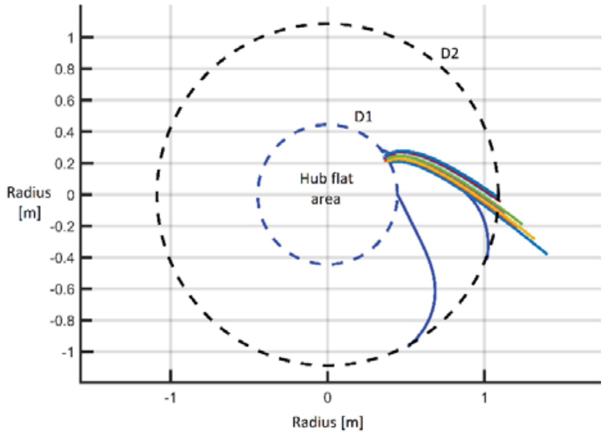


Fig 2a: Blade form of the improved design.

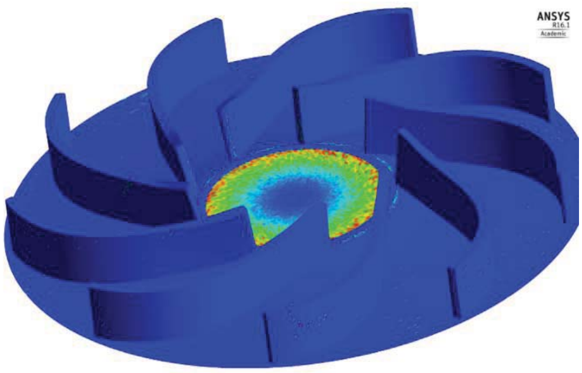


Fig 2b: Erosion rate on blades and hub

The most damaged part of the impeller is the hub flat area where the averaged lost material increased to 5,6 mm / day. The impact distribution differs from blade to blade and is concentrated at LE and near TE at the blades near the narrow part of the volute.
The averaged material loss at the blades is of 0.16 mm / day, which is a decrease of around 77 % compared to the original design. Refer to fig. 2b.

Further development of the optimized compressor design

Rotating parts like open-impellers are prone to structural problems as the maximum material strain can be exceeded at design rotational speed and thus material failure may occur. To avoid structural failure, a top disc is introduced to reinforce the impeller design.
Fig. 3a shows the failure occurring at the blade tips in the open impellers design while no excess in the von-Mises strain is registered once the top disc is introduced as is shown in fig. 3b.

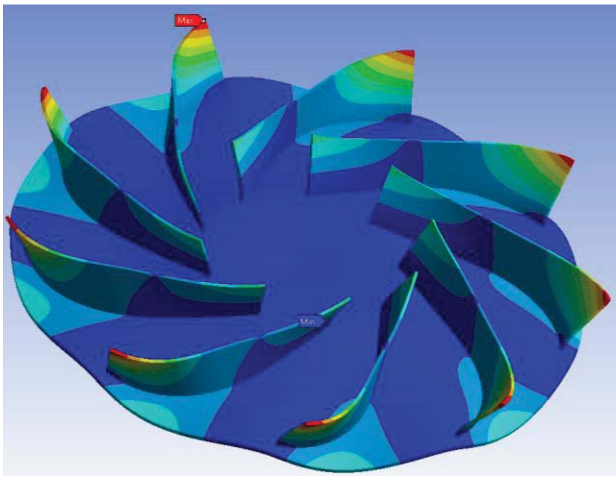


Fig 3a: Strain on the blade tip exceeding material failure limit

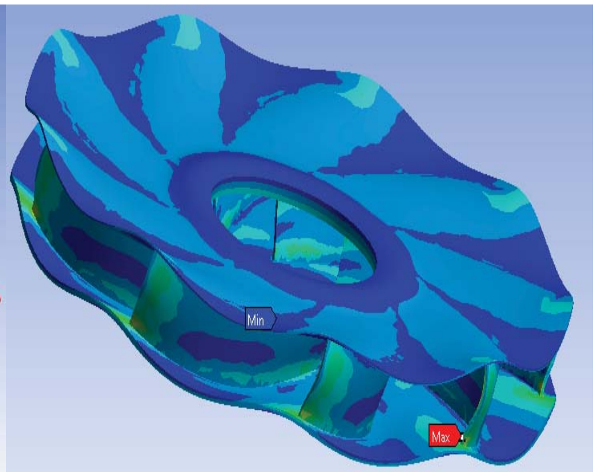


Fig 3b: Strain on the blade and the top disc remains within failure limits

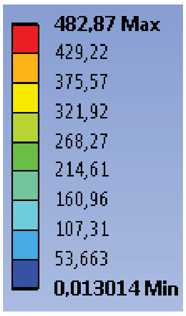
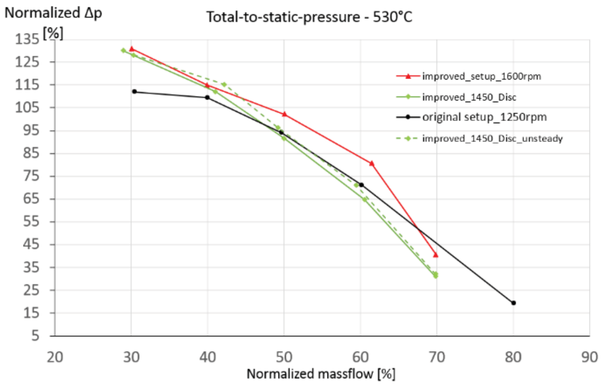


Fig 3c: Von-mises criterion for the material strain in MPa

The introduction of the top disc has been advantageous for the mechanical structure of the impeller but it included a drop in the pressure rise at higher flowrates and a notable increase near surge. The total to static efficiency registered a rise over all the simulated working points in comparison to all previous designs without undermining the achieved reduction in the erosion wear. These results have been confirmed by the unsteady simulations of the final design as is shown in fig. 4a and 4b.



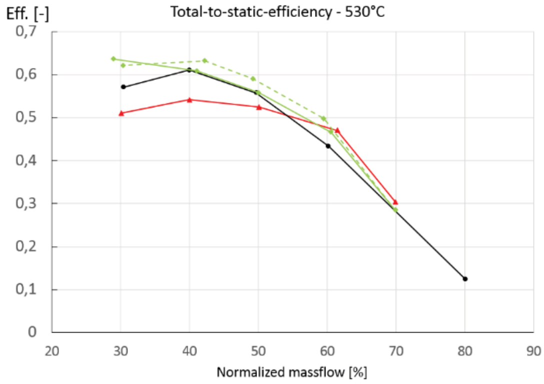


Fig 4a: Pressure-speedlines of the different compressor designs

Fig 4a: Efficiency-speedlines of the different compressor designs

Simulation results of the to-be measured test rig

The test rig could not be constructed in the real dimension of the pyrolysis plant compressor. An available compressor has been chosen from an array of already aerodynamically tested compressors (table 1) to conduct the erosion test by introducing the particles via a rotary valve as is shown in fig. 6 and 7.

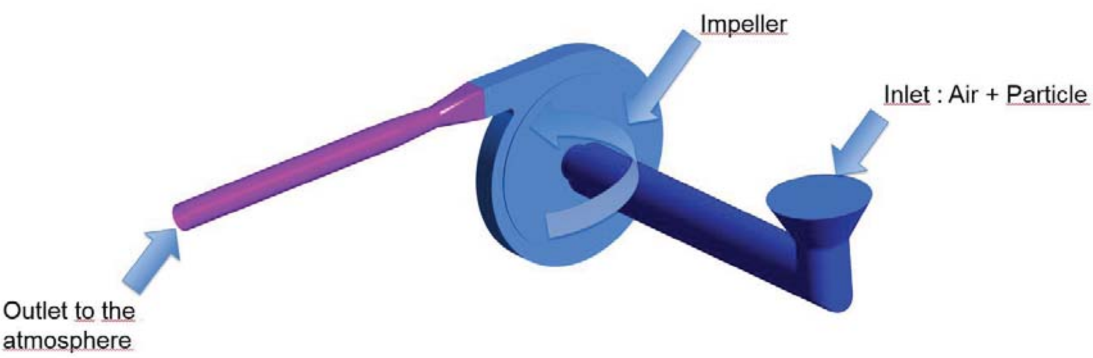


Fig. 5: Numerical setup for the measured impeller

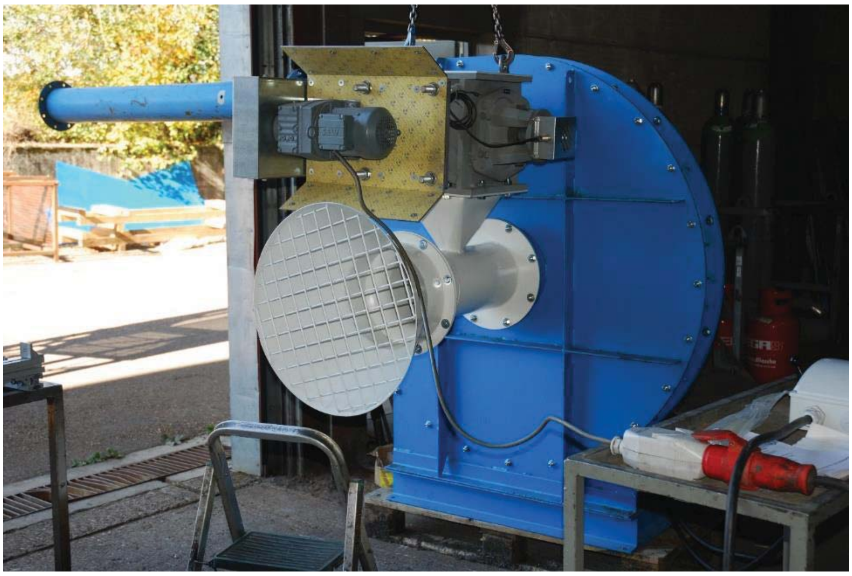


Fig. 6: Setup for the measured impeller

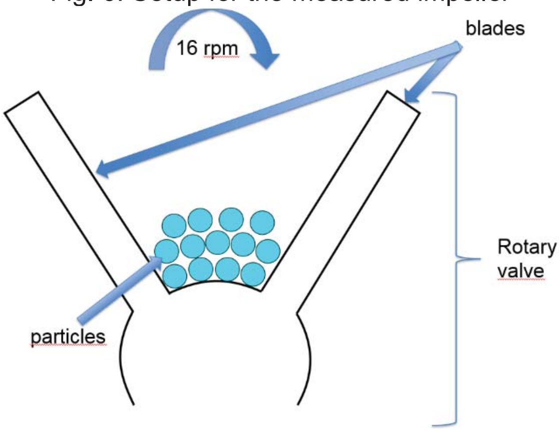


Fig. 7: schematic representation of the rotary valve

Table 1: Characteristics of the intake air and particles in the test case

Design point	900 [l/s] (3240[m³/h])
Max. Volume flow	1500 [l/s] (5400[m³/h])
Rotational speed	2950 [rpm]
Particle diameter	Up to 3mm
Particle mass flow	Depends on the operating points VF

Different particle loadings have been numerically investigated: C1 = 0,00114 [kg/m³] and C2 = 0,0114 [kg/m³]. The simulated erosion rate at the maximum efficiency point shows different results. The damage to the blades wall is almost linear to the particle loading as the material loss is ten times higher once the particle loading is likewise increased as shows fig. 8

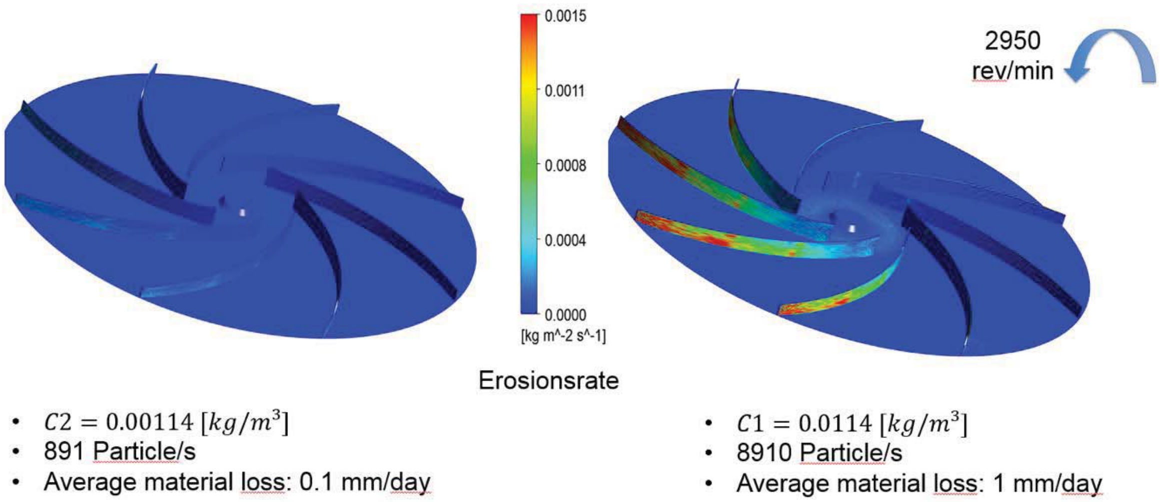


Fig. 8: numerical investigation of different particle loading

Case setup for the measurement

Fig. 6 shows the final setup for the experiment on the chosen impeller. A grid is mounted on the air-inlet to break any non-axial component of the air inlet-velocity. The rotary valve is mounted shortly after the air-inlet.
Particles of steel ranging in dimension between 1mm and 3mm are introduced into the volute via the rotary valve which is responsible for regulating the abrasive mass flow. The abrasive mass flow rate (MF) is defined using the gaseous volumetric flow rate (VF) of introduced air and the average particulates loading (C) according to the EPA 2005 as follows:

$$C = MF/VF \quad (2)$$

The impeller as well as the volute inner-walls have been treated with two different paint films: the first one in blue, the second one in white and each 1mm thick for the sake of recognizing the erosion distribution as well as its amplitude on the inner-walls.
With an abrasive mass flow of 19,16 g/s the measurement has been conducted for 10 min. After this short time the following observations have been made:

- In the hub central area both of the paint films have been completely wiped-out by the particles' first impact. Refer to fig. 9
- Away from the central area, the distribution varies between blade and hub and pressure side and suction side.
- Most of the damage on the blades is concentrated on the pressure side as it has already been seen in the simulation, while the suction side shows practically no damage. Refer to fig. 9
- An interesting but still not fully understood fact of particle impact damage is noted near the TE of the blades and on the hub around it. This particularly damaged area is observed as a simulation result as well as during the measurement. See fig. 10. It is believed that this particular damage results mainly from rebounding particles from an impact on the volute wall which may have been trapped in the blade wake.

Fig. 9: Erosion damage to the central hub area and no damage to the blade suction side

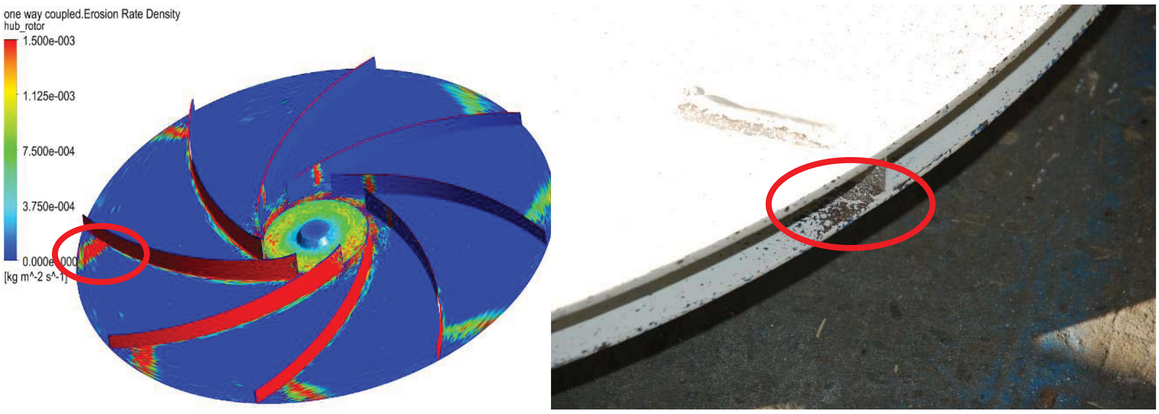


Fig. 10: Erosion damage to the area near the blade TE

Conclusion

An impeller design with novel aerodynamics has been presented. The aim of the design was to ensure a low erosion rate on the inner walls from metal particle impacts. CFD simulations coupled with erosion calculations based on particle trajectories of the original impeller have been studied to issue a new design strategy for the matter at hand. The controlled particle trajectory in the new setup led to a 57 % reduction of the erosion rate on the blades.
Setting up a test rig to compare the numerical modeling to the measurement showed remarkable qualitative similarities in the central hub area, pressure and suction sides of the blades as well as at the area surrounding the blade TE.
These observations confirm that an adequate erosion modeling has been adopted for the qualitative study of erosion damage.

Acknowledgment

Many thanks to everyone who has been involved in this study from LSTM and Rußwurm AG.

Literature

R.Omri et al., 2017, “Design Study of a pyrolysis Plant Compressor with Heavy Wall Erosion From Metal Particle Impact”, Proceedings of the Fluids Engineering Summer Conference FEDSM 2017, Waikoloa, Hawaii
Finnie, 1960 “Erosion of surfaces by solid particles”, Wear, pp 3(2):87-103.
Vieira, et al. 2015 “Experimental and computational study of erosion in elbows due to sand particles in air flow”, Powder Technology.

Y.I. Oka et al., 2005 “Practical estimation of erosion damage caused by solid particle impact”, Wear269-109.
Roco, M. C., et al. 1986 “Casing headloss in centrifugal slurry pumps” Trans. ASME, J.Fluids Engng, 108(4), 453-464
K.Minemura et al., 1990 “Calculation of the three-dimensional behavior of spherical solid particles entrained in a radial-flow impeller pump”, IMechE.
Menter, F. R., 1993 “Zonal Two Equation k-Omega Turbulence Models for Aerodynamic Flows”, AIAA Paper,1, pp 93-2906.
ANSYS CFX-Solver modeling guide, ANSYS, Inc. Release 16.1.
NSW Environment Protection Authority (EPA), 2005 “Approved Methods for the Modeling and Assessment of Air Pollutants in New South Wales”.
B.Gary. 2006 “Use of CFD to predict and reduce erosion in an industrial slurry piping system”. Proceedings of Fifth International Conference on CFD in the Process Industries, CSIRO, Melbourne, Australia.