EXPERIMENTAL AND NUMERICAL INVESTIGATION OF CO₂ DRY-ICE BASED AIRCRAFT COMPRESSOR CLEANING

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ABSTRACT
On-wing cleaning of engine compressors for commercial aircraft is a required maintenance task which results in greater operating efficiency and lower emission rates. It is typically carried out by injection of water and detergents into the intake of an engine while the engine is being cranked by the starter (i.e. dry-cranked). The dry-ice blasting process, a cleaning system which uses an air-flow and CO₂ dry-ice particles as cleaning agent, has been proposed as an alternative method which is potentially capable of efficient cleaning.

In this context, an experimental and numerical investigation of the dry-ice defouling process is presented. A prototype of the new cleaning-system is used to defoul the compressors of a GE CF6-50 engine in a test-rig. The injected dry-ice particles disintegrate into smaller fragments and defoul the airfoils upon collision inside the dry-cranked engine. The study addresses an insight into the dry-ice particle behavior during the process and the numerical assessment of the defouling efficiency.

Air-flow measurements, particle-tracking experiments utilizing a high-speed camera (HSC) and airfoil surface-mapping experiments are presented. The particle recordings are made at three positions inside of the engine and these are two-dimensionally post-processed. The airfoil surface-mapping utilizes photographies and image post-processing to compare the airfoil surfaces before and after cleaning. The airfoils investigated are coated with polyexymethylene, which is used to visualize the defouling effect in large scale engine experiments.

The process is simulated in steady state with Ansys CFX and the implementations of the newly developed particle breakup- and erosion models for dry-ice are used in an Euler-Lagrangian formulation. Rotational periodicity is assumed, and the airfoil domains are linked with a mixing-plane approach. Predicted air flow properties of the dry-cranked engine, particle size and particle velocity data, and defouling patterns of the blading are compared using experimental data where possible. Cleaning efficiency is assessed at various instants of time using various parameters of the particle breakup model and of the particle injection formulation.

The overall agreement of predicted and experimental data is found to be satisfactory for engineering purposes. The mean deviations encountered range from 9.7 to 22.4%. Possible improvements of the numerical strategy presented are identified and discussed.

KEYWORDS
particle laden flow, defouling erosion, dry-ice cleaning, HSC experiment, numerical simulation
NOMENCLATURE

α_{idx} \quad [deg] \quad \text{angle}

χ \quad [any] \quad \text{replacement character}

δ\xi_{idx} \quad [1] \quad \text{defouling energy ratio}

δh_{pc} \quad [J] \quad \text{heat of fusion}

δm_{sub} \quad [kg] \quad \text{sublimated mass}

γ^0 \quad [J/kg^2] \quad \text{internal bond energy}

ρ_{idx} \quad [kg/m^3] \quad \text{density}

ξ \quad [1] \quad \text{random number}

BLMH \quad \text{bell-mouth}

BYPSS \quad \text{bypass}

DIT \quad \text{Dublin Institute of Technology}

EGT \quad \text{exhaust gas temperature}

FEM \quad \text{finite element method}

FVM \quad \text{finite volume method}

HPC \quad \text{high pressure compressor}

HSC \quad \text{high speed camera}

IGV \quad \text{inlet guide vanes}

LHT \quad \text{Lufthansa Technik AG}

LPC \quad \text{low pressure compressor}

OGV \quad \text{outlet guide vanes}

PTFE \quad \text{polyexymethylene}

hda \quad \text{Hochschule Darmstadt}

i, j, idx \quad \text{indexes (specified in text)}

ps \quad \text{pressure side}

ss \quad \text{suction side}

INTRODUCTION

On-wing compressor cleaning is used by commercial aircraft operators to improve aircraft engine performance, which enhances the operator’s competitiveness. Engine maintenance cost represents ca. 35 to 40% of an airline’s total maintenance cost according to Ackert (2011). Compressor fouling causes a range of negative effects on engine performance. An increase of airfoil roughness and fouling layer thickness leads to decreasing pressure and temperature ratio, decreasing core mass flux and, hence, a decrease of the surge and stall margin and of the efficiency of the compressor (i.e. component efficiency and pressure ratio). These represent ca. 70% of an engine’s total thermal efficiency according to various authors such as Meher-Homji (1987); Diakunchak (1991); Kurz and Brun (2000); Meher-Homji and Bromley (2004); Mund and Pilidis (2006); Oosting et al. (2007); Kurz and Brun (2012); Martín-Aragón and Valdés (2013). To maintain constant thrust when engines are fouled, more fuel must be burned during operation. This leads to higher fuel consumption, higher emission rates and higher exhaust gas temperatures (EGT). An increased EGT deteriorates the hot path of the engine. Combustion chamber and turbines face higher stresses. Corrosion of compressor blades is also possible.

Cleaning systems, such as the currently-used water-wash system, are applied directly to the on-wing engine during aircraft ground time. In order to remove the fouling, an air flow, which is laden with solid or liquid detergents, is injected into the dry-cranked engine. The general procedure is shown schematically in fig. 1 using the example of CO₂ dry-ice cleaning. Compressor blades are defouled by particle-wall (or droplet-wall) interaction. Extensive investigations by Lufthansa Technik (LHT) revealed that fuel savings in the range from 1.0 to 1.2% and decreases in EGT up to 15°C are possible if engines are regularly washed.
Figure 1: Schematic illustration of aircraft compressor cleaning with dry-ice.

The engine cleaning procedure is an ongoing research topic for LHT. In this context a dry-ice based cleaning system has been developed recently in cooperation with Hochschule Darmstadt (hda) and Dublin Institute of Technology (DIT). The main focus of this study is to present numerical simulations of the dry-ice based defouling process of an axial aircraft compressor section and the comparison of the predicted values with experimental data.

Engdar et al. (2004) investigated off-line water-wash injection paths through the bellmouth of a stationary Siemens GTx100 gas turbine by means of the FVM-based CFD code Star-CD. Boundary conditions for droplet injection (i.e. diameters and velocities) were taken from experiments. Initial water temperature had negligible influence upon the results and predicted wetting of the machine’s IGVs was qualitatively comparable to experimental data.

Mund and Pilidis (2005) investigated water-wash system parameters of a stationary gas turbine intake and discussed air mass flux and droplet diameter, velocity, injection angle and spatial distribution of the droplets using Ansys FLUENT. The main goal of the study was to find a setting which provides a uniform droplet distribution at the compressor inlet. The authors found air mass flux to be sensitive to the washing and suggested to search for optimum parameters of wash-systems for individual (i.e. problem specific) wash-operation conditions.

Giljohann et al. (2012) reported Euler-Lagrangian simulations with Ansys CFX of a preliminary dry-ice cleaning study of an aero-derivative test engine, type GE CF6-50E2. The particle paths through the engine compressors were discussed. The particles mainly impacted upon the leading edges and pressure sides of the blading. Defouling predictions from standard erosion models were qualitatively compared to experimental data but showed unsatisfactory agreement. The future work needed to overcome the simulation procedure’s weaknesses, which was partially identified in Giljohann et al. (2012), was addressed in Rudek (2018) and this study highlights some of the major findings.

An appropriate multiphase-flow simulation strategy using newly developed particle breakup and erosion models for the numerical prediction of detailed flow and cleaning patterns are therefore presented. Typical particle laden cleaning flows, fouling materials and geometries are considered. The models are used with CFD simulations utilizing Ansys CFX in an Euler-Lagrangian simulation context. The final goal of this work is reliable numerical prediction of defouling erosion (here airfoil defouling), which can be used to understand and optimize the cleaning process and various cleaning-system parameters, and to provide reliable aircraft compressor cleaning predictions.
EXPERIMENTAL AND NUMERICAL STRATEGY

Experiment

The test engine used for the application case study consists of low- and high-pressure shafts which are aerodynamically coupled. The low-pressure compressor (LPC) consists of three and the high-pressure compressor (HPC) of 14 stages. The engine is mounted on a stationary test-rig and the high pressure shaft is driven by an external electric motor. In the dry-crank mode, which is investigated for the defouling process, 20% of the nominal shaft speed is applied (i.e. ca. 2000 rpm). The low pressure shaft turns at approximately 166 rpm.

A sectional view of the engine is shown in fig. 2, left, and the indicated positions of instrumentation are described below. The engine is equipped with short-headed Prandtl probes with integrated type K thermocouples. These probes are located along the flow path in the compressor and can be turned (i.e. to measure counter-current flows). Their positions can be varied in radial direction (i.e. to measure span-wise flow profiles). The first probe position is in the IGV row behind the fan (LPC-IGV) and followed by five downstream positions in the HPC stages 1, 3, 5, 9 and 14 (HPC-1 to -14). Static pressure probes, type K thermocouples and a hot-wire anemometer are used to measure air velocity in the bell-mouth (BLMH) and bypass (BYPS) of the engine. Ambient pressure, temperature and humidity are measured away from the flow path.

Dry-ice particles are sized and tracked with HSCs placed at specific positions in the HPC. The procedure and the experimental set-up of the HSCs and the lighting system are described in detail in Rudek et al. (2016). Two positions are accessed and these are the IGV row of the HPC (HSC-I) and a position behind the OGV row of the HPC (HSC-O). Figure 2, mid, shows a photograph of the test-rig prepared for a defouling test run. It displays the bell-mouth and the intake of the engine with a prototype of the new dry-ice based LHT-Cyclean wash unit placed in front.

The HPC of the test-engine is accessible and the blading can be removed. The photograph of the opened HPC in fig. 2, right, shows a number of stator and rotor blades before cleaning. It is possible to apply artificial PTFE fouling in large-scale experiments and this data is used...
to compare the numerical to experimental results in this study. The blades are photographed before and after defouling tests outside the engine in a controlled lighting environment and post-processing of these photographs is carried out with a before-after comparison procedure, comparable to that described in detail in Rudek et al. (2016). This procedure provides the desired defouling statistics.

**Numerical simulation**

The engine is simulated with pure air flow in the dry-crank mode before the actual defouling simulations are carried out. The simulation model is designed assuming periodic symmetry, and a stream channel is selected which consists of single airfoils for each row of the engine. There had been no grid independence study executed. The simulations are made on a scalable mesh with resolved boundary layers. Approximately 100,000 grid-points are used per airfoil passage. The meshing of the engine was carried out by LHT, and the ICEM mesh generator was used.

![Figure 3: Numerical set-up for GE CF6-50 simulations: boundary conditions and most important modelling assumptions are specified.](image)

The stationary and rotational domains are linked by stage interfaces and the mixing plane approach is used to handle the conservation equations (see for example AnsysINC (2013)). The final numerical set-up is shown, with boundary conditions, in fig. 3. The simulation strategy for the dry-crank mode consists of two steps. In the first step, the set-up is initialized with a numerically stable setting with first order discretization schemes and strong under-relaxation (referred to as step 1). In a second step the numerical damping is lowered and higher order discretization schemes are applied (referred to as step 2). The second step turned out to deliver fluctuating results, and these indicate a transient flow state.

The particle phase is introduced into the region of interest using a boundary patch for the simulations of the defouling procedure at the intake of the engine model. Although the flow simulations are steady-state, cleaning information generated is time-dependent. To account for a representative proportion of dry-ice particles in the simulation, the total mass of dry-ice particles used in the actual cleaning process \( m_{TOT} \) is scaled to the proportion of the engine considered (first term in parentheses in eqn. (1)) and to the actual period of time considered (second term in parentheses) and with this assumption the number of simulated dispersed particles is adapted.
Equation (1) scales the actual angle of the proportion of the intake considered in the numerical model \( \alpha_{SIM} \) (i.e. related to the whole engine, \( 2\pi \)) and it scales the number of simulated rotations \( N_{SIM} \) (i.e. related to the total number of rotations of the actual defouling process obtained by the multiplication of the rotational speed of the LPC \( n_{LPC} \) with the total cleaning process time \( t_{TOT} \)):

\[
m_{SIM} = m_{TOT} \cdot \left( \frac{\alpha_{SIM}}{2\pi} \right) \cdot \left( \frac{N_{SIM}}{n_{LPC} \cdot t_{TOT}} \right)
\]

(1)

The continuous air flow is simulated by means of the Euler approach using the energy equation and Newton’s material law and the dispersed particle phase is simulated by means of Lagrangian particle tracking. Therefore, the particle’s ODE of motion

\[
m_P \cdot \frac{d^2 x_P}{dt^2} = \sum_{i=1}^{n} F_i
\]

is solved in the area of interest. It relates particle inertia forces (represented by its mass \( m_P \) and acceleration) to the sum of \( n \) external forces \( F_i \) acting on this particle.

If the particles collide with the engine’s blading they disintegrate into smaller fragments and a proportion of the fouling is removed from the airfoil. To account for this in the simulations, an experimentally based particle breakup model and a defouling erosion model for CO\(_2\) dry-ice particles have been developed in Rudek (2018). The basic assumption of both models is a mass- and energy balance and mass

\[
m_P = \sum_{j=1}^{q} m_i + \delta m_{sub}
\]

(3)

as well as kinetic energy (index \( kin \))

\[
E_{P,kin} = \sum_{j=1}^{q} (E_{i,kin} + E_{i,bu}) + E_{sub} + E_{er}
\]

(4)

of the impacting particles (index \( P \)) are conserved by balancing the primary particle variables with these of the \( q \) secondary particles. All dispersed secondary particles and the sublimated proportion of primary particle mass (index \( sub \)) are considered in the mass balance, eqn. (3). The energy balance, eqn. (4), accounts for the kinetic energy, the breakup energy (index \( bu \)), the sublimation energy and the energy used for the defouling erosion (index \( er \)).

It is derived from a theoretical model analysis and simplified based on a sensitivity analysis. A fundamental HSC experiment is made, where single dry-ice particles are recorded while impacting solid walls at a range of impact velocities, angles and wall temperatures. The data acquired from post-processing of these recordings represents the statistical database for the new particle breakup model.

An unfouled (i.e. clean) target is considered for the basic observations of the dry-ice particle breakup processes. Erosive energy contributions to eqn. (4) are neglected because no erosion
of the target material is expected. Following these assumptions, the energy balance of an un-fouled system, considering particle breakup and possible sublimation on particle-wall collision, is explicitly written as:

\[
\frac{1}{2} \cdot m_P \cdot \vec{v}_P^2 = \sum_{i=1}^{q} \left[ \frac{1}{2} \cdot m_i \cdot \vec{v}_i^2 + \gamma^{(0)} \cdot A_i \right] + \delta m_{sub} \cdot \delta h_{pc}
\]

and the corresponding mass balance is given as:

\[
\rho_P \cdot \frac{\pi}{6} \cdot d_P^3 = \sum_{i=1}^{q} \rho_i \cdot \frac{\pi}{6} \cdot d_i^3 + \delta m_{sub}.
\]

The numbers of secondary particles \(q\), the particle masses \(m_i\) (represented by \(\rho_i\) and \(d_i\)), the particle velocities \(\vec{v}_i\) and the sublimated proportion of the primary particle mass \(\delta m_{sub}\) are determined from experimental recordings using an appropriate post-processing strategy and statistical data processing methods. All material properties and dry-ice temperature are assumed to be constant, such as the heat of fusion of dry-ice \(\delta h_{pc}\).

Introducing \(\chi\) as the replacement character for variables \(q, m_i\) and \(|\vec{v}_i|\), general statistical relations are assumed to be valid and various statistical fits are considered, depending on the experimental results. This leads to the general functional relations

\[
\bar{\chi}, \chi' = f[d_P, \vec{v}_P, T_{tar}].
\]

It is assumed that primary particle size (in terms of equivalent spherical diameters \(d_P\)), particle velocity \(\vec{v}_P\) and target temperature \(T_{tar}\) are possible variables in the breakup process and therefore they have to be varied in the experiments. Final variables of secondary particles from primary particle breakup can be calculated

\[
\chi = \bar{\chi}(d_P, \vec{v}_P, T_{tar}) + \xi[i+\delta] \cdot \chi'(d_P, \vec{v}_P, T_{tar})
\]

and the stochastic manner of the breakup process is considered by scaling case-dependent fluctuations \(\chi'\) with appropriate random numbers \(\xi\) which are varied from \(i\) to \(j\).

The defouling erosion is accounted for by means of defouling functions, such as:

\[
d_{IMP}^{\{part,fou,\alpha\}} = \left(K_1^{\{part,fou,\alpha\}} \cdot \ln (v_P) + K_0^{\{part,fou,\alpha\}} \right) \cdot d_P.
\]

These correlate the equivalent sphere diameter of the defouled area \(d_{IMP}\) to the particle impact velocity \(v_P\) and size \(d_P\) by means of experimentally derived correlation coefficients \(K_i\). The defouling mechanism proved to be dependent on the particle material (superscript \(part\)), the fouling material (superscript \(fou\)) and the impact angle (superscript \(\alpha\)).

The amount of energy necessary to penetrate and remove a certain proportion of the fouling layer is accounted for by:

\[
E_{er}^{\{part,fou,\alpha\}} = \left[ \frac{\rho_{ref}}{2} \cdot \delta z^{\{fou,0^\circ\}} \cdot \left( v_{ref}^{0^\circ} \right)^2 \right] \cdot f_{IMP}^{\{part,fou,\alpha\}} \cdot V_{IMP}^{\{part,fou,\alpha\}}
\]
This equation consists of an experimentally based measure of the defouling energy from reference material particle impacts (index \( \text{ref} \)) which is scaled by a defouling area correction function \( f_{IMP} \) and multiplied by the volume of removed fouling material \( V_{IMP} \). The correction represents the ratio of the actual area defouled by dry-ice particles related to the area defouled with the reference material particles.

A deeper insight into the particle breakup model will be published in a future communication by the authors, which is currently in preparation, and details of the energy based defouling erosion procedure can be found in Rudek et al. (2018). Both models are extensively discussed in Rudek (2018).

The full set of particle boundary conditions is obtained by using simplified experimental particle size distributions and mean experimental particle velocities. More details about the related experiments can be found in a previous communication by the authors, i.e. Rudek et al. (2016). The air flow from the injection system and the positioning of the system in the intake of the engine are neglected. To consider this situation, an expensive multiple domain approach (i.e. multiple blades per row) would be necessary and it is not possible to account for this with the symmetry assumption presented here. The impact of the particle phase upon the air flow in the engine remains neglected in this study and this is done by applying CFX expert parameters to freeze the flow field. It is assumed that the numerical symmetry approach presented here is able to predict the mean cleaning effect of the rotors and the maximum cleaning effect of the stators in the main cleaning flow.

**APPLICATION CASE STUDY**

**Air flow investigation**

Representative results from the simulations of the flow field in the HPC are discussed in fig. 4. Pressure, velocity and turbulent kinetic energy are shown in the meridional plane view (i.e. the mid-channel flow between two airfoils). There is a pressure rise of up to 10,000 Pa in the HPC. A clearly separated flow region is predicted in the velocity and in the turbulence field which develops at the IGVs and settles at the outer part of the HPC. This separation region can be distinguished from the undisturbed region by the disordered velocity contours at the outer part of the engine compared to their regular appearance at the inner part. In the separation region, high amounts of turbulence kinetic energy are predicted. The predicted disturbance vanishes at the 8th stage of the engine. It must be noted that these simulated results are not strictly steady state and, depending on the number of iterations calculated, the predicted vortex field appears slightly different in the post-processing.

Indicators for the predictive capability of the simulations with both set-ups in comparison to experimental data are given in fig. 5 and 6. The left-hand display in fig. 5 shows trends for static pressure and the right-hand display those for axial velocity values. The predicted values are averaged over the channel height of the potentially undisturbed flow (i.e. as predicted by simulations) and the corresponding experimental mean valued samples are taken in three positions which are located around the middle of the undisturbed flow channel. The ranges of possible numerical fluctuations from step 2 simulations are highlighted by scatter bars whereas the results from step 1 simulations do not show fluctuations. The fluctuations indicate a non-converged numerical solution and transient phenomena which cannot be captured by means of the simulation strategy presented here.
Figure 4: Numerical results of HPC: contours of static pressure (upper), velocity in stationary frame (HPC - mid) and turbulence kinetic energy (lower) in meridional plane view.

The results prove an adequate prediction of the global trends. Differences in the results may be caused by local effects in the probe measurements and from the simplifications of the numerical approach. The mean values of both pressure and velocity trends are predicted with a mean accuracy of 16% by the step 1 simulations, the pressure field is predicted with a lower mean accuracy of 22% but the velocity field predictions are better with 7% when using the step 2 set-up.

Typical axial velocity profiles are compared in fig. 6 for sample measurement positions in the separated and undisturbed flow region. The span variable shows the relative position along

Figure 5: Engine simulations - comparison of numerical to experimental data in undisturbed flow channel; static pressure (left) and axial velocity (right); measurement uncertainties indicated.
the span of the corresponding vane with 0 representing the hub (i.e. towards the engine axis) and 1 representing the tip (i.e. towards the engine casing). At the measurement position HPC-3, there is a clearly visible experimental indication for the predicted separation region. The qualitative velocity profiles are sufficiently well predicted and the global trends in fig. 5 are in good agreement with experimental data. These results show that it is possible to simulate the dry-crank mode of the engine with a reasonable accuracy for the final defouling simulations presented below. The temperature field is not discussed in this work.

Figure 6: Engine simulations - comparison of numerical to experimental velocity profiles at various measurement positions (i.e. 3rd and 8th stage); measurement uncertainties indicated.

Particle laden flow predictions

The engine cleaning simulations comprise the assessment of the cleaning of artificially fouled test-engine compressor parts (fouled using PTFE) and the corresponding tracking of dry-ice particles. Periods of the first 1%, 10% and 100% of the total actual process time are considered by modifying the total mass introduced into the system according to eqn. (1). Figure 7 shows typical particle tracks in the LPC for the simulation of 1% of the process time. Particle breakup occurrences can be seen up to the third stage of the LPC but the predominant disintegration of large primary particles into smaller secondary fragments happens in the fan stage where the particles come into contact with a rotating airfoil for the first time.

The particle phase is dominated by small particles downstream of the fan. A number of large particles is ejected via the fan through the bypass, and this phenomenon was also encountered in the experiment. Only a small number of particles flows over the suction sides of the blades compared to the pressure sides. The particles tend to concentrate at the outer radius of the engine when exiting the LPC. However, some, mostly large, particles counteract this general behaviour which is attributed to the stochastic secondary particle velocities resulting from the breakup process or to vortices in the flow field.

The same particle tracking state is displayed in fig. 8 for the HPC. Most of the particle breakup, induced by the higher rotational velocity of the HPC, compared to the LPC, can be seen in the first stages. The flow is dominated by small particles downstream of the IGVs. Almost no particles hit the suction side of the first blade, and this can be attributed to the strong vortex predicted at the inlet.
The separated outer flow region and the undisturbed inner flow channel at front HPC stages are recognizable in the particle tracks. Ordered particle tracks can be seen in the region of the undisturbed flow and the particle tracks tend to concentrate at the outer radius of the engine if these are downstream of the vortex region (i.e. behind stage 6). Before this position these tracks mainly concentrate at the outer radius of the undisturbed flow region.

The computational particle tracking results are compared to experimental data where possible and this is shown in fig. 9. The graph at the left-hand side shows cumulative probability trends for the particle size distributions at the injection position (LPC in), at the inlet of the HPC (HPC in) and at the outlet of the HPC (HPC out), and the right-hand side shows similar trends for the particle velocity distributions.
The experimental trends from the injection position and from the inlet position of the HPC are based on more than 100,000 particles each. Those from the outlet of the HPC consist of only approximately 550 because the quality of the recordings from the higher stage was not sufficient to visualize more of the very small and fast particles. The smallest particles considered have a diameter of approximately 40 \( \mu m \) and the derived particle size distribution at the inlet is used as boundary condition for the particle tracking.

Good overall agreement of the numerical and experimental distributions can be seen for all trends presented with the exception of the particle sizes at the inlet into the HPC. In the latter case the simulation predicts significantly more smaller particles compared to the experiment. The particle sizes at the outlet of the HPC are slightly underpredicted. The deviation of the particle size distributions at the inlet of the HPC can be attributed to factors related to the experimental measurement such as local aggregation of larger particles in the field of observation of the HSC and influences of the location of the experimental control volume close to the inner radius of the channel whereas the numerical data is taken from the whole channel.

The numerical velocity distributions in fig. 9, right, are in good agreement with the experimental trends. The experimental velocity data from the inlet position into the HPC appears to be bi-modal but this second mode is not predicted to the same extent. A probable cause for this difference could be cross-flowing particles (i.e. induced by collision with the first rotor) which are observed in the experimental trends. This effect may be underpredicted in the simulation due to the limited number of secondary particles considered. The velocities at the outlet of the HPC are slightly overpredicted.

A comparison of computed to experimental mean values reveals that the model predicts the actual behaviour with a reasonable accuracy for the desired defouling simulation. The average deviations of the variables considered range from 10 to 23%.

**Defouling erosion predictions**

In the final step of this work the PTFE defouling erosion predictions are discussed and, where possible, compared to experimental data. The upper display in fig. 10 shows the defouled areas on the blading after 10% of the Cyclean process time and the lower display the corresponding results after 100% of the process time. There are only suction sides of rotors and pressure sides of stators displayed but the results discussed below are valid for both types of

Figure 9: Defouling simulations - local comparison of numerical to experimental data, particle sizes (left) and particle velocity (right).
Figure 10: Numerical defouling results: LPC (left) and HPC (right), rotor ss, 10% process time (upper) and 100% process time (lower).

The pressure sides of the LPC are largely defouled after 10% of the cleaning process. However, there is a significant difference in the defouling of the suction sides between both times. Cleaning of suction sides, and particularly the fan suction side, is less effective.

The entire pressure sides of the LPC and a proportion of the suction sides are cleaned by the main particle flow, whereas total cleaning of suction sides is reliant on deflected particles. Prediction of this cleaning effect requires prediction of secondary particle tracks and particle breakup. The breakup process significantly increases the number of particles in the engine and changes the particle trajectories thereby increasing the probability of particles impacting suction sides. This flow of secondary particles is less effective in the cleaning process and, therefore, requires a longer time to achieve cleaning.

The more efficient (i.e. earlier) cleaning of the pressure sides can also be observed in the HPC simulations if the results are compared to these from the LPC. Cleaning of the suction sides is limited to particular patterns and approximately 40 to 60% of the surfaces. The cleaning pattern at the suction sides of the front stages, where the outer flow is separated, appears to be different from this at the blading of rear stages. No particle tracks are seen to impact the suction side of blade 1 because these particles are redirected by the strong flow separation predicted at this position. Hence, there is no defouling visible in the results at this surface.

Finally, the simulated defouling values are compared to experimental values, and these are shown in figs. 11 and 12. Figure 11 shows average trends for the experiment with the largest sample size comprising a total of 336 rotor blades and 1260 stator blades (i.e. thick colored trend lines) and three comparable experiments with the same parameters but lower sample sizes comprising a total of 70 rotor blades and 75 stator blades each.

The left-hand diagram in fig. 11 shows the trends for pressure sides of the rotor blading and the right-hand side those for suction sides. The experimental trends are clearly met by the
predictions. The cleaning prediction is good at the pressure sides up to stage 7. After this stage the numerical defouling prediction decreases significantly at stage 8 but this significant decrease can be found only in particular experimental data and it starts at rear stages such as 10 and 11.

Prediction of the suction side cleaning is good in the front part of the engine up to stage 9 and the numerical results show underprediction at rear stages. There is more scatter in the experimental results for the suction sides compared to the pressure sides, and there is one experimental dataset which deviates from the others over several stages. The underpredictive character of the numerical results at stages downstream of stage 7 can be attributed to significantly lower numbers of model particles in the simulation compared to the experiment.

The equivalent comparison is discussed for the stator blading in fig. 12. Only the large scale experiment is considered because the predictions are only valid for the mean particle path and it was clearly identifiable only with this experiment. The experimentally maximally cleaned
stator blades can be compared to corresponding data from the simulation. However, the mean experimental values of the stator cleaning (i.e. the overall result derived from all stator blades experimentally investigated) are also presented in the diagrams.

The maximum cleaning efficiency of the pressure sides is well predicted and the predicted decrease of the values shows reasonable agreement with the experimental data. The comparison of the suction sides in the right-hand diagram shows that the maximum value predictions are in good agreement with the experimental data at the rear stages of the HPC.

The defouling values predicted are in good agreement with experimental data. The main cleaning patterns as well as the overall trends of the cleaning process are predicted with a reasonable accuracy, with deviations in the range from 11 to 21%.

CONCLUSIONS

An application case study for simulations of the new dry-ice based 'Cylean' aircraft compressor cleaning system was presented including a brief description of new models for particle breakup and erosion. It was shown that it is possible to successfully predict the effectiveness of the actual dry-ice cleaning process with these models and simulation set-ups presented, even if several assumptions must be made to achieve an efficient procedure.

The numerical set-up consists of a stream-channel approximation of the engine using rotational periodicity and coarse meshing. Good agreement between the predicted and the experimental flow field was achieved and mean pressure and velocity values were predicted with accuracies in the range from 7 to 22% in average. All global velocity profiles were well predicted. Particle injection was simplified in the simulation and a method was presented to use measured particle injection properties in a modified boundary condition for steady state simulations. Comparison of measured and predicted particle tracks revealed a prediction accuracy ranging from 10% to 22% for particles sizes and velocities at particular positions. The global trends of the particle sizes and velocity distributions were satisfactory predicted by the simulations apart from the particle size distribution at the inlet into the HPC. The defouling simulations were compared to a range of defouling experiments in which artificial PTFE fouling was used. A global surface comparison of the defouled blading showed good agreement between the predictions and the experiment. Some regions with mismatches were encountered. Mean deviations between the defouling predictions and the experiments range from 11 to 21%.

Future work will encompass a parameter study of dry-ice based cleaning of various engine types and fouling materials. Extensive simulations and experiments of the test-engine are planned using original fouling. In addition it is planned to investigate a 90° symmetry volume of the test-engine in conjunction with the development of big-data methods to overcome memory limitations during the simulation and in the post-processing. This will facilitate the use of these larger models and efficient evaluation of their outputs.

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