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FRAP MEASUREMENTS IN A STABILITY ENHANCED HIGH PRESSURE COMPRESSOR

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Abstract

The investigation of the interaction between fluid injection and rotor passage flow of a high pressure compressor is presented. By using a fast response aerodynamic probe for unsteady flow measurements (here the FRAP-system of Limmat Scientific) physical data of the rotating blade passage flow can be revealed. This is especially important in the region where the mixing of the injection flow and the energy transfer occurs. The analysis unveils the complete rotor passage flow structure with and without injection.

Nomenclature

A, B	operating points
SL	surge line
NEWAC	New Aero Engine Core Concepts
FRAP	Fast Response Aerodyamic Probe of Limmat Scientific, Zurich

Introduction

Today's gas turbines require a high degree of flexibility in operability. For an aeroengine gas turbine the stability of the compressor is essential to support uninterrupted operation due to safety reasons. Stationary gas turbines have to adapt their work output according to changing requests, especially in the case where gas turbines operate simultaneously in a network with renewable power generators as wind turbines and solar cells.
Both scenarios require that the compressor has to maintain a stable operation at a high level of efficiency. Especially, at part speed this request is very challenging. The so-called surge margin which marks the margin of stable compressor operation to unstable operation is typically very narrow for front stages at part speed. The aerodynamicists have to provide a certain surge margin in order to enable a stable operation which can tolerate inlet distortions and rapid changes of compressor operation. Even more challenging, the increase in efficiency runs adverse to the available surge margin.

An attractive way to overcome the dilemma is the additional stabilization of the most critical stage which initiates the compressor surge. Common methods are casing treatments or injection of air into the tip region of a rotor.

Since casing treatments are usually a geometrically fixed modification, their influence on the main gas path is always perceivable. The fluidic injection, in contrast, can be linked to an engine control system which provides the flexibility to enable it whenever necessary.

In this paper the investigation of the interaction of tip injection with the compressor rotor passage flow, that was done within the European project NEWAC, is presented. The above mentioned Fast Response Aerodynamic Probe (FRAP) of Limmat Scientific was used to perform unsteady flow measurements which allows to investigate physical data within the rotating blade passage flow of the rotor where the mixing of the injection flow and the energy transfer occurs.

Test configuration

The tests were carried out on an eight-stage HPC with three variable guide vanes. The airfoils represent the latest standard of 3D blade aerodynamics. It includes rotor sweep at the front stages and blade bow for the middle vanes. The first rotor's profile was adapted to tip injection in order to reduce the hazard of rotating stall. To allow an increased operating range at part speed, the stator blading was improved to reduce the occurrence of corner stalls.
The rig was tested at MTU's compressor rig test facility which is illustrated schematically in Fig. 1. Upstream of the compressor rig a series of noise attenuators, an inlet throttle and a settling chamber were installed. The inlet throttle reduced the inlet pressure to allow a variation in Reynolds number. A swan neck duct between the settling chamber and the compressor, in combination with radial distortion screens, generated an inlet pressure profile representative for an engine environment. A diffuser followed by a plenum representing a typical combustion chamber volume was placed downstream of the last stage in order to maintain typical overall surge dynamics.

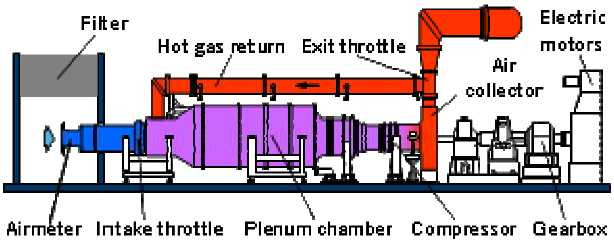

Fig. 1 MTU's compressor rig test facility

The compressor rig was equipped with a surge detection system including surge overpressure valves and a fast response exit throttle.

Tip Injection Configuration

The highly-loaded front stage was equipped with injection nozzles in order to enable investigations of fluid injection on a single stage in a multi-stage environment. Twelve injection nozzles were placed upstream of the rotor's leading edge, mounted equally spaced around the compressor casing. Fig. 2 shows the experimental setup of the injection system. The flow path geometry between the six connection ports and the twelve injection nozzles was designed to ensure a separation-free channel with a Coanda-like entrance into the annulus. The shape of the nozzles did not penetrate into the main gas path, i.e. the annulus flow was completely undisturbed by the nozzles. Comparative measurements with a smooth wall configuration confirmed the equivalence of the compressor performance for both configurations.

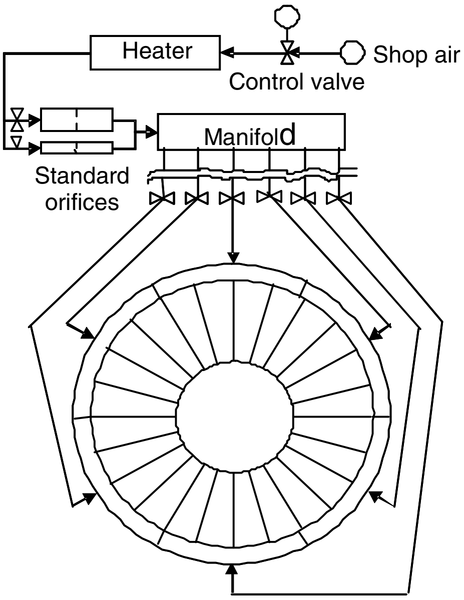

Fig. 2 Scheme of the injection set-up

The nozzles produced high speed jets directed towards the leading edge of the front stage rotor tips. The injection system was fed by an external air supply which delivered the required mass flow at constant pressure. An electrical heater provided the possibility to condition the injection air temperature. But in the case of the FRAP measurements, the heater was switched off and the injection temperature was ambient.

Instrumentation

The test rig was extensively instrumented. Among others, inlet and exit flow conditions were measured by pressure and temperature probes as well as the mass flows (core, injection) by calibrated orifices. For the determination of the stage characteristics, all vane rows were equipped with leading edge instrumentation in combination with static pressure measurements downstream the vanes.

The injection mass flow rate was measured using two orifices calibrated for different injection mass flow levels. The air temperature was measured inside the manifold. Additionally, pressure sensors were located at each connection port to verify the uniformity of the injection mass flow through each of the six feeding ports. Furthermore, two injection nozzles were instrumented with total and static pressure probes to measure the aerodynamic condition of the injected flow. Data acquisition was performed by an online monitoring and analysis system. The software collected all test bed data. It performed rig monitoring and full thermodynamic analysis of the compressor, too.

FRAP measurement system

The FRAP measurement system is produced by Limmat Scientific AG, Zurich Switzerland. The Fast Response Aerodynamic Probe measures unsteady flow parameters like pitch and yaw angle, static and dynamic pressure and Mach number. Therefore, the probe head contains two miniature silicon pressure sensors which are placed directly behind two pressure intakes located on angled faces (see Fig. 3).

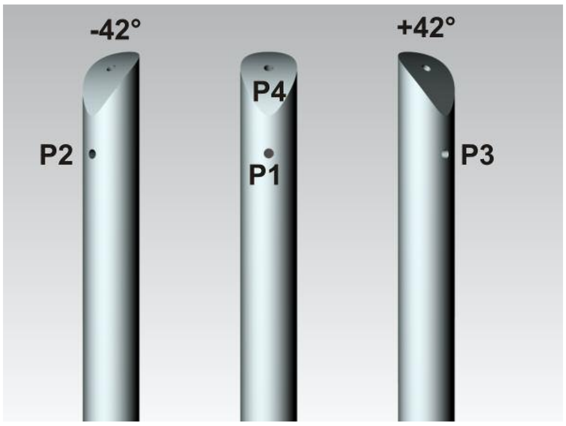

Fig 3 Orientations of the FRAP-probe with respective pressure measurement positions

These two positions give the pressure values P1 and P4, while rotating the probe along its axis by ±42° gives P2 and P3, measured with the same sensor already used for P1 (see Fig. 3). By referring to a static and an aerodynamic calibration, the above mentioned set of flow parameters can be derived.
The static and aerodynamic calibration is done at the free jet facility of the ETH Zurich, covering yaw angles of ±28°, pitch angles of ±20°, and Mach numbers up to 0.8 in 5 discrete steps.

Since the FRAP-probe uses differential pressure sensors, the inside pressure of the probe has to be carefully controlled. The static pressure in the test rig was well below atmosphere, therefore a vacuum pump had to be attached to the probe pressure control system.

In order to get a spatial distribution, the probe had to be traversed radially and circumferentially. The radial traversing was done by the traversing system delivered by Limmat Scientific, while the circumferential movement was performed by using MTU-equipment. In order to save measurement time and minimize human interaction, the FRAP-control-software has been altered. To achieve fully automated measurements, a modbus interface to the MTU test bed has been implemented, which also significantly reduced measurement time. Additionally, real-time monitoring of the mean values of total and static pressure as well as both flow angles has been implemented.

The measurement procedure for one field traverse is as follows: In order to compensate offset- and gain-drifts of the pressure sensors, the probe tip is retracted out of the flow into an area with known static pressure and one dataset is recorded. After that, the probe is positioned at the first grid point close to the casing and the pressures are measured as described above. This step is repeated for all predefined radial positions. At the end of one radial traverse, the offset- and gain-correction is performed again. This procedure is repeated for each circumferential position.

Aerodynamic effect of tip injection on compressor performance

The general purpose of fluid injection is the extension of the operating range of a compressor. A larger operating range is beneficial in terms of compressor’s resistance against inlet flow disturbances, faster acceleration without jeopardy of a compressor surge and, finally, it promises an additional efficiency benefit by raising the compressor working line. Details are described in [4] and [6].

Influence of tip injection on the stage performance

Tip injection directly affects the tip flow and the relevant loss mechanism inside the rotating blade passage. Consequently, the energy transfer from blade to fluid and the operability of the stage are affected as well.
A series of compressor tests unveiled the stage related effects of tip injection as well as the interaction of the affected stage with the adjacent stages within the multistage compressor environment. Since HPC stability at part speed is of major interest, the measured data presented in this paper focus on a relative aerodynamic speed of 90%.

Fig. 4 shows the stage characteristics of the front stage during a standard throttling test cycle from choked condition till compressor surge. The diagram shows stage pressure ratio vs. compressor core mass flow entering the front stage.

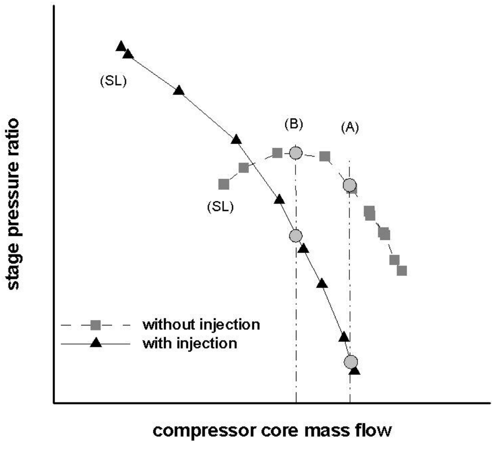

Fig. 4 Stage characteristics of the front stage

Without injection, the stage operated on its stable branch of the characteristics until the stage reached the peak of its characteristics. Once the peak was reached local flow disturbances at the blade tip appeared which yielded to large stall cells while throttling further. The stage operated then on its unstable characteristics with a positive gradient. However, the disturbances generated by the stage were damped by the whole compressor till the last stable working point was reached and the complete compression system fell into a surge cycle.

In contrast, tip injection influenced the one-dimensional stage characteristics in a way that the disturbances and losses at the rotor blade were not generated so that the slope of the stage characteristics was always negative and the stage operated always stable while throttling. The process continued until a different stage within the multistage compressor reached its stability limit and the compression system fell into a surge cycle again. However, in this case the initiation of the surge cycle was not caused by the front stage since it was stabilized by the tip injection.

Analysis of the front stage performance

Three important reference operating conditions are marked in Fig. 4. Point (A) and (B) were selected in a way to get valid measurable operating points at equal core mass flows for both the stage with and without injection. The last points ((SL)-surge line) at the curves mark the last stable measured operating point before the compressor surged.

The significant change in the shape of the stage characteristics was caused by a considerable change in rotor passage flow which can be visualized by the leading edge instrumentation of the vane downstream.

Fig. 5 shows the radial total pressure distribution of the afore mentioned operating points (A), (B) and (SL).

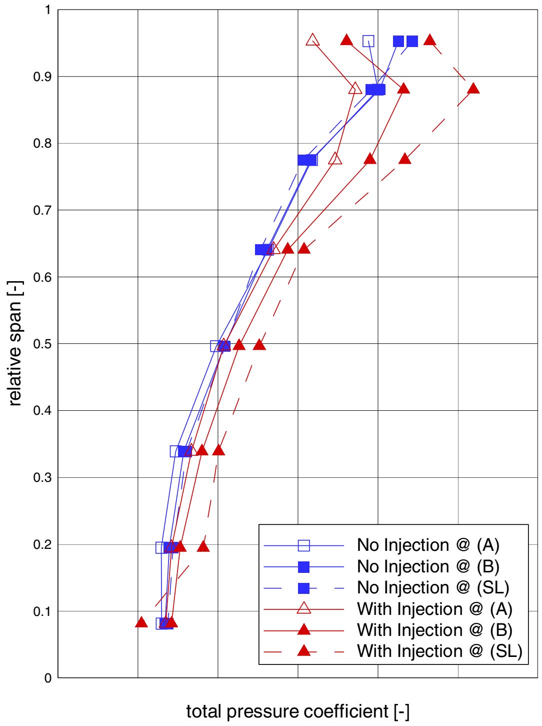

Fig. 5 Radial total pressure profile at vane leading edge downstream the front stage rotor

The stage without injection shows only little changes during throttling which is not surprising since the variation in pressure ratio (compare Fig. 4) is small.

In contrast to that, the configuration with injection shows a considerable total pressure rise at 80% blade height and above. This pressure rise was the result of the interaction of the blade tip flow with the injection jet within the rotor passage and was the reason for the changed stage characteristics including the significant improvements of stage stability.

Measurement techniques for the rotor passage flow

The previous paragraph described the observations made in the rig's fixed frame of reference by analyzing the downstream vane's leading edge instrumentation. These data do not unveil the processes which occurred inside the moving rotor passage. The application of the FRAP probe makes the indirect measurement of physical values in the rotor's frame of reference possible.

During the first measurement with FRAP, the real time check showed that one of the sensors was lost. However, it was decided to continue the measurement campaign after a short re-configuration of the analysis software. Due to the malfunction of the single sensor, the radial flow angle could not be measured. Previous measurements performed with a 5-hole probe confirmed that the (averaged) radial flow angle in the most interesting flow region was small compared to the peripheral flow angle. So the drawbacks of the FRAP probe operating only in a virtual 3-hole mode were not severe.

Measurement procedure

The compressor was thermally stabilized at the operating points shown in Fig. 4. The probe was positioned successively at 21 radial measurement points. The orientation of the FRAP probe was chosen in a way that the main flow direction was opposite to the P1 measurement orientation (see Fig. 3).

The FRAP probe recorded the unsteady pressure signal with a sampling rate of 200 kHz. In order to generate a 1/rev signal for synchronization purposes, the compressor was equipped with a shortened blade.

The recorded pressure signals were used to calculate the (absolute) total and static pressure, the flow angle and Mach number by applying the probe calibration. These data were ensemble averaged with a window width of one revolution. The data within the rotating rotor frame (relative data) were derived from these data in combination with the rotational speed.

Rotor's flow field

The following graphs allow a detailed comparison of the rotor flow field at various operating conditions and show the situation directly downstream the rotor exit plane. The view is aft looking forward and the turning direction of the rotor is counter-clockwise in the pictures. Although the color scale of the graphs is not given numerically, the ranges are equal and thus allow a direct comparison.

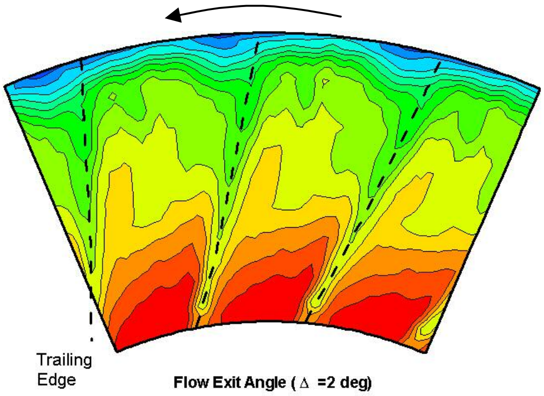

Fig. 6 Absolute flow exit angle at point (A) without injection

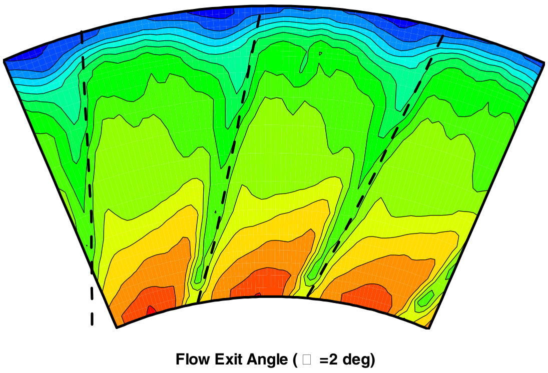

Fig. 7 Absolute flow exit angle at point (SL) without injection

Fig. 6 and 7 display the absolute flow exit angle which changes across the rotor passage under the influence of tip clearance flow.

While throttling from a de-throttled operating point (Fig. 4, case (A)) towards stall, the absolute flow exit angle decreases (Fig. 7). (Remark: A flow exit angle of 90 deg represents axial flow direction while 0 deg is in blade revolution direction, respectively).

After activating the tip injection, the tip clearance leakage was suppressed significantly and the outermost passage flow was dominated by a flow which mainly followed the passage (Fig. 8).

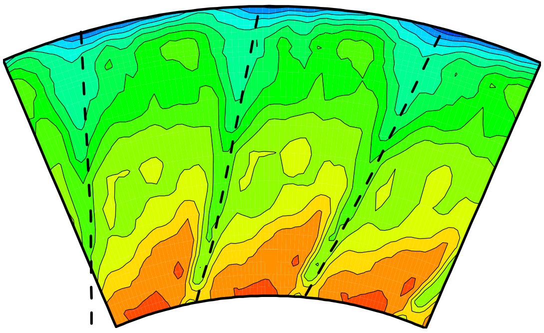

Fig. 8 Absolute flow exit angle at point (SL) with injection

As a result of the increased axial flow component, the flow at the casing was turned back towards axial direction.

Rotor tip clearance flow

The significant modification of the tip gap leakage flow due to injection can be observed in the following two graphs.

Fig. 9 shows the ensemble averaged static pressure at the peak of the stage characteristics (Fig. 4, case (B)). Under this condition the tip flow was dominated by significant flow separations resulting in strong fluctuations.

These separations were generated at the suction side of the rotor blade near the leading edge due to the higher incidence angles at the throttled operation. Low energy fluid cells were transported by the tip vortex towards the pressure side of the neighbor blade. Due to their low velocity they capture the static pressure of the rotating system. The large peripheral extension or blur is the expression of the strength of the tip vortex fluctuation. The vortex fluctuation is rather chaotic in peripheral direction. Additionally, any fluctuation along the rotor blade was visible as a phase shift in the recorded pressure signal.

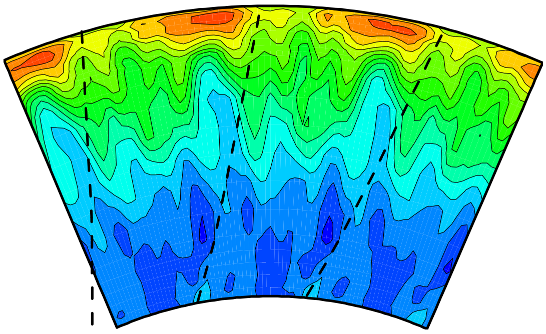

Fig. 9 Static pressure at the operating point (SL) without injection

The significant amount of fluctuations can be seen by visualizing the ensemble averaged signal of all rotations compared with the pressure signal of randomly selected revolutions inside the measurement time window at 95% blade height (Fig. 10).

It should be noted that the dominating part of the three-dimensional flow contained more randomness than regular structures at throttled conditions. However, the repeatability of the ensemble averaged pressure field between the blade passages was excellent.

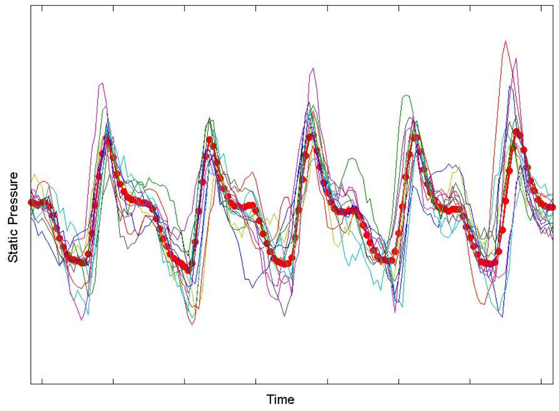

Fig. 10 Ensemble averaged (dotted) and randomly selected pressure signal

Applying tip injection, the flow field structure was changed significantly. Most obvious is the additional high pressure region at the suction side of the rotor blade (Fig. 11). Concurrently, the peripheral extension of the high pressure region at the pressure side of the blade was reduced considerably. This indicates that the blade tip section was unloaded, especially at the rear part of the blade. Consequently, the respective tip leakage and losses were reduced, too.

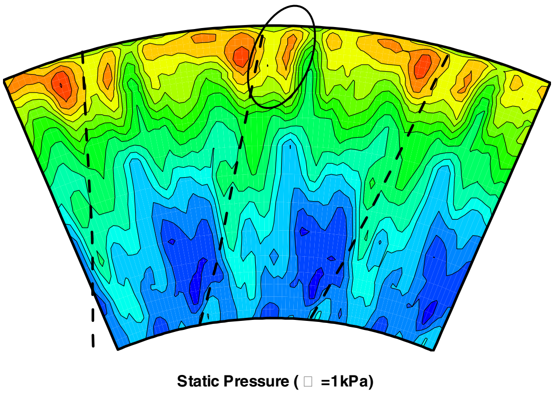

Fig. 11 Static pressure at the operating point (SL) with injection

The blade tip flow close to the casing was re-structured and re-directed similar to the common passage flow (compare Fig. 7 and 8). No amplification of the tip clearance vortex could be observed. Therefore, the outer blade sections transfer more energy with injection than without (compare Fig. 5).

A confirmation of the improved flow structure within the rotor passage can also be found by comparing the relative flow velocity. Without injection the relative velocity level is quite low (Fig. 12).

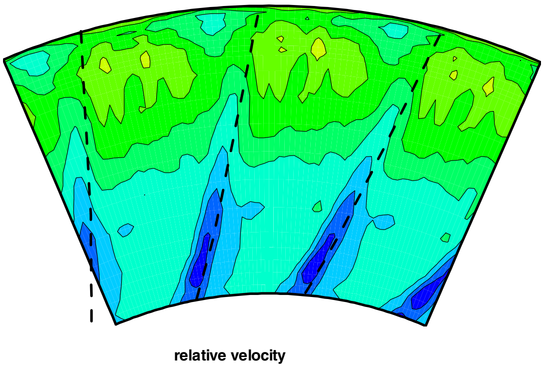

Fig. 12 Relative velocity in the rotor passage without injection

With injection activated (Fig. 13) the relative velocity reached a level comparable to the dethrottled state (not shown here).

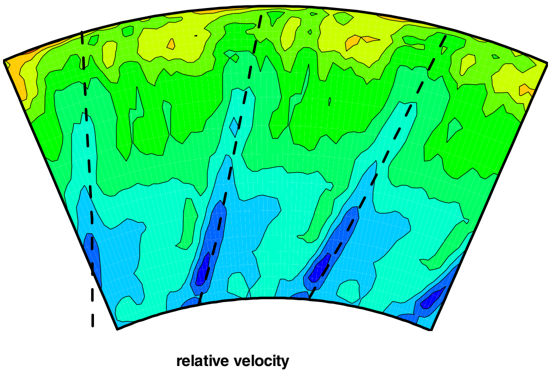

Fig. 13 Relative velocity in the rotor passage with injection

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The comparison of both graphs displays clearly a significant reduction of the de Haller criterion at the outer blade sections. The inner part of the blade is fairly unchanged (see also Fig. 5).

Conclusions

1. Tip injection is an attractive method to improve the rotor passage flow. It changes the stage characteristics and improves the stage stability significantly.
2. The tip injection restructures the blade-to-blade flow, especially under highly throttled conditions.
3. The outermost blade sections were unloaded and, consequently, the de Haller criterion of the rotor passage is decreased significantly.
4. The blade exit flow angle for throttled operating points was changed and reached values comparable to working line conditions.
5. The effect of tip injection is noticeable at the outer rotor blade sections mainly. The inner core is less affected.

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