Analysis and Optimization of Partial Admission Stages

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INTRODUCTION

This article represents the results of a numerical study of a two stage compartment of a 10 MW industrial turbine for a compressor drive. The turbine was originally designed as a single cylinder reaction machine with partial admission control stage.

The general objective of the study is to investigate the potential for turbine efficiency improvement for a turbine’s future upgrade and in this article we are focusing on the partial admission control stage redesign and downstream stage performance improvement options.

To be more specific:
- for control stage redesign options, we are considering efficiency improvements by applying an algorithm of optimization for the main stage parameters, strongly influencing stage performance, like level of partiality, blade height and angles. The calculation study was performed with 1D and 2D design algorithms, integrated into the Preliminary Design module of the AxSTREAM™ design suite
- for downstream located stages, to mitigate the negative effects of partial admission, the application of multiple admission arcs with uniform circumferential distribution, has been studied. Considering complex effects of partial admission on flow structure and parameters distribution, the study was done with 3D CFD simulation of a two stages compartment with mixing a chamber between the first and second stages.

3D CFD results have also been used to verify and correct tip leakage loss models for the partial admission stage, which is routinely used in 1D and 2D codes for performance calculation.

PARTIAL ADMISSION STAGE OPTIMIZATION

The analysis of the partial admission was performed on the first two stages of a high-speed mechanical drive reaction steam turbine with the live steam pressure of 42 bar (609.2 psi) and enthalpy of 3279.7 kJ/kg (1410 btu/lbm).

The first stage of this turbine (the control stage) has partial admission of 50% and the second one -the full admission arc. Due to the fact that non-axisymmetric flow, which comes out from the first stage, doesn’t dissipate instantly, the second stage, in spite of being full admission, also suffers from the partial admission. Not to such an extent as the first one, though. A special chamber (plenum) is present after the first stage to reduce the partial admission influence.
The crown minimum passage area (3D throat) is formed by aerofoil height and throat area (gauging angle), and is one of the fundamental parameters that influence the flow in turbines. Thus, proper consideration of this parameter has to be performed during the design or redesign. For turbines with the relatively small volume flow rate at the inlet, the crown minimum passage area may require blade heights and gauging angles that are too small from a manufacturing point of view.

For the core parameters influence study, the Preliminary Design module uses the Meanline Inverse Task solver that studies the numerical combinations of design parameters within a small period of time.

### Analysis approach

Preliminary design is a procedure of flow path geometry obtained using a predefined set of boundary conditions and design variable ranges. For purposes of machine geometry generation and evaluation in preliminary design, the inverse task was selected because of the possibility to quickly review a number of designs, without certain defined geometry, that matches the selected criteria. A uniform approach can be applied to all types of turbomachines, but different design parameter combinations should be used for each particular one. The sequence of the preliminary design steps is next:

1. Combination of design parameters for selected machine type
2. Variation of design parameters in selected ranges
3. Geometry generation from selected set of parameters and constraints verification
4. Inverse task calculation
5. Selection of best design based on selected criteria

As it is stated above, the meanline inverse task was selected as the most satisfactory for rapid and flexible preliminary design generation. Depending on the machine type, the selection of combined design variables is different, and for axial machines it can be described by this data:
- Number of stages
- Specific diameter (hub, mean, tip)
- Geometry constraints (blade height, gauging angle, diameter/blade height ratio)
- Velocity ratio or work coefficient
- Axial velocity ratio distribution between stages
- Additional constraints on flow path diameters and axial sizes, which can be applied to restrict search to more specific ranges

Design generation should be performed based on some initial set of parameters. A set of multiple design variables should be studied and all possible design combinations considered, so different approaches could be used for this operation to cover the whole range. The proposed method is the LPτ search, that generates quasi-random sequences. These are uniformly distributed sets of L=M\(^N\) points in N-dimensional unit cube I\(^N\). The advantage of the algorithm selected is that unlike pseudo-random sequences, quasi-random sequences provide uniform distribution in spaces. This also makes it possible to increase the search points density by setting additional parameters.

From the selected set of parameters, geometry is generated and evaluated in the inverse task solver. Additional parameters, such as clearances, chords, and number of blades are selected based on the prescription given for the specific machine type and sizing ranges, as specified above.

A general theoretical overview of the presented approach methodology for an axial turbine and compressor is given in [5].

The essence of the inverse task calculation is solving an equation set to find unknown angles θ1 and θ2, when velocity coefficients \(\phi\) and \(\psi\) (i.e. losses) are supposed to be predefined based on some known correlations or prescribed efficiency charts (such as Spencer-Cotton, Smith, and Baines diagrams). The task of determining \(\xi_1\) and \(\xi_2\) angles is to find the maximum search criterion as a function from set of design variables:

\[
\text{max } \eta_i(\bar{a})
\]  

To improve the design selection flexibility, the best possible solution can be chosen based on predefined search criteria such as: internal or polytropic efficiency maximum and maximal power. The process chain described below is representing a machine synthesis procedure.

![Fig. 2. Design procedure scheme](image)

The Craig&Cox loss model [1] was used as a primary (profile) loss model and the Stepanov loss model, [2] as a secondary one. The combination of these two models proved the agreement with...
the experimental data and performance tests for various turbine types [3]. The partial admission losses are considered as a sum of windage (pumping, ventilation) losses and sector end losses. The windage loss refers to the effect of pumping in the inactive blade channels rotating in a steam filled casing. The sector end loss originated from the filling and emptying of the passages as the blades pass through the active sector. Stodola [5], Traupel [6, 7] and Roelke [8] independently found the windage power loss to be proportional to the cube of blade speed.

The equation (1) represents windage loss:

\[
X_{\text{wind}} = \frac{k_w}{\sin \alpha_{\text{gauge}}} \frac{(1 - e)}{e} \left( \frac{U}{C_0} \right)^3
\]

And equation (2) -sector end loss:

\[
X_{\text{segm}} = 0.25 \frac{b_{\text{segm}}}{b_{\text{bl}} \left( \frac{U}{C_0} \right)} \eta_{\text{segm}}
\]

The application of the approach mentioned above allowed the generation of thousands of designs within a short period of time, thus making it convenient to analyze the influence of gauging angle, blade height and partial admission on performance. For the studied case, all three parameters were changed simultaneously so that it was possible to find the best combination. Each point on the charts below represents a different design with its own combination of geometrical parameters.

**Nozzle height influence**

As it was mentioned before, the nozzle height value has its minimum that is defined by not only manufacturing complexities but also the fact that for very short blade the endwall regions with relatively high secondary losses will occupy almost the whole channel.

For the current design, the optimal nozzle height is around 14 mm, which is far from the original design (17.75 mm).

**Gauging angle influence**

The gauging angle defines how greatly the flow is swirled in the tangential direction. Thus, if it is too small of a gauging angle, the centrifugal force that appears due to its rotation (radial equilibrium) can force the flow to separate at some point.

From the picture below, it’s obvious that the decrease of the gauging angle for the current case from 20 deg to 14 deg almost has no influence on the efficiency. Now, efficiency starts to decrease due to the reasons mentioned before.

**Partial admission influence**

Partial admission can cope with a small flow rate, though it decreases the performance because of additional losses present. In particular

The partial admission for the particular combination of boundary conditions has an optimum at around 0.4-0.5, which is fairly close to the original variant and does not need to be corrected.

**Recommended upgrade:**
Blade height change from current 17.75 mm to 14 mm, which gives two stages efficiency improvement Delta Eff. = 0.4%, which resulted into 7 kW power gain.

**VERIFIYING CALCULATION**

Among many different types of losses in turbine stages, the leakages provide the most significant effect on performance, especially
in small turbines with short blades. The traditional approach for leakage losses calculation \([5, 6]\) does not take into account the effect of complex 3D flow structure in the partial admission stages, which leads to leakage losses over estimation with meanline and streamline design algorithms. This was observed several times by authors in their design experience by comparing calculations and test data for partial admission stages. Tip leakages loss model verification and correction was performed based on the two stages compartment CFD study.

### 3D CFD model

The 3D CFD model represents a detailed simulation of the two stages compartments with a mixing chamber between them in a "goose neck-like" shape, disk cavities and sealing above blades, shroud and under the diaphragms.

![Two stages CFD model views with 50% admission first stage](image1)

Fig. 6. Two stages CFD model views with 50% admission first stage.

Total CFD mesh size has over 20 million elements with high quality nozzles and blades passages meshing (over 50k elements per passage) with boundary layers. Examples of meshes for blade passage, tip, shroud and diaphragm seals are presented at Figures 7 and 8.

![Mesh examples for nozzle and blade passages](image2)

Fig. 7. Mesh examples for nozzle and blade passages

![Mesh examples for tip shroud and diaphragm seals](image3)

Fig. 8. Mesh examples for tip shroud and diaphragm seals

### 2D tip leakage model correction

In the 2D approach, the value of leakages is calculated with:

\[
\Delta G = \mu F \frac{P_0}{V_0} \sqrt{\frac{1 - e^2}{z}}
\]  

(3)

Table 2 below represents the leakages comparison for CFD data and the 2D aero design algorithm for the uncorrected tip leakages formula.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CFD</th>
<th>2D</th>
<th>(\Delta, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st rotor tip leakage, %</td>
<td>5.1</td>
<td>7.8</td>
<td>2.7</td>
</tr>
<tr>
<td>2nd nozzle gland leakage, %</td>
<td>4.8</td>
<td>6.1</td>
<td>1.3</td>
</tr>
<tr>
<td>2nd rotor tip leakage, %</td>
<td>4.0</td>
<td>4.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Some discrepancies were observed between the values of relative leakages (leakage/inlet MFR) calculated with 2D and CFD approaches. The biggest difference was for the first stage rotor tip leakage. This was caused by the fact that there is no pressure difference at the inactive part of the arc; consequently there are no significant leakages. At some locations, the flow even goes in the reverse direction. But the leakage calculation approach used in 2D supposes that the leakage takes place over the whole circumference, thus it overestimates the rotor tip leakages and the error is the more the less is partial admission. Another aspect attributed to leakages calculation is related to pressure reduction at the arcs ends, which also leads to leakages overestimation.

Both of these factors were considered with the correction coefficient \(k = f(e, N_{segs})\), which was determined as a correlation function of two parameters – partial admission ratio and number of segments.

\[
\Delta G = k \mu F \frac{P_0}{V_0} \sqrt{\frac{1 - e^2}{z}}
\]  

(4)

Such corrections resulted in a leakage value decrease to 3.9%, ipso facto decreasing the discrepancy between CFD and 2D calculations from 2.7% to -1.2% for first partial stage.

### EFFECT OF ADMISSION ARCS POSITIONING ON DOWNSTREAM STAGE PERFORMANCE

There are two main aspects about partial admission stages related to turbine aerodynamics, which need to be accounted for during turbine design.

Firstly, in the partial admission stages, additional aerodynamic losses are generated - windage and sector end losses. These losses can be easily accounted for in the design process by using the above mentioned equations (1) and (2). Secondly, in multistage turbines the first partial admission stage generates substantial circumferential non-uniformity and downstream stages experience circumferential pressure gradients and flow angle variations that produce additional losses in the downstream located stages. There is no proposed simple approach/method to evaluate this type of loss so far in the open sources, besides experimental study and 3D CFD analysis.

The effect of circumferential flow non uniformity and pressure gradients were experimentally investigated by Lewis [9] in a 4 stages test turbine – see picture below.
According to Lewis, the results of the circumferential flow deformation were rapidly weakening downstream-wise with the two front stages operating significantly off-design and the two rear stages were less affected. Lewis concludes that the effect of partial admission on the downstream stages can be significant and much of it depends on partiality and the mixing capacity of chambers between the first and downstream stages.

Another conclusion was that the use of several admission arcs is a preferable option, comparing to a single arc of admission for a multistage turbine. The same conclusion was also confirmed in some other studies for partial admission stages. The efficiency improvement of the overall performance for multistage turbines by using an increased number of admission arcs at a given admission rate was observed in CFD analyses by He, L., [10] and Hushmandi, B.N. [11] and confirmed in a test by Jens Fridh [12]. Multiple admission arcs with uniform circumferential location enhance the tangential mixing further downstream and thereby facilitate an improved performance of downstream stages, although the performance of the first partial stage evidently decreases. The results from Jens Fridh’s [12] Doctoral Thesis are shown at Figure 7 for experimental turbine set up and second stage penalty loss, where the efficiency decrease is less from one to two admission arcs, for the two-stage turbine at 52.4% admission, than for the single stage turbine.

The effect in 6-7% for the second stage efficiency improvement was observed, which resulted from two admission arcs instead of a single one [12]. To evaluate the effect of the multiple arcs option for the turbine modernization project, the 3D CFD analysis was done based on the above mentioned CFD model. The variants studied included admission sectors varying from one to five uniformly distributed in circumferential direction -Figure 8.
Figure 14. Total Pressure distribution at second stage inlet for single sector and five sectors variants

Figure 15 demonstrates a multi-sector variant advantage compared to a single sector by producing more power, which could be observed from the power per channel distribution chart below.

The two stages compartment performance variation with different numbers of segments was determined for all variants in comparison with a single sector case. The first stage performance was determined by a 2D algorithm and the second stage performance was determined based on 3D CFD results. The summary table is shown below.

In spite of the first stage performance drop, the second stage demonstrated better performance for the multiple sector arrangement. In total, the two stages power increased by 43.4 kW for the 5 sectors variant.

Table. 3 Performance summary for different number of segments

<table>
<thead>
<tr>
<th>Number of segments</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔN stg1, kW</td>
<td>0</td>
<td>-5.14</td>
<td>-15.18</td>
<td>-20.24</td>
</tr>
<tr>
<td>Δηtt stg1, %</td>
<td>0</td>
<td>-0.46</td>
<td>-1.39</td>
<td>-1.86</td>
</tr>
<tr>
<td>ΔN stg2, kW</td>
<td>0</td>
<td>20.1</td>
<td>50.4</td>
<td>63.6</td>
</tr>
<tr>
<td>Δηtt stg2, %</td>
<td>0</td>
<td>1.66</td>
<td>4.15</td>
<td>5.11</td>
</tr>
<tr>
<td>ΔNstg1 + ΔNstg2, kW</td>
<td>0</td>
<td>14.96</td>
<td>35.22</td>
<td>43.36</td>
</tr>
</tbody>
</table>

CONCLUSION
The calculation study was undertaken for a two stages compartment with a partial admission control stage for a 10 MW industrial turbine with the purpose to identify potential options for a future turbine upgrade.

For the first partial admission control stage the proposed upgrade option was to change the blade height from its original 17.75 mm to a new 14 mm, which resulted in an additional 7 kW power for a two stages compartment.

For the second stage, the multiple admission sectors arrangement was studied with 3D CFD. A five sectors variant resulted in 43.36 kW of additional power.

The final decision of both considered options should be done based on a cost versus performance trade-off analysis.

Additional results included the 2D design algorithm extension with regards to more accurate tip leakage calculation for partial admission stages.

A detailed 3D CFD model developed for a turbine upgrade project and analysis of CFD results offer more possibilities to investigate such a complex flow behaviour for partial admission stages. It was done and presented in the course of this work. Authors will continue to study and reveal the numerous aspects of the partial admission turbines related to aerodynamics and blades forcing analysis in their future publications.

BIBLIOGRAPHIC REFERENCES


