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Analyses of Temperature Distribution on Steam Turbine Last Stage Low Pressure Buckets at Low Flow Operations

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ABSTRACT

Steam turbine power plant operations during start up and during operation at high exhaust pressure have the potential to result in an extremely low steam flow through the Low Pressure (LP) turbine. This inevitably leads to windage and results in significant temperature increases in the Last Stage Buckets (LSBs). High steam temperature can also initiate potential thermo-mechanical failure of the LSBs. Temperature prediction for a wide range of operational regimes imposes a significant challenge to modern LSB design. Extensive numerical and experimental investigations on an LP section steam turbine with LSBs of different lengths at typical low flow operation conditions have been conducted with the primary focus on LSB temperature prediction. A Low Pressure Development Turbine (LPDT) test rig was used to help develop and validate Computational Fluid Dynamic (CFD) based temperature prediction methodologies, which later were applied to predict operational temperatures for multiple LP section configurations under development. This article presents some important results of LPDT test measurements as well as CFD predictions of LP turbine flow structures and temperature distributions in last stage buckets.

Keywords: low pressure steam turbine, last stage bucket, low Flow operation, windage, high temperature

NOMENCLATURE

L-0	Last LP stage
G	mass flow rate
GV	volumetric flow rate
nom	operational (nominal) point
ref	reference point
GV_{nom}	design point volumetric flow rate
$\overline{G}\,\overline{V} = \dfrac{GV}{GV_{nom}}$	relative volumetric flow rate
W	windage power (kW)
y+	dimensionless wall distance

INTRODUCTION

One of the most challenging problems steam LSB designers face during the design process is long term reliability of the LSBs at low load operation, which takes place during start up, shut down and also at high exhaust pressure conditions.

Low load operation is characterized by low flow rate through the LP turbine end. The relative volumetric flow $\overline{G}\,\overline{V}$ is the criterion defining the change in the LP section flow regime and steam flow structure around the last stages of the LP section.

The flow structure in the last stages at low flow operation essentially differs from those seen at a nominal (design) operating mode and is characterized by the occurrence of windage and a temperature increase at the turbine end, considerable backflow zones in the exhaust diffuser, flow separation and recirculation in the last stages, and flow instability. All these effects are the result of the last stages of the LP section operating in a compressor mode, when steam flow trapped by the LSB moves radially to the periphery and obtains high velocity at the bucket tip exit. Steam in this location receives a considerable amount of kinetic energy from the rotor, which is transformed to thermal energy and results in a significant temperature rise. Lagun *et al*. [1] for the first time investigated this effect of compressor mode operation at the last stage of a steam turbine. Later other researchers were engaged in studying this phenomenon by both experimental and numerical methods [2,3,4,5]. In [2] the phenomenon of low flow operation has been investigated numerically and experimentally on a 3-stage model turbine, demonstrating good agreement between test and numerical data and showing capability to predict the basic flow characteristics by means of 3D CFD analysis with reasonable accuracy. The majority of referenced publications concentrate on a general physics of this process: flow structure deformation and transition from power production to power consuming operation mode (windage). Most of the previous studies also described significant temperature rise at the LSB and downstream in the exhaust diffuser.

In our work extensive numerical and experimental investigations on LP section steam turbines at typical low flow operating conditions have been conducted, with a focus on LSB temperature prediction. This publication contains two parts.

The first part represents the results of an experimental and numerical investigation of a model steam turbine with a primary focus of developing the 3D CFD methodology for numerical prediction of the LSB temperature distribution at low flow operation. The object of investigation was a 4-stage model steampath with subscale last stage buckets (design A), tested in the LPDT test rig, which incorporated a steel LSB with a cover and mid span connection. Some information of the LSB (design A) is presented in Table 1 and can be found in [6,7].

The CFD calculations are based on the model turbine steampath geometry, with some simplifications of the last stage bucket shroud geometry.

Table 1 Operating points

L-0 main features		Test Model	Design A
Scale		0.331	1.000
Speed	rpm	9063	3000
L-0 Bucket Height	m	0.404	1.219
Inner Ring Diameter	m	0.622	1.880
Annulus area	m^2	1.302	11.869

Measurements of steam pressure and temperature were made in various sections of the LPDT steampath, including rakes at the stage interfaces and stationary sidewall locations. In addition, LSB airfoil surface metal temperatures were measured using thermocouples mounted on the airfoils. The thermocouple measurements at LSB tip and root sections have been compared with computational predictions, obtained with a coupled Thermal-CFD solution.

The second part of this publication shows results of the numerical analysis of a temperature condition for a newly designed last stage bucket (design B) at low flow operation.

The 3D CFD methodologies are also discussed. Attention is paid to a detailed analysis of:

- Flow structure transformation at low load operation to understand development of exhaust diffuser backflows, tip and root recirculation zones into last stage;
- Power output to understand the start point of compressor mode (windage) operation;
- Last stage steam and LSB metal temperature distribution in a wide range of low flow regimes.

In the second part of the work, the temperature analysis has been performed in the frame of a coupled Thermal-CFD approach, with solid (metal) LSB and rotor domains included in the CFD model.

1. EXPERIMENTAL DATA AND CFD MODEL VERIFICATION

1.1 MODEL TURBINE

The experimental investigation of the LSB (design A) in a 4-stage LP steampath was performed in the LPDT test facility (Figure 1). A steam boiler provides superheated steam to the LPDT through a conversion valve that controls both the steam pressure and temperature at the turbine inlet. The LPDT is

Figure 1. Test model turbine

equipped with mass flow, speed, and torque meters. Some operational data of investigated points are presented in Table 2.

Table 2 Operating points

Test point	Inlet Temperature T/T ref	Inlet Pressure P/P ref	Exhaust Pressure P/P ref	GV relative, %
Point 1	1.75	5.53	1.25	14.9
Point 2	1.46	32.23	2.57	33.1
Point 3	1.43	31.54	4.05	22.2

The LPDT turbine is equipped with pressure taps at tip and root walls and Kiel-types probes to measure temperature, mounted at the Nozzle's leading edges (Figure 2).

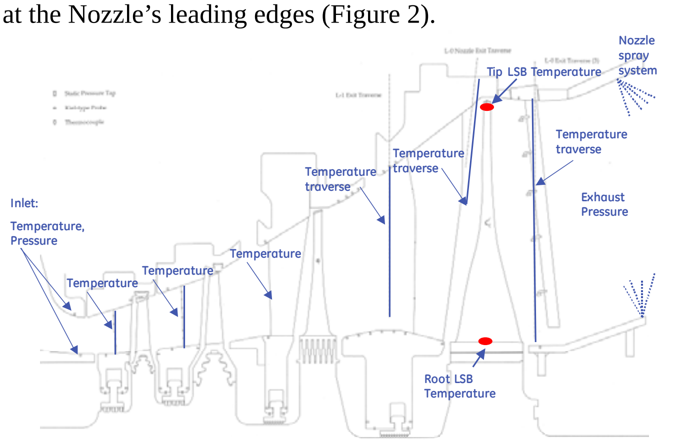

Figure 2. Test rig measurements

The flow temperature into the last stage was measured using traverse probes in three planes, which provided a detailed radial distribution of the temperature profile while the LSB airfoil temperatures were measured using airfoil mounted thermocouples.

1.2 NUMERICAL MODEL

1.2.1 Model and Grid details.

CFD model of the grid structure of the steampath, inlet and exhaust diffusers is created as a one passage model with periodic and steady stage interfaces between stationary and rotating domains (Figure 3).

Considering the significant influence of backflows from the condenser on LSB temperature and flow structure in the last stage, the full 3D hood grid has been incorporated into the CFD model to provide correct boundary conditions at the exhaust diffuser exit. One passage steampath mesh and 3D hood grid were collected in one CFD model.

The 4-stage steampath grid was created with CFX Turbogrid and the 3D 360-degree full hood grid was generated using ANSYS ICEM CFD.

As mentioned previously, the solid (metal) LSB domain has been incorporated into the CFD model and the whole problem was solved using coupled Thermal-CFD approach. By such an analysis, the LSB metal temperature can be obtained within one coupled solution and does not require a separate thermal analysis. The size of the full CFD model is around 6 million elements.

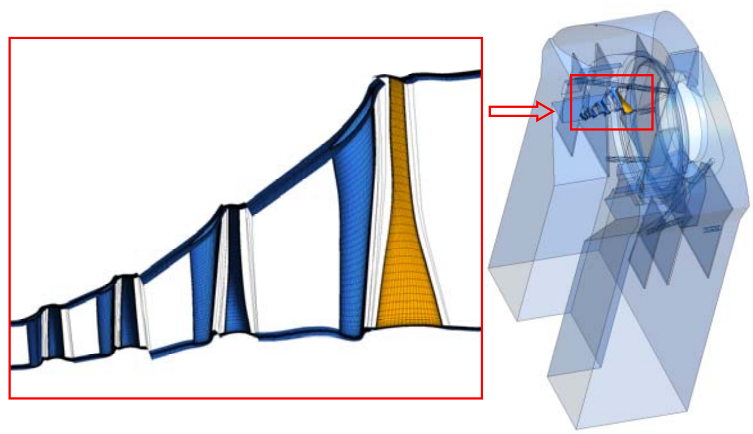

Figure 3. Steam path grid and full CFD model

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1.2.2 Solver.

The flow solver used for this study was the commercial program ANSYS CFX. CFX uses an implicit finite-volume approach, with a second order (high resolution scheme) accuracy and SST turbulence models. The Y + values are ~1 for steampath walls and ~ 5 for hood walls. Calculations were computed in parallel mode on a 64 processor cluster.

1.2.3 Steam Properties.

ANSYS CFX real steam properties were modeled based on the IAPWS-IF97 properties database [8].

1.2.4 Boundary Conditions.

Inlet and outlet boundary conditions correspond to experimental data for each test point. Inlet boundary conditions are total pressure and temperature. Outlet boundary conditions at the hood exit plane are set as an opening that allows backflow from the condenser.

The measured static pressure and steam quality were used as boundary parameters at this plane.

1.3 RESULTS

One of the advantages of CFD analyses is the ability to provide deep insight into flow structures which are complex at these low flow operational points. The investigated experimental and calculated points include a series of low flow regimes in a range of relative volumetric flows $\overline{G}\overline{V}$ from 15 to 33% (Table 2).

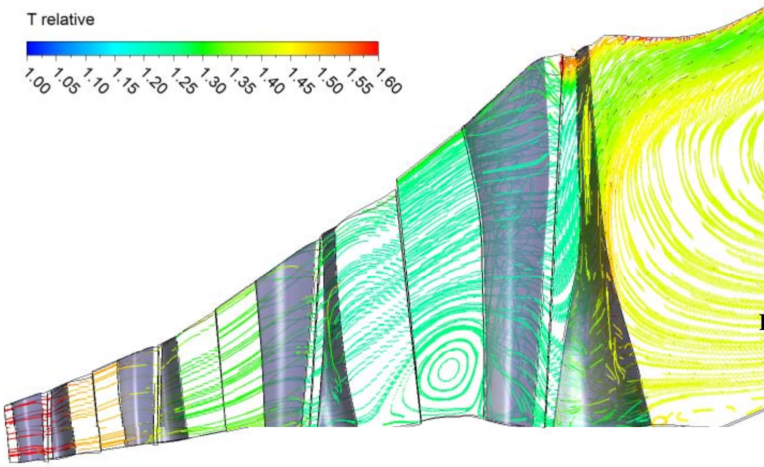

Figure 4. Flow structure at 15% relative volumetric flow.

Characteristics of a flow field with a 15% relative volumetric flow ($\overline{G}\overline{V}$ =15 %) are as follows (Figure 4):
- Exhaust diffuser backflows;
- Recirculation zones below bucket the tip and into last stage.

The very similar flow structure was observed in Stuttgart University [2] at $\overline{G}\overline{V}$ =13.5%.

Using the same model, a comparison of experimental and numerical data for the averaged temperature distribution into the steampath is made (Figure 5). It shows good agreement between averaged measured and calculated steam temperatures at planes between stages. In the L-0 stage gap between the Nozzle and Bucket, the temperature measurements were performed by a traverse probe only at the periphery of the zone. At this plot we can observe two high temperature points (test and CFD) corresponding to the tip area (Figure 5). Also we can see the calculated average temperature across the entire cross section, which is lower than the temperature for tip zone alone. Since measurements were done only the tip section, there is no corresponding measurement.

Using the same model simulating Test Point 1, a radial distribution of steam temperature at the bucket surface averaged around bucket profiles as well as the bucket metal temperature are obtained as a result of the coupled Thermal-CFD solution (Figure 6).

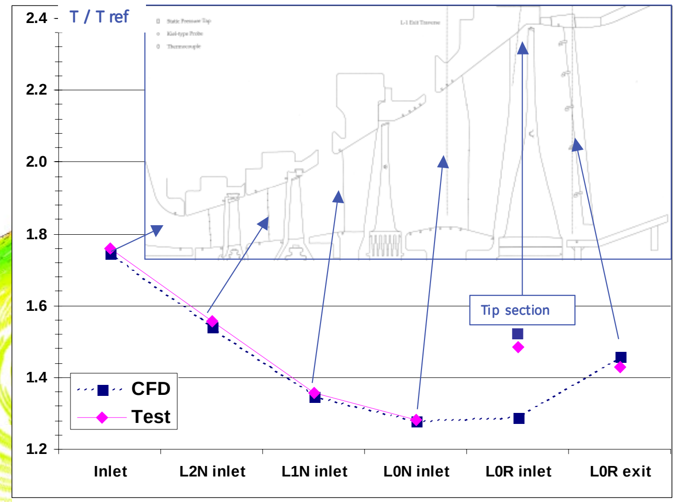

Figure 5. Temperature distribution comparison along steam path.

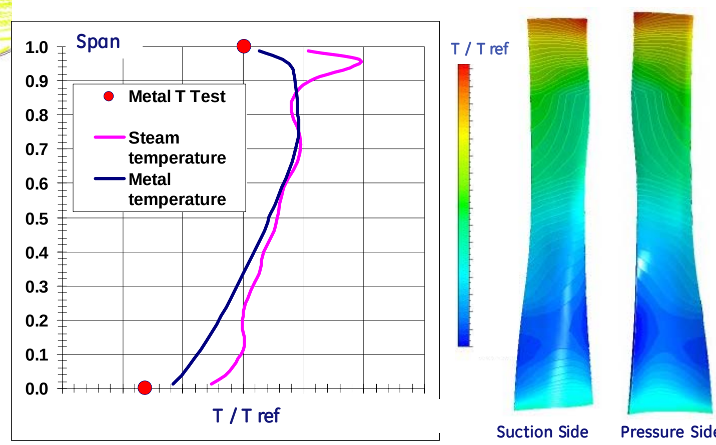

Figure 6. Radial temperature distribution at last stage bucket.

Temperature boundary conditions for bucket solid (metal) domain are applied only at the root section, as an average between an inlet and exit steam temperatures at the bucket root. Other bucket solid (metal) domain surfaces do not require any thermal boundary conditions to be applied as they have an interface with fluid (steam) domains. Measured LSB airfoil temperatures (measured by airfoil mounted thermocouples that are installed at the root and tip of the bucket) are compared to the calculated values (Figure 6). Calculated and experimental metal temperatures are in good agreement. Some minor difference at the root is a result of heat sink (flux) from the bucket to rotor, which was not accounted for in the CFD model.

Figure 6 shows the metal surface temperatures for the pressure and suction sides of the bucket. The peak temperature is located at bucket tip near the leading edge. Such temperature distribution and maximal temperature location is in good agreement with results presented in [2].

The same calculations were completed for Test Points 2 and 3 (Table 1). For all the test points we have a good agreement between measured and calculated metal bucket temperatures (Figure 7). Steam temperature is somewhat higher than that for the metal and this difference increases as the mass flow rate reduces (note that for Test Points 2 and 3, CFD calculated steam and CFD calculated airfoil metal temperatures are virtually identical (Figure 7)). The methodology demonstrated good agreement between numerical and experimental data, and was applied to predict operational temperatures for multiple LP section configurations under development.

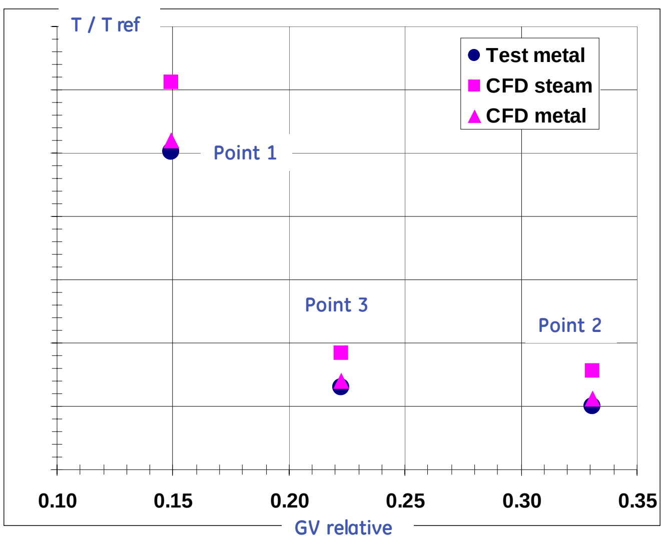

Figure 7. Test and calculated metal temperature at tip section LSB

The second part of this publication demonstrates the results of this methodology applied to a newly developed LSB.

2. TEMPERATURE PREDICTION FOR LAST STAGE BUCKET DESIGN B

Developed and validated CFD based temperature prediction methodology (as described in Part 1 of this paper) was applied to predict operational temperatures for a new LSB design (design B). The temperature prediction methodology and results of those predictions for a 3-stage LPDT test rig with this LSB design are discussed below.

One of the aspects presented in the first part of the work was an uncertainty in the temperature boundary condition at the LSB root section applied in coupled Thermal-CFD analysis. In order to reduce this uncertainty, the solid (metal) domain was extended to encompass the full rotor (Figure 8).

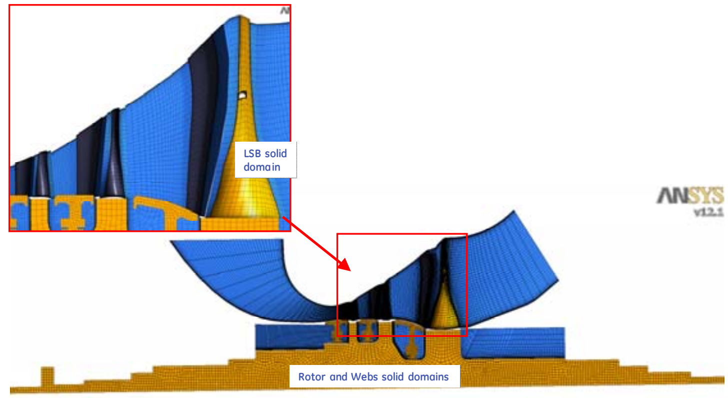

Figure 8. CFD model with Rotor solid domain.

In the coupled Thermal-CFD model configuration there is no need to apply temperature boundary conditions at any LSB surface, as they have an interface with fluid domains and rotor solid domain at the root. On the rotor surfaces that are in contact with the steam, the temperature boundary condition is applied as the steam temperature, taken from previous calculations. Temperature boundary conditions are also applied to the rotor bearing surfaces and butt-ends.

An example of the temperature prediction at a relative volumetric flow $\overline{GV}$ =13 % is demonstrated on Figure 9. The LSB metal temperature field at both sides of the bucket for the same operating conditions and a plot of the radial profile of the averaged metal temperatures is shown on Figure 10. The maximum temperature on a LSB surface is at the leading edge near the blade tip. At the root, one can observe a smooth temperature transition from bucket to disk.

The detailed analyses have been completed in a wide range of operational regimes $\overline{GV}$ = 4%...100% to investigate:

- Flow structure transformation,
- 3-stage LPDT test rig output and windage start point
- LSB airfoil temperature distribution.

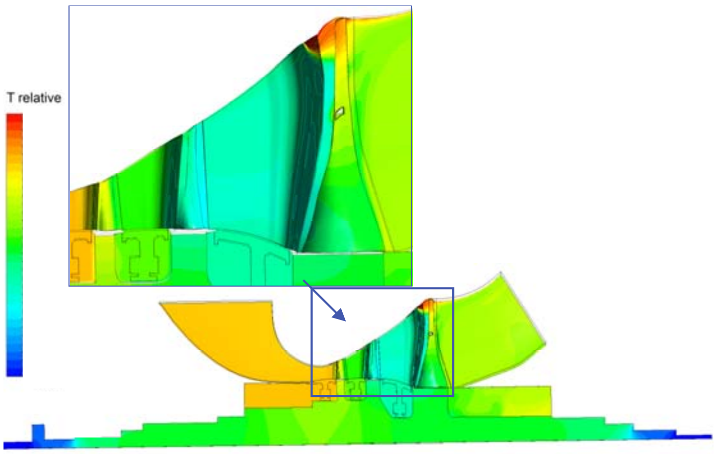

Figure 9. Full CFD model Temperature field for $\overline{G}\,\overline{V}$ =13%.

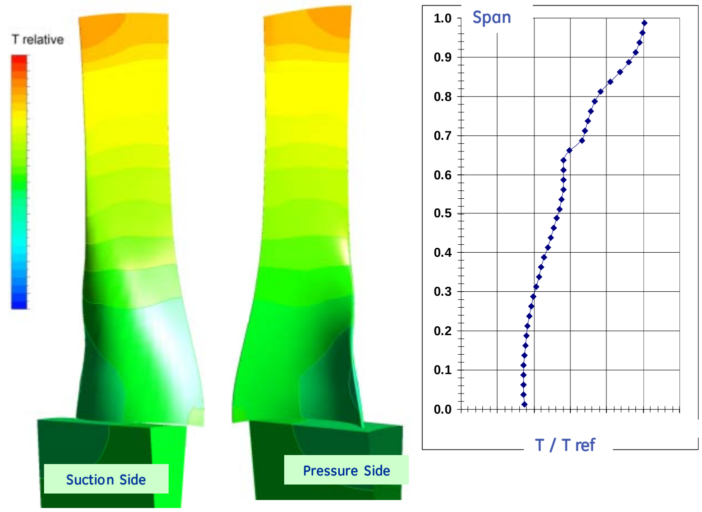

Figure 10. Last Stage Bucket Temperature distribution at $\overline{G}\,\overline{V}$ =13%.

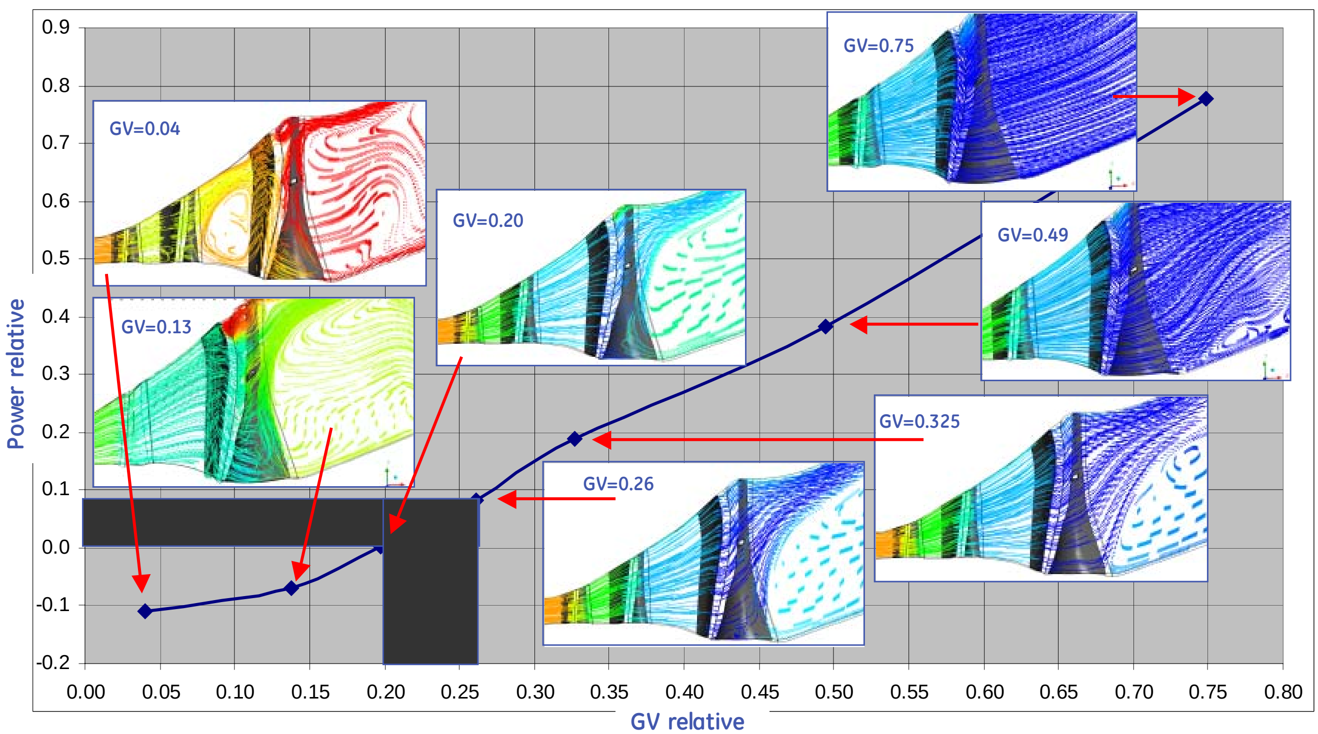

Figure 11. Output and Flow structure transformation in wide range of operational regimes

Figure 11 illustrates power output and flow structure transition from design regime to low flow operation by flow structure pictures (colored by steam temperature) at corresponding calculation points.

- The analysis of the flow structure transformation suggests that flow separation into the exhaust diffuser and backflow from the hood corresponds to a regime of $\overline{G}\,\overline{V}$ <50%.

- The start of flow recirculation at the tip between Last Stage Nozzle and Bucket corresponds to $\overline{G}\,\overline{V}$ <20%.

- The beginning of flow recirculation in a root zone between two last stages corresponds to $\overline{G}\overline{V}$ <15%.

The last stage compressor mode (windage) starts at $\overline{G}\overline{V}$ <25% and the 3-stage steampath starts consuming power at $\overline{G}\overline{V}$ <20%. The transition zone is indicated on the plot by a dark gray color (Figure 11).

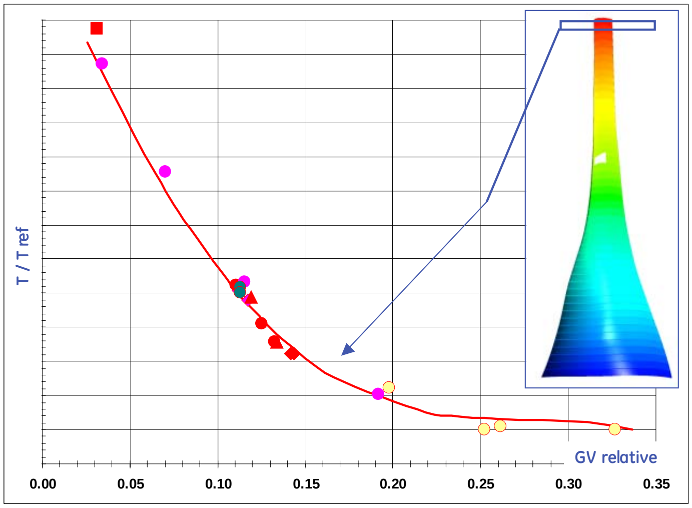

Figure 12. Last Stage Bucket Tip average metal temperature vs. relative volumetric flow

As a result of this study the LSB metal temperature was obtained (Figure 12). The start of the temperature increase correlates with the starting point of the last stage windage process (25%$\overline{G}\overline{V}$). Results show a strong trend for the temperature rise as the steam flow decreases. The peak LSB temperature corresponds to a minimum flow of $\overline{G}\overline{V}$ =4% in our series of analyses.

The predicted LSB and rotor temperatures were used for bucket thermo-mechanical calculations and for LPDT model turbine test preparation.

3. CONCLUSIONS

Extremely low steam flow conditions through LP turbines during start up and high back pressure operation results in windage conditions and a temperature rise in the last stage bucket. The temperature prediction at these extreme conditions is challenging for last stage bucket designers.

Extensive numerical and experimental investigations on LP section steam turbines with LSBs of different lengths at typical low flow operation conditions have been conducted, and are being used during the design process.

Temperature prediction methodology based on a coupled Thermal-CFD approach has been developed and validated against test data over a wide range of low flow operational regimes. The comparison of test and numerical results was provided for steam temperatures in various locations of the steampath and for LSB metal temperature. A good agreement between test results and numerical predictions has been demonstrated. The developed methodology was used to predict temperature for a newly designed LSB.

In addition, a detailed analysis of flow structure, windage, and LSB temperature as a function of relative volumetric flow was obtained.

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