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Aerodynamic performance of super-critical steam turbine high pressure stage at off-design condition

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ABSTRACT

In order to learn aerodynamic performance of swept blade, the super-critical steam turbine high stage cascades were selected as prototype blade (PB). Chord-wise fore-sweep blade (SWF) and chord-wise aft-swept blade (SWB) were constructed and conduct off-design working condition numerical simulation of prototype, forward-swept and aft-swept blade stages respectively. The simulation results indicated that three cascades stages maintain a good aerodynamic performance in a wide range of inlet-flow. Forward-swept stage has the highest isentropic efficiency and smallest axial thrust than the other two.

Keywords: Chord-wise Sweep Blade; Off-Design Condition; Isentropic Efficiency; Axial Thrust

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INTRODUCTION

The design parameters of modern turbine machinery are required to more rigorous, the aerodynamic performances are better, the off-design condition characters are wider and the sizes are more compact, which will result in that the impeller machinery internal flow is more complex and design research is more difficult. However, turbine machinery is the key part of gas turbine, steam turbine and aircraft engine and other important devices, it plays a decisive role in the national economy and national defense security and its internal flow has been one of the key research contents to science researchers.

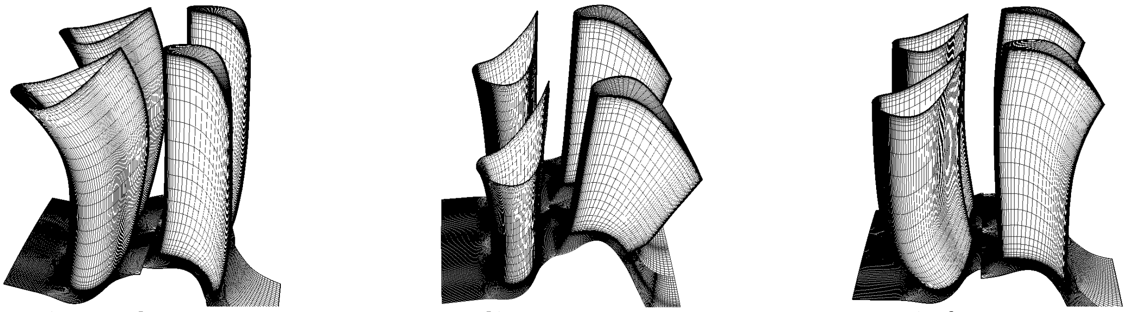
Cascade load change is bigger when turbine unit runs under off-design condition, velocity distribution on the surface of blade also has changes especially the blade leading edge velocity distribution. The overlarge entrance incidence angle (both positive and negative) may be caused separation in the blade leading edge surface thus causing loss. It exists an optimal attack angle for any blade type [1], the loss is minimal at this time. Incidence angle loss is one of the off-design losses which have many research results at home and abroad[2-7]. The optimum attack angle of compressor is generally positive and the turbine is usually negative. Solomon[8] studied the effect of turbulence intensity and cascade consistence on boundary layer development in the low pressure turbine under off-design condition in 2000. Gier et al[9] studied the effect of decreasing blade quantity on three-level low pressure turbine. In 2004, An Botao[10], et al have made valuable conclusions through detailed studying the geometric parameters of blade oriented to off-design condition characteristic. In this paper we will mainly study the aerodynamic performance change law under off-design condition after the high pressure stage blade of steam turbine unit is transformed to forward-swept and aft-swept, dynamic and static blade are matched to investigate the working performance of sweep blade level under off-design condition, that provide theoretical foundation and reference for the design of turbine machinery.

2. SWEEP BLADE MESH AND BOUNDARY CONDITION

The prototype blade is high-pressure stage blades of supercritical steam turbine unit, the blades are modified along the chord-wise. The sweep angle is ±10°, the sweep height is about 30% of blade height. Sweep blade stage is made up by constructed sweep prototype static and rotor cascade, there are three simulation schemes coupled with the prototype high pressure stage, it can be shown in figure 1. Three kinds of cascade stages are proceeded off-design condition simulation under variable flow conditions to study off-design aerodynamic performance of sweep stage. Discuss the effect of chord-wise sweep on turbine through the comparison of three kinds of cascade aerodynamic performance.

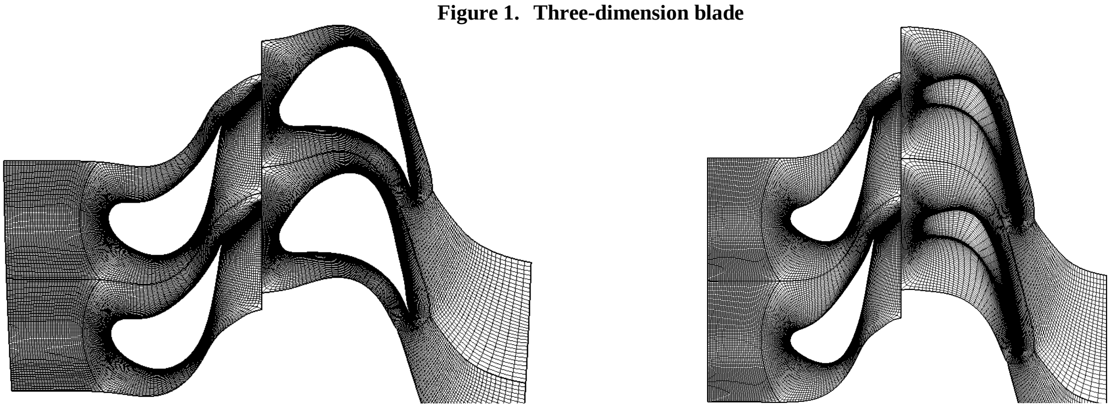
Numerical simulation uses NUMECA software, the meshes are generated by the software package of NUMECA-AutoGrid, using fluid calculation software NUMECA-Fine to calculate and the turbulence model is Spalart-Allamara. As shown in fig.2, H-O-O-C combined computing meshes are generated in the cascade top, the static blades entrance sections of the meshes are Type H, static and rotor blades flow channel sections are Type O, the rotor blade exit section meshes are Type I, the total amounts of mesh nodes are 1.03 million. The inlet conditions are that: The total import pressure is 5.958 MPa, the total import temperature is 625 K, the export static pressure is 5.02 MPa, the rotate speed of rotor blades is 3000 RPM. The static pressure value in intermediate diameter at the outlet boundary conditions is given. Simple radial equilibrium equation is used to calculate radial distribution of exit static pressure and the adiabatic zero slip boundary condition is adopted for solid wall boundary.

Using numerical calculation to solve three-dimensional steady Reynolds averaged N-S equations and grid center type finite volume method is used. Spatial difference scheme uses second-order windward difference scheme, time discretization uses explicit fourth-order Runge-Kutta to accelerate convergence by using local- time step method. The multiple and full multigrid methods are adopted to accelerate convergence combined with variable time step as well as the residual smoothing methods, then the three sets of grids are single-stage calculated respectively.



a) Forward-swept stage **b) Prototype stage** **c) Aft-swept stage**

Figure 1. Three-dimension blade



a) Blade root mesh **b) Blade top mesh**

Figure 2. Mesh schematic diagram of blade root and top

3 THE ANALYSIS AND DISCUSSION OF NUMERICAL SIMULATION RESULTS

3.1 THE OFF-DESIGN CONDITION HIGH PRESSURE STAGE REACTION DEGREE, ISENTROPIC EEFICIENCY, OUTPUT POWER,AXIAL THRUST CHANGE ALONG WITH THE FLOW

It can be known from fig.3, the reaction degree of chord-wise fore-sweep, chord-wise aft-swept and prototype stage hadn't changed much in the flow range of 0.7 ~ 1.2 times design conditions, the reaction degree keeps basically 0.5. That means the enthalpy drop is basically equal within the scope of the static and rotor blade cascade which results in the consistency of flowing, thus the steam flow velocity of steam turbine changes gently, the air-operated loss is little in the range and isentropic efficiency is higher. It can be seen through comparing with figure 4 that reaction degree and isentropic efficiency have consistency. But the larger reaction degree shows that the pressure difference before and after rotor blade is very large, so the rotor under axial thrust is very big. The reaction degree is largest at 0.8 relative flow rate. When relative flow is less than 0.5, the average reaction degree will decrease sharply, the reduced reaction degree shows that isentropic efficiency and rotor blade axial thrust also decrease sharply. Increasing design conditions flow will make reaction degree have decreasing trend, the prototype stage keeps larger reaction degree comparing with forward-swept and aft-swept cascades.

Fig.4 shows the isentropic efficiency changing curve of three kinds of cascades stage after altering working flow. When relative flow is less than 0.7, the isentropic efficiency will decrease sharply and it will change little when relative flow is more than 0.9. Forward-swept isentropic efficiency is larger in the range of 0.8~1.2 relative flow and it can be average increased by 0.2%. However, aft-swept is opposite which drops a little, but the magnitude is very small, the three kinds of cascade stages can be kept high work efficiency in this flow range.

We can know that from fig.5, the output power will be increased along with the increasing of relative flow, the output stage power of forward-swept can be somewhat more than prototype and aft-swept stage before designing flow operating point, but the forward-swept output power which is deviating from design flow operating point has not been improved. It shows that forward-swept cascade is beneficial to average output power at design flow operating point. It can be seen from fig.6, the rotor blade axial thrust is also increased among three cascades along with the increasing of relative flow, but the axial thrust of static forward and aft-swept is less than prototype stage in the range of 0.7~1.2 relative flow. Sweep blade is good for steam turbine from decreasing rotor blade axial thrust.

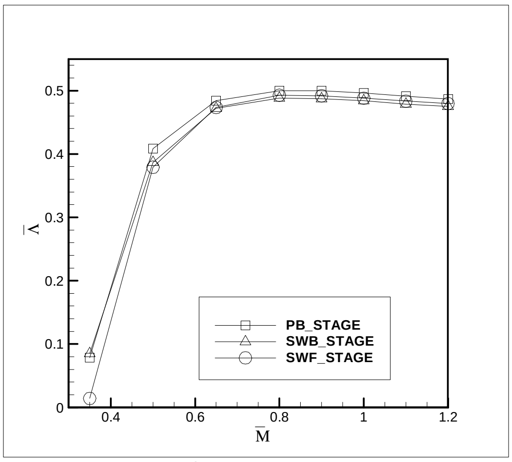


Figure 3. Variable flow stage average reaction degree

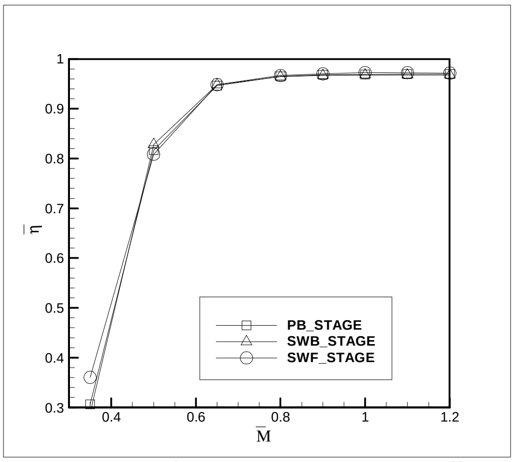


Figure 4. Variable flow stage average isentropic efficiency

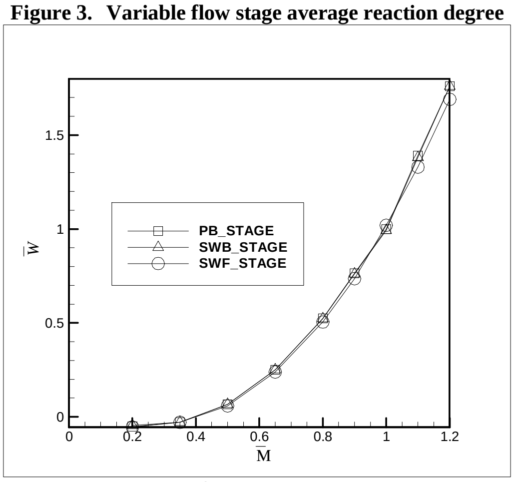


Figure 5. Variable flow stage average output power

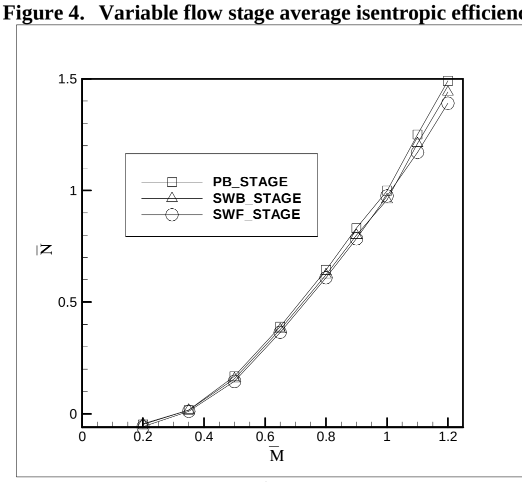
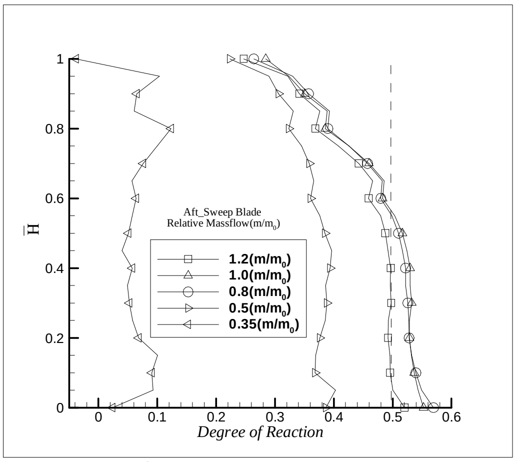


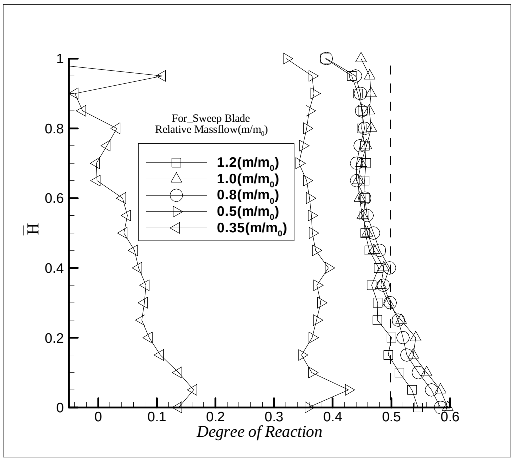
Figure 6. Variable flow stage axial thrust

3.2 THE OFF-DESIGN CONDITION HIGH PRESSURE STAGE REACTION DEGREE CHANGES ALONG WITH THE FLOW

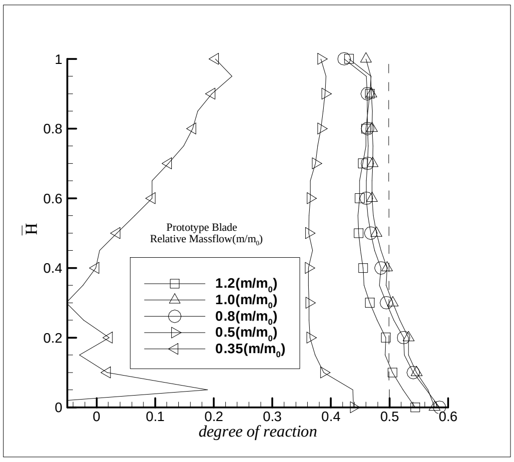
Fig.7 shows the curve graph of three kinds of cascades stage reaction degree changes along with the flow. Three kinds of cascade reaction degree decrease with the decreasing of relative flow on the whole, when beyond the operating point, reaction degree is also reduced. Its variation trend is similar under 0.8~1.2 relative flow operating condition and the extent of change isn't much. Reaction degree along the direction of leaves has little change in most area when its relative flow reaches to 0.5, it has larger change only in the range of 20% blade tip.



a) Aft-swept stage reaction degree



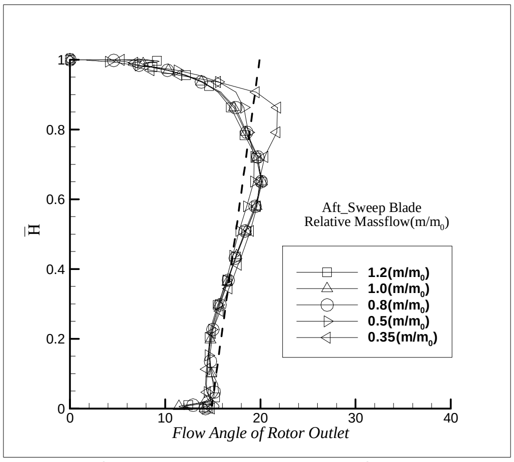
b) Forward-swept stage reaction degree



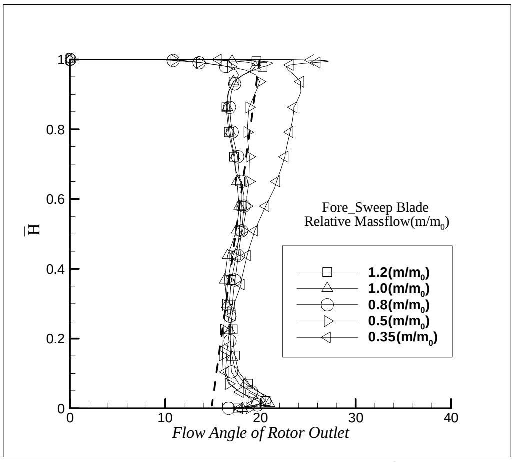
d) Prototype stage reaction degree

Figure 7. High-pressure stage reaction degree changes along with flow

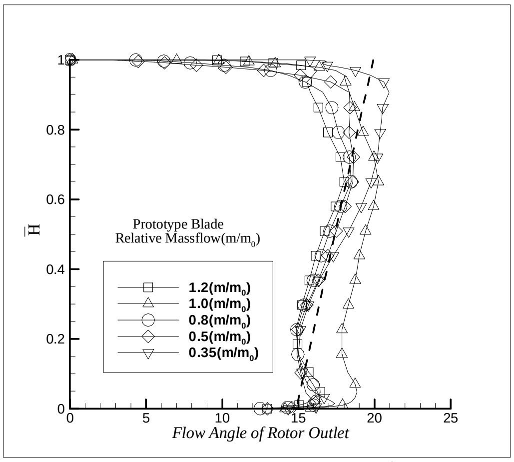
3.3 THE OUTLETFLOW ANGLE OF VARIABLE-OPERATING CONDITION HIGH PRESSURE STAGE WILL BE CHANGEDALONG WITH THE FLOW



a) Aft-swept rotor cascade outlet flow angle



b) Prototype stage rotor cascade outlet flow angle



c) Forward-swept rotor cascade outlet flow angle

Figure 8. Outlet nodal distance average flow angle of high-pressure stage rotor cascade

Fig.8 shows three kinds of blade profile flow rotor cascade outlet nodal distance average flow angle. The flow angle of aft-swept cascade fundamentally remains unchanged, flow angle decreases obviously when it is increased 0.7 times relative flow rate, the flow angle in the root has smaller increasing in the range of 0~0.1 blade unfold. Flow angle of the rotor blade gap will decrease as flow decreases, it explains that it can be more fluids are divulged when gap eddy get weaken. The flow angle doesn't change much in 0~0.4 blade unfold range after prototype cascade flow has been changed which above 0.4 relative blade height both have larger attenuation. Flow angles are deviated from the design conditions whether it is a large flow or small flow after changing forward-swept cascade flow, then the lack of deflection can be formed, flow angle will be increased lesser along with the decreasing of flow and the lacking deflection of 1.2 times relative flow is the most serious.

CONCLUSION

The variation trend of three kinds of blade stage reaction degree, isentropic efficiency, output power, axial thrust is similar in the flow range of 0.3~1.2 times design conditions, as the reaction degree and isentropic efficiency don't change much, so it means the enthalpy drop is basically equal within the scope of the static and rotor blade cascade which results in the consistency of flowing, thus the steam flow velocity of steam turbine changes gently, the air-operated loss is little in the range and isentropic efficiency is higher. When relative flow is less than 0.5, the average reaction degree will decrease sharply. The output power and axial thrust will increase along with the increasing of relative flow. Forward-swept efficiency has a small increase within a wider off-design conditions and the axial thrust is smaller. It explains that forward-swept has more excellent aerodynamic performance within wider off-design conditions.

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