The Application and Numerical Study of Highly Loaded Blades in the Industrial Steam Turbine

Hong Yao[1,2, a], Xun Zhou[1,b] ,Wanlong Han[2,c] and Zhongqi Wang[1,d]

[1] Energy Science and Engineering School, Harbin Institute of Technology, Harbin, Heilongjiang, China

[2] QingDao Jieneng Steam Turbine Co., Ltd, QingDao, ShanDong, China

[a]mchyh@tom.com, [b]zhouxun@hit.edu.cn, [c]lingyunxiaoshan@126.com, [d]wzq@hit.edu.cn

Keywords: highly loaded blade; industrial steam turbine; aerodynamic design; CFD.

Abstract. The blades are the key components of industrial steam turbine, and the manufacturing of the blade is about one third of total manufacturing. Reduction of the number of the blades is will lower the manufacturing cost. In the present paper, the aim of the research is to develop high efficient highly loaded blades, and bring forward the design methods and requirements adapting to use for highly loaded of industrial steam turbine. The full 3D aerodynamic design software, are used to the aerodynamic design of the highly loaded baldes. The research is consist of the flow characteristics around the stator and rotor blade profiles in the transonic flow region, the spatial stacking method and the stages matching. In this design, the inlet angle of stator increased to 50˚, stage load increased by 30%, the full 3D aerodynamic performance of the last stage flow field is also analyzed. The design is conducted for a industrial steam at design flow rate with a signle workstation. It is demonstrated that the highly loaded blade design produces performance gains at design point and also at off-design points. At the same time, the number of stages in the industrial steam turbine is reduced by 1/4, and the manufacturing cost is greatly reduced.

Introduction

In an industrial market with a growing contribution of renewable power sources the operational flexibility of industrial steam turbine is becoming more and more important. Industrial steam turbines can ensure a high level of operational flexibility in a power spectrum up to 100MW. Due to their variable rotational speed they are often used as drive for pumps or compressors. The strong competition among turbomachinery companies to satisfy customer requirements pushes towards the design of machines with high efficiency and reliability and reduced costs [1]. In order to reduce the manufacturing cost, the most effective method is to reduce the number of stages and reduce the number of blades. High load design method can reduce the number of blades, and reduce the cost of manufacturing.

The unit cost and component length whilst maintaining competitive cycle efficiencies can be reacted to in various ways. The aero-engine market developed so-called “high-work” high pressure turbines which allow expanding the working fluid to pressure rations of up to five within one, instead of two stages. Thereby, a significant effect on component length and part count is to be expected [2]. The uniform flow angle distribution in inlet of the downstream stages can ensure a high efficiency of the downstream stages. Thus, it is important that uniform outflow angle of the highly loaded blades. In order to suppress flow separation recommends increasing the ratio of inlet to outlet area to realize an accelerated flow [3]. Engelmann et al described this loss calculation method in detail with some amendments [4]. This loss calculation method is used in this paper. Blades are crucial components for industrial steam turbines, and 10% stage load improvement will decrease number of stages by 10%. Similar to aircraft engines [5], that require operate at high-level efficiency and pressure ratio together with wide operating flow range, also industrial steam turbine require operate at high-level efficiency together with wide operating flow range.

On suction surface of positive curved blade, the “*C*” type static pressure distribution along the blade height is created, and the load of the blade is changed along the blade height and chord, which are the main factors to affect the flow in cascade [6]. The conclusion will be used for the design of this work. Three dimensional design techniques of the blade bowed circumferentially and the blade bowed in its chord normal directions can control second flow in cascade, their physical principal are different [7]. In here, the focus on the description of the aerodynamic philosophy, on the conducted design for stator and rotor as well as on the promising results achieved.

Design philosophy

The feasible aerodynamics concept for an industrial steam turbine with high loaded needs, in particular, to address the following issues:

1. Moderate losses of the stator and rotor at design point and off design point conditions in order to allow for a smooth trend of industrial steam turbine efficiency.
2. Minimum shock losses at design point, the highly load leaded to supersonic flow in the exit of the cascades.
3. High flow turning of the cascade for highly load.
4. Suitable outflow condition of stage to the upstream blade row.

In the concepts of cascade designs for highly load blade for both a stator and a rotor cascade, main requirements translate into: first, avoid flow separation on the stator for any exit Mach number; second, exit area matching with the exit Mach number at design point; finally, minimize the strength of the shock system.

Numerical method and industrial steam turbine geometry

The flow field is computed with commercial CFD solver ANSYS CFX which is based on a combined finite volume and finite element algorithm. It uses a coupled solver for mass and momentum equations as well as an algebraic multigrid scheme for convergence acceleration. Further solver specifications, grid attributes, flow parameters and used boundary definitions are described below. A block structured hexahedron grid, generated with ANSYS ICEM-CFD, is used for the numerical simulation. The numerical results presented in this paper are performed with the SST-RM turbulence model, it based on the common SST turbulence model. Radial pressure and velocity distribution is predicted with smaller difference to measured results than with the SST standard formulation.

The investigated industrial steam turbine consisted of 8 stages; power is 15MW. Inlet total pressure of 0.587MPa, total enthalpy of 2951kJ/kg, and the outlet static pressure is 0.0056MPa. Table 1 lists the most important performance parameters of the initial industrial steam turbine.

Table 1: Initial industrial steam turbine performance parameters

Stage index	1	2	3	4	5	6	7	8
Mass flow / kg/s	12.627	12.627	12.159	12.159	12.159	11.012	11.012	11.012
Enthalpy drop / kJ/kg	77.815	78.974	82.922	86.785	88.176	92.970	130.20	159.48
Speed ratio	0.429	0.429	0.423	0.420	0.428	0.444	0.433	0.445
Reaction	0.04	0.05	0.06	0.07	0.09	0.17	0.24	0.32
Power / kW	808.23	829.54	842.21	886.65	904.69	854.90	1186.7	1399.2

These parameters are calculated by 1D and CFX, both flow rate and power halved a slight difference, the maximum deviation is less than 0.5%. In fact, it is very difficult to calibrate one dimensional calculation program by empirical formula. The practical method is the comparison between different programs. When the results of the different programs are consistent, it can be seen that these programs are correct.

This kind of industrial steam turbine has been produced over decades, and the actual performance shows a good accordance with the test and design.

Design modifications

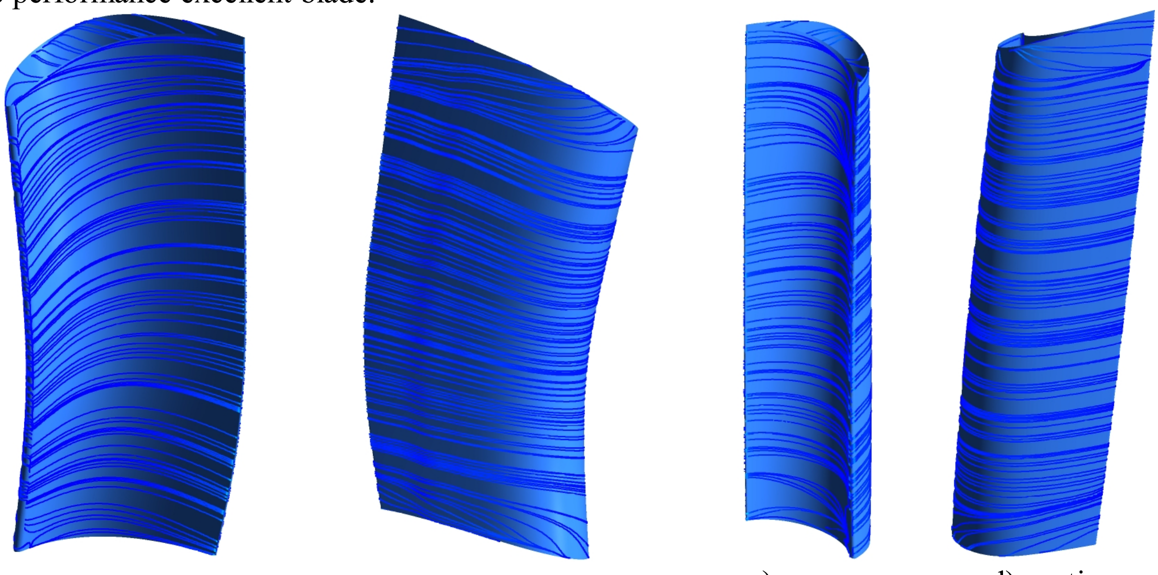
After redesign enthalpy drop per stage increased 30% and speed ratio of each stage dropped 0.42, the load of each stage increased by 30%. Thus, the number of stages reduced to 6 stages. Compared with initial scheme the power has increased. Results indicate redesign is feasible. At the level of blade design need to use the highly load blade, decreased inlet angle and control flow separation, remained smaller attack angle.

Table 2 lists the most important performance parameters of the redesigned industrial steam turbine. As compared to table 1,

Table 2: Redesign industrial steam turbine performance parameters

Stage index	1	2	3	4	5	6
Mass flow / kg/s	12.625	12.625	11.957	11.957	11.039	11.039
Enthalpy drop / kJ/kg	113.846	111.567	121.532	136.828	171.016	155.420
Speed ratio	0.356	0.370	0.378	0.389	0.386	0.451
Reaction	0.134	0.132	0.158	0.192	0.264	0.312
Power / kW	1149.17	1154.46	1209.33	1377.97	1535.12	1396.66

To evaluate aerodynamic performance of profiles, important aspect is the static pressure distribution along the blade surface. In order to ensure satisfactory performance the static pressure distribution must meet the following three requirements: 1. Have a large area of static pressure distribution on the suction and pressure surface. 2. The reasonable accelerating gradient on the suction surface. 3. The flow curvature method confirmed that the pressure of the suction surface at the lowest point, from this point to the beginning of the trailing edge of the pressure. When the pressure gradient is too large, reduce the trailing edge length and inverse pressure increased pressure, is the key to design the pneumatic performance excellent blade.



a) pressure surface of stator b) suction surface of stator c) pressure surface of rotor d) suction surface of rotor

Figure 1: streamline at the blade surfaces

Figure 1 showed that branch of horseshoe vertex at the root wall of the pressure side meets branch of horseshoe vortex from adjacent blade, the junction point is located between leading and trailing of suction side. There is a vortex near the suction side after the throat, which is induced by the passage vortex, associated with a large loss of the wake vortex at the trailing edge, but the separation location is limited, at the 5% span.

Under the condition of highly load and strength limited, the blades still maintain highly efficiency. The secondary flow loss is much more in the total loss, reduce the intensity and influence scope of the vortex system can further improve the efficiency. But in the design need to meet the intensity requirements.

Figure 2 and Figure 3 showed the CFD approach introduces deviations near the interaction region of the trailing edge shock and laminar suction side boundary layer.

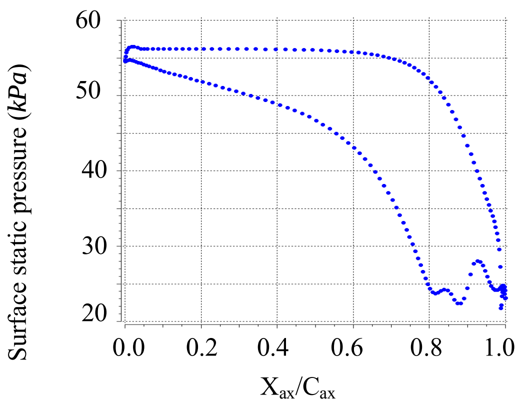


Figure 2: Pressure distribution along stator blade

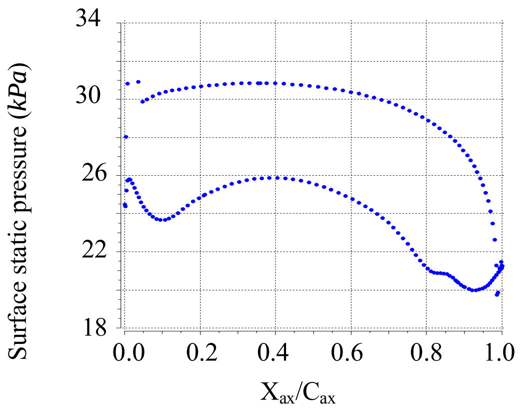


Figure 3: Pressure distribution along rotor blade

Conclusion

This work described aerodynamic design of the highly load blade of industrial steam turbine. Limited to space, in this paper does not list all six of the calculation results. The results show that the predictions of 1D, Q3D and 3D are basically consistent with the power, flow rate and efficiency, and the total to static efficiency is 80%. By results of CFX, total power of redesign scheme is 7.821MW, compared with the original scheme improving the 0.08%. Redesign reduced by two stages compared to the initial scheme, which greatly reduces the production cost. Important is that there is future for further improvement in the performance of the redesign scheme.

The reasons for the further improvement performance of the highly load blades are: each blade with different meridian angle, increasing the complexity of the flow in cascade channels; strength requirements limit the scope of the design, so in the root and top region have a greater loss. The wide of the operating conditions required optimization design, efficiency does not big change.

This work proves that the design method of the high load of the small steam turbine is feasible, the magnitude of the load increase is about 30%, and stages number is reduced by two stages.

Bowed blade for industrial steam turbine can change reaction distribution along span, reduce tip reaction, increase hub reaction; under the similar conditions, twisted and bowed blade can not only improve the efficiency, also helps to reduce water erosion of last stage blade

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