Investigation of a Steam Turbine with leaned blades by Through Flow Analysis and 3D CFD Simulation

Xiaodong WANG[1], Shun KANG[1] and Ke YANG[2]
1. Key Laboratory of Condition Monitoring and Control for Power Plant Equipment, Ministry of Education
North China Electric Power University, Beijing, 102206, China
(E-mail: wangxd@ncepu.edu.cn)
2. NUMECA-BEIJING Fluid Engineering Co. Ltd, Beijing, 100081, China

Abstract: In order to get more insight into the influence of blade lean angle on the flow performance in the design process of a one-stage turbine with large diameter/height ratio, a through-flow tool of AxSTREAM is employed for investigations. Based on the optimization of design, stage performances of variable working conditions for twenty-one lean angles in stator and in rotor are simulated respectively through DoE analysis. Simulated results for five typical lean angles are validated with the data of 3D CFD simulations performed with FINE/TURBO software. The variation of reaction and static pressure distributions under different lean angles are presented, with discussion and analysis of the influence of parameters, such as diameter/height ratio and rotation speed, on the best lean angle.

Keywords: Through flow, 3D CFD simulation, steam turbine, leaned blade, DoE analysis

1. INTRODUCTION

In recent decades, with the developments of CFD technology, full 3D (F3D) numerical simulation, based on Navier-Stokes equations, has been increasingly used, especially in the complicated internal flow fields. However the TF (through flow) analysis is still playing a very important role in turbine design process.

Generally, the development processes of turbomachinery design methods could be summarized as three phases [1]. The first phase is about before last century 60s. Through flow calculation is the primary simulation method used because of the limitation of computer resource and the arithmetic technology. Most of blades are straight blades. Second one is till the last 80s. The iterative calculation of S1/S2 stream surfaces is used in the analysis and design process. The precision is then enhanced since the variations of flow parameters along radius are taken into account. Some new twisted blades begin to be designed and used. The third one, began from recent years, solves the 3D Reynolds averaged Navier-Stokes equations. Flow details in cascades or even multistage with real geometry, such as tip clearance, seals, cavities, balance holes, etc. could be simulated with increasing accuracy. It improves the understanding of 3D viscous flow structure and loss generation mechanisms that is helpful to get higher efficient turbomachinery design. Usually, the losses in steam turbine designed by this method could be reduced by 3%-4% than in the first phase [1]. However the F3D simulation is still very time-consuming for practical application. It needs a lot of time to reset and recalculate even through there are any changes of the geometry or boundary condition. So it is not convenient and efficient enough to be combined with automatic optimization methods to search for the best design. On the contrary, rapidity is the strongpoint of TF simulation. So the TF simulation was chosen for the main investigated method in this paper.

In modern turbine design, leaned, curved and twisted bladings are widely used in stator blade profiling. They could modify the radial distribution of static pressure in the flow passage and reduce the losses of stage. In 1962, M. E. Дейч first proposed a curving blade design [2]. Since that, researchers have investigated the effects of leaned and curved blade on the cascade performance through lots of experiments and numerical simulations [3-6]. Most of results of these investigations indicate that leaned blades could reduce the losses of the stage and improve the aerodynamic performance. However some others did not [7]. Reference [8] analyzed the reasons. The positive blade leaning mainly improves the flow condition in the blade hub region since the intensities of the leading edge horseshoe vortex and passage vortex in hub region are reduced. Meanwhile, the loss of tip region is more or less increased since the intensities of these vortexes raised [7]. WANG and his co-workers proposed forward the concept of best lean angle [8] and pointed out that the curved blading could overcome this drawback. These had been proved by their subsequent investigations [9]. But not all the curved blades could reduce the losses of stage because of some other character’s effect. The matching between stator and rotor is one of the important factors. Reference [10] has shown that curved blades couldn’t increase the efficiency of stage if the matching problem was neglected.

Till now, the curved blade was used rarely in rotor cascade because of the moment stress. But investigation on curved blading in rotor has been the hot point. Reference [11, 12] has shown that the curved blades could be used in rotor and it maybe makes even more effect on stage performance.

Although curved blading is superior to the leaned blading in practical application, the investigation of the leaned blade is simple, resulting in a base for curved blading investigation. And most of the investigations on leaned blading are based on cascades with certain of given geometry and working conditions. The effects of leaned blades under variable geometry and gas dynamic parameters are still not clear yet. To expose these effects of leaned blade in stator and in rotor, this paper takes a one-stage steam turbine to investigate the influence of blade lean angle on the flow performance in the design process. This steam turbine is from an optimization case in actual engineering. A through-flow tool of AxSTREAM is used to make the optimization through Design of experiment (DoE) analysis. Then comparison and validation with the results of 3D RANS software of Fine/Turbo are made, followed with discussions.

Nomenclature and glossary

N	capacity
Eff	internal total-to-total efficiency
G	mass flow rate
P0*	inlet total pressure

P1	static pressure downstream stator
P2	static pressure downstream rotor
T0	inlet total temperature
T2	static temperature downstream rotor
Rt	tip reaction
Rm	mean reaction
Rh	hub reaction
L1	the lean angle of stator
L2	the lean angle of rotor
n	rotation speed
U/C0	isentropic velcocity ratio
A1mid	outlet flow angle at mean diameter
D	mean diameter
l	blade height at trailing edge

2. METHODS AND PARAMETERS

2.1 Software Description

Two kinds of software are used. One is Axstream from SoftInWay Company for TF/q-3D simulation, and the other is Fine/Turbo software package from NUMECA International for 3D viscous flow simulation. Their brief descriptions are given below. Refer literatures [13, 14] for more details.

AxSTREAM, majored in design and optimization of axial/radial turbomachinery, uses the method of streamline-curvature to solve the axisymmetric problem with a view on engineering. It is based on the experiential models, and combined with DoE analysis approach and automatic optimization methods. Reference [15] had shown that the simulated results of AxSTREAM which is based on good experiential or quasi experiential models are reliable.

FINE/TURBO solves the time dependent Reynolds averaged Navier-Stokes equations with one or two equation turbulence models for closure. It is based on a structured multiblock, multigrid approach, including non-matching and full non-matching block boundaries and incorporates various numerical schemes based on either a central or upwind discrimination.

2.2 Main parameters

The main geometry and aerodynamic parameters of original design and optimized design without leaned blade were presented in table1.

2.3 Through flow optimization and analysis

The blade profiles of stator and rotor were optimized through AxSTREAM. In order to meet the geometry restriction, the blade height and axial length were kept to the elementary values during optimization. The reaction was normally distributed that was much higher in tip range than in hub range. In recent years, some engineers designed some leaned or curved and twisted blades to get the reversed “C” type distribution of reaction. Even some made the reaction decreased from hub to tip in order to control the loss of tip leakage. So in this design, leaned blade was used in stator to improve the performance of stage.

The variable geometry conditions performance with different leaned blades in stator cascades was simulated through DoE analysis in AxSTREAM. In DoE analysis, twenty one points were calculated with the lean angle increasing from -5° to 15°, listed in Table2. It should be noted that it is far more difficult to 3D calculation because any geometry changes needs much time and labor to change the topology and grid.

Table 1 Main parameters of the stage

Parameters	original	optimized
Number of stator vanes	168	44
Number of rotor vanes	140	49
hub diameter (mm)	939.5	939.5
blade height (mm)	115.037	115
inlet total pressure (kPa)	7903.06	
inlet total enthalpy (kJ/kg)	3205.98	
outlet static pressure (kPa)	6732.6	
rotation speed (rpm)	3000	

Table 2 Computation points of different lean angle.

	AxSTREAM	FINE/TURBO
Lean angle (°)	-5, -4, -3, -2, -1	-5
	0, 1, 2, 3, 4	0
	5, 6, 7, 8, 9	5
	10, 11, 12, 13, 14	10
	15	15

2.3 3D CFD simulations

In 3D CFD simulation, straight blades and other four typical leaned blades, sketched in Fig.1 and Fig.2, were investigated. The 3D geometry was exported from AxSTREAM and the computation mesh was built by AutoGrid5 integrated in FINE/TURBO package.

The mesh was shown in Fig.3 with the total grid number of 673372 for one blade passage of the stage. The one equation model of Spalart-Allmaras was used for closure. Convergence criteria of residuals were 1.0e-4 and the difference between inlet/outlet mass flow rates was less than 0.1%.

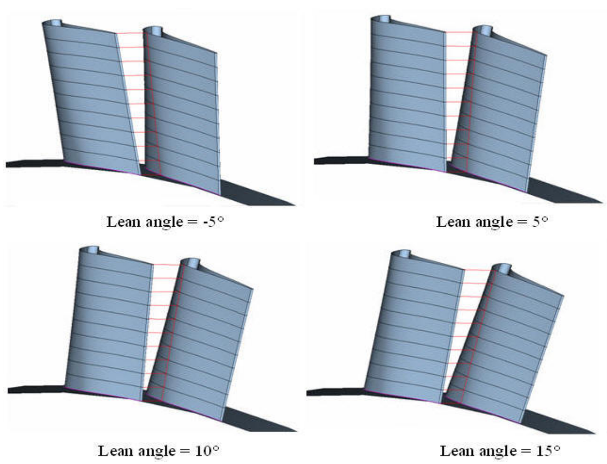

Fig. 1 Sketches of lean blades in stator.

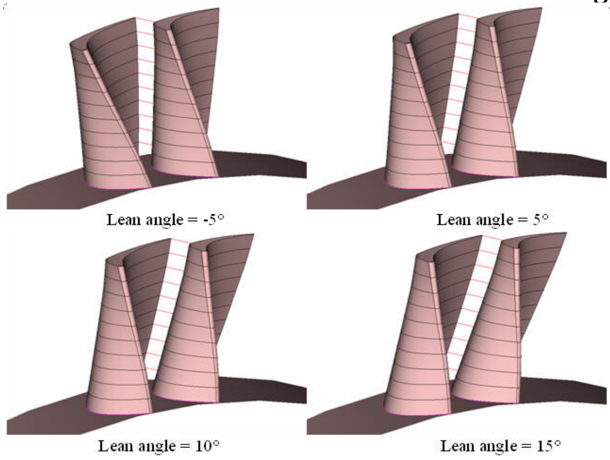

Fig. 2 Sketches of lean blades in rotor.

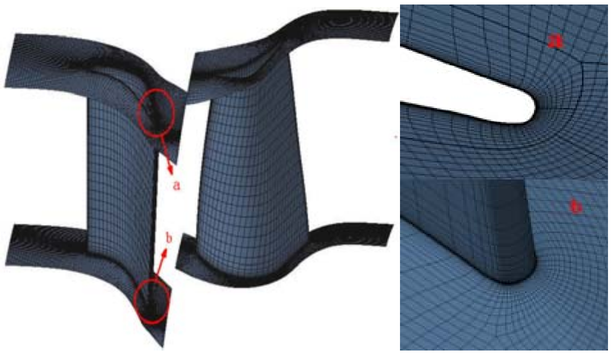

Fig. 3 Geometry and Mesh.

3. RESULTS AND DISCUSSIONS

3.1 Design point performance

The azimuthally averaged results and the comparisons with the elementary design's performance were presented in Table 3. The 3D validated results of optimized design were also listed in this table. Other four results can be found in Fig 4. The max error between two results was only 0.88%. The comparison between through flow calculation and 3D CFD would not be discussed here since which had been discussed by many papers.

Table 3 TF calculation results

Parameters	original	optimized	3D CFD
Eff_iz	0.889	0.903	0.910
Gin (kg/s)	563.3	563.3	563.2
Gout (kg/s)	563.2	563.2	563.2
P0* (MPa)	7.90306	7.90306	7.90306
P2 (MPa)	6.7326	6.7326	6.98
T0 (K)	696..88	696.72	695.92
T2 (K)	674.12	673.65	677.71
Rt	0..36	0.626	0.62
Rm	0.242	0.515	0.45
Rh	0.13	0.370	0.41

3.2.1 Effects on Efficiency and P1

The function curves between eff and L1 and L2 were shown in Fig.4. It can be found that the variation of eff in this case was small because of the limited effect of leaned blade on it. The max raise of eff was only 0.09% by L1 and 0.14% by L2, but eff changed more quickly with L1 than L2. It also can be found that the efficiency after adjusting the rotor inlet mental angle to stator outlet flow angle (marked with "matched" in Fig 4) was increased obviously. The max raise reached 0.17%. So the match between stator and rotor was a important factor can not be neglected.

The reason for the limited changes with eff was presented below. The leaned blade mainly reduced the secondary flow loss through modifying the radial distribution of pressure. The Fig. 5 shows the difference of P1 between tip and hub region was reduced when the leaned angle increased positively. This change may lead to the different entropy variations in tip and hub regions. In Fig.6, it can be seen that the variations of entropy in hub and tip regions were not the same when lean angle changed. When L1 = 15°, the entropy in tip region was obviously increased, however the entropy in hub region was reduced quickly. The variations under L1=-5° was on the contrary and the condition of L1 = 5° was between the former two conditions. So the efficiency maybe will not raise much for the two contrary changes. Even it will be worse if the lean angle was too large. The effect of leaned blade on rotator's performance could be seen in Fig.6. The conditions of 5° and 15° were much better than -5°, that was benefit from the P1 were relatively uniform distributed resulting in the improvement of the flow condition at rotor inlet. The things would be different too with different D/l. In steam turbine with large D/l that the secondary flow loss took a relatively small share in total losses, which was different in turbine with small D/l. So, commonly, the application effect of leaned blade in small D/l condition was more powerful. In this case, D/l is 9.17, relatively large. Then the eff_iz variation range was only from 0.9027 to 0.9044. Although, it still could be found that there was a best lean angle at which the eff_iz of stages reached the peak. In this case, L1 = 0 is not the most efficient point. The best L1 without matching was about 5°, but the best L1 increased to be about 10° after adjusting. The best L2 kept being about 14°. It should be noticed that this best lean angle concept was different to the concept in reference [8] since the latter was corresponding to one row of cascade. In this paper, the best lean angle was corresponding to one whole stage.

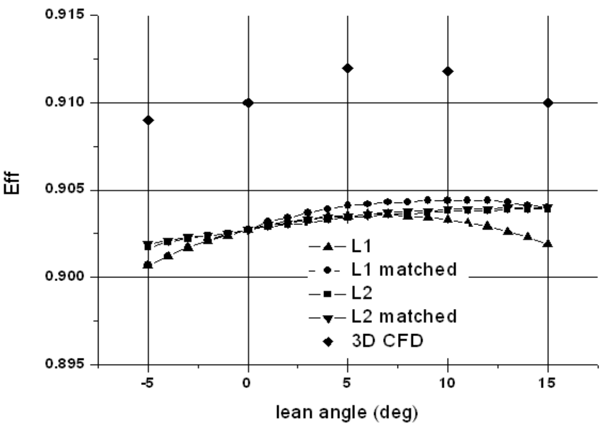

Fig. 4 Eff with L1 and L2.

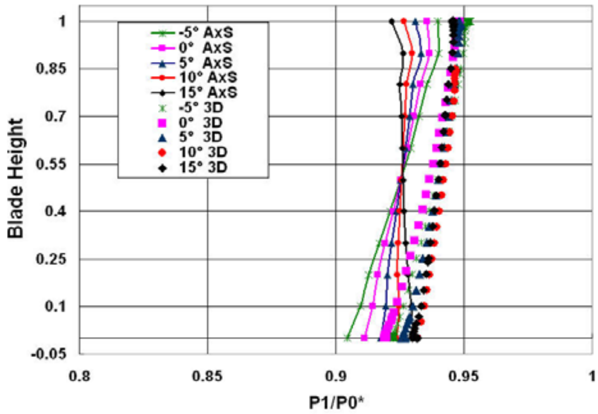

Fig. 5 P1 in radial.

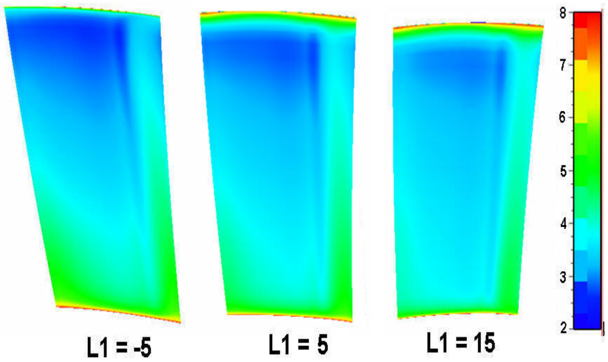

Fig. 6 Entropy at outlet of stator (J/ (kg*k)).

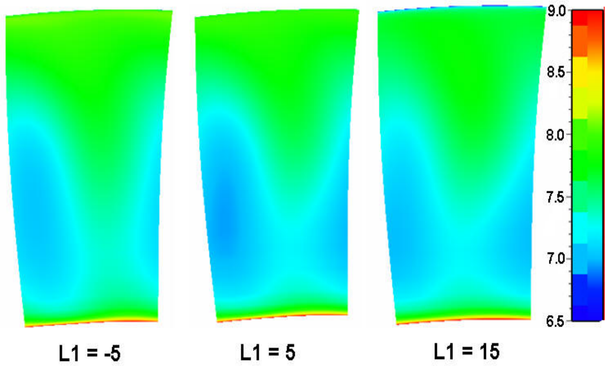

Fig. 7 Entropy at outlet of rotator (J/ (kg*k)).

3.2.2 Variation of U/C0 and Reaction

It was not difficult to understand that U/C0 would decrease with increasing of L1, which was shown in Fig. 7. When L1 increased positively, the blade height in radius was reduced, resulting in the decreasing of U, while C0 was not changed nearly. So the ratio of U and C0 decreased. Since L1 would not be changed so large that the U/C0 would decrease slightly. Things were totally different with the reaction which was really sensitive to the variation of lean angle. The distribution of reaction in hub, mean and tip regions were presented in Fig.8. It is obviously shown that the change of L1 affected reaction distribution greatly. In straight cascade, the reaction along radius is increased form hub to shroud usually because of the centrifugal. The positive leaned blade could reduce the difference of reaction between tip and hub. The Rh increased rapidly from 0.35 to 0.53 with the increase of L1. However, the Rt decreased from 0.61 to 0.49. And the variation of reaction was not so obvious at mean diameter. Rh changes quickest. The reason can be found in Fig.6. With the raise of lean angle, the static pressure of hub increased rapidly, but the static pressure of tip reduced a little. Almost when the lean angle reach to 12° ,the reactions in tip, mean and hub regions are equivalent. This best lean angle is much smaller than the best lean angle corresponding to the highest efficiency. So the stage performance was not best although the reaction was uniform distributed along radius. It means that reaction's distribution was not the factor should be concerned mostly. The variations of A1mid, U/C0 and R under different L2 are the same which are omitted here.

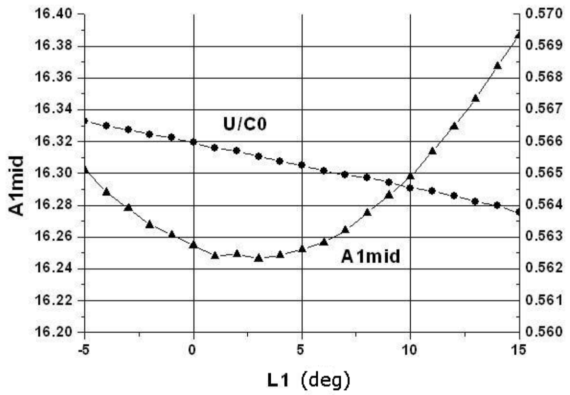

Fig. 8 A1mid (azimuthally averaged) and U/C0

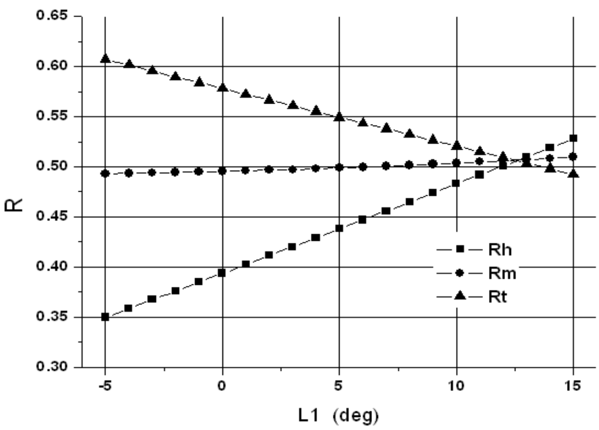

Fig.9 Reaction in hub, mean and tip region.

3.3 The variable working condition and variable D/l

The leaned blade's effect on stage performance under variable working condition was important since the turbine or compressor often worked not on design point. Some researchers had investigated the flow character in cascade passage with leaned blade. This paper mainly focused on the efficiency of stage. Fig 10 and Fig 11 shows the changes of efficiency with rotation speed changing under different L1 and L2. In this case, with rotation speed rising from 2600 rpm to 3600 rpm, the best L1 raised nearly from 5 ° to 10 °. But the best L2 changed little. The change of eff with inlet mass flow rate was seemed to the rotating speed condition, presented in Fig.12 and Fig.13. It seemed that the best L1 was more sensitive to the working condition. It also could be seen form these figs, the positive leaned blade of stator could improve the variable working condition performance of stage. But the effect of leaned blade of rotor was very limited.

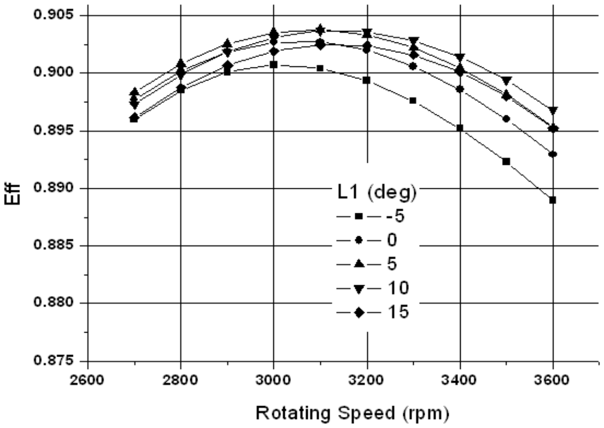

Fig. 10 rotating speed with L1

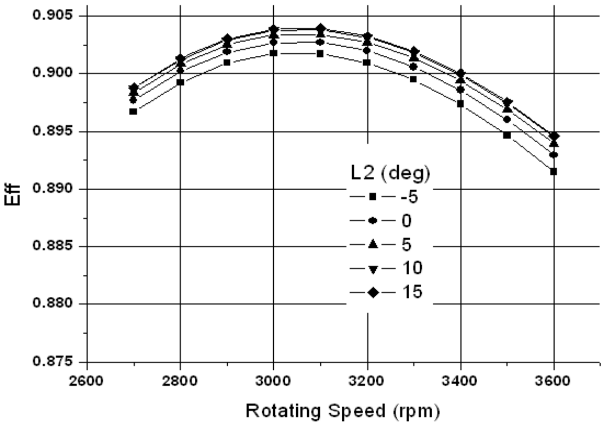

Fig. 11 rotating speed with L2

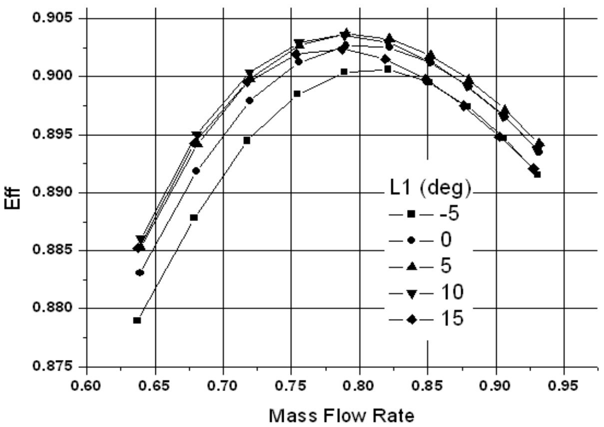

Fig. 12 Mass Flow Rate with L1

In many cases, the same profile of blade will used in different stage with appropriate scaling. So effect of same blade lean angle under different D/l should be think over. The relationship between the best lean angles and n and D/l were presented in Fig 14 and Fig15. It could be found that the effect of D/l to the lean angle was not so great as working condition. And the best lean angle changes were not alike to the rotating speed condition. The best L2 changed greater than the best L1 with different D/l.

Searching for the reasons for the changing law of lean angle with different gas dynamic and geometry condition needs compare the aerodynamic parameters in detail and analyze them with 3D CFD. Since more different geometry conditions needed reset which will take works and time, more detailed investigation about relationship between the best lean angle and D/l, n would be performed in next step.

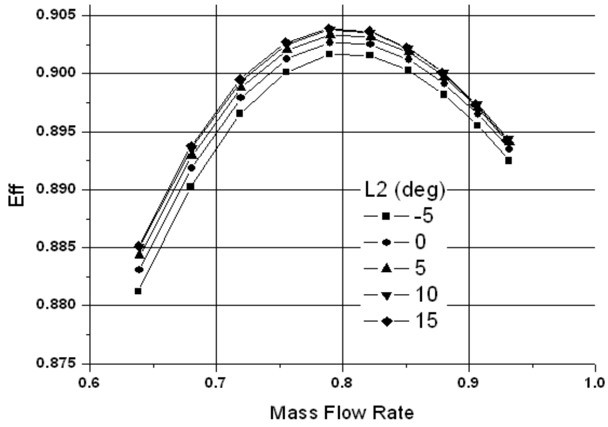

Fig. 13 Mass Flow Rate with L2

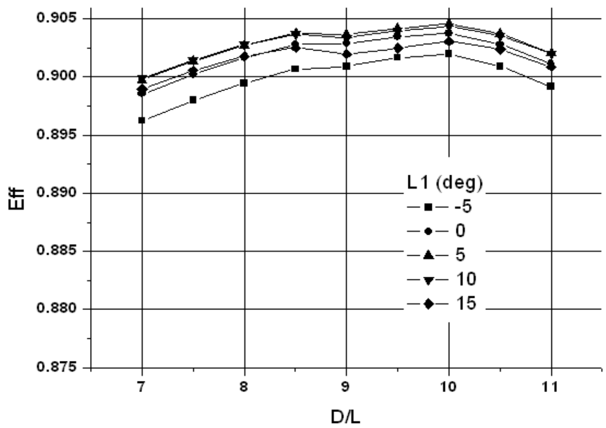

Fig. 14 D/l with L1

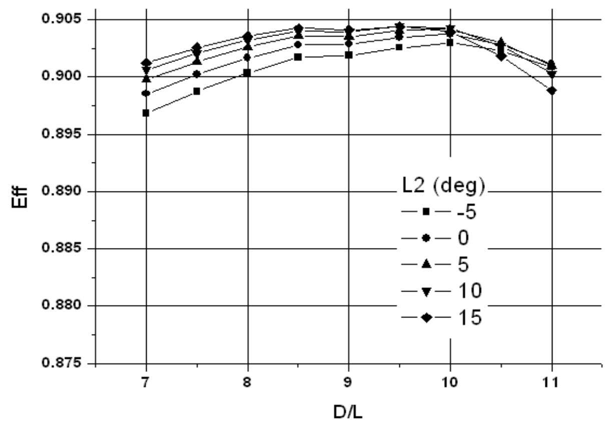

Fig. 15 D/l with L2

5. CONCLUSIONS

1. The investigation shows that positively leaned blading in stator could not only help to improve the flow condition of stage, but also reduce the losses, though this effect on the steam turbine with large D/l is small relatively. The

effect of leaned blading on the flow condition in hub region is larger than in tip region.

2. The matching between stator and rotor could enhance the effect of leaned blade.
3. The positively leaned blade could provide more uniformed distribution of P1 and reaction in radius. During the design process, P1 has more influence than the reaction.
4. The best lean angle of stator blade will be changed with the rotating speed and the inlet mass flow, while the best lean angle of rotor blade will be almost the same. However, the latter was sensitive to D/l than the former.

REFERENCES

[1] H. D. JIANG and H. CAI etc, “Set-up of Aero thermodynamic Design System for the Third Generation Steam Turbine and Its Engineering Verification,” *Electric Power*, Vol.32, No. 11, pp. 26-29, 1999.

[2] M. E. Дейч, A. B. Губарев, , F. A. Филиппов, “Новый метод профилирования направляющих решеток ступеней с малыми d/l,” Теплоэнергетика, 1962, No. 9, PP. 31-35

[3] Z. Q. WANG, W. Y. XU,, W. J. Han, “An Experimental Investigation into the Influence of Blade Leaning on Secondary Flows in Annular Cascades with a Small Diameter-Length Ratio,” ASME Conference, USA, 1985

[4] N. YUAN, Z. Q. WANG and G. T. FENG etc, “Influence on Reaction adopting Bowed Blade in the last stage of 300MW Steam Turbine,” *Journal of Engineering Thermophysics*, Vol.20, No.4, pp. 36-40, 1999.

[5] H. R. ZHOU and G. T. FENG, “Design Thinking and Design Criteria of Twisted Blade and Its Application in Steam Turbine,” *Turbine Technology*, Vol. 43, No. 6, pp. 328-330, 2001.

[6] H. S. WANG, J. J. ZHONG and Z. Q. Wang, “Numerical Investigation of Secondary Flows in a Compressor Cascade with positively leaned Blades,” *Journal of Engineering for Thermal Energy & Power*, Vol. 17,No.4, pp. 375-378, 2002.

[7] C. TAN, “An Experimental Investigation into the Effect of Blade Curving on the Performance of Turbine Cascade Flowfields,” *Doctor Dissertation*, Harbin Institute of Technology, 1993

[8] Z. Q. WANG, W. J. HAN, W. Y. XU, “An Experimental Investigation Into the Influence of Diameter-Blade Height Ratios on Secondary Flow Losses In Annular Cascades with Leaned Blades,” ASME Paper No.87-GT-131

[9] Z. Q. WANG, W. J. HAN, W. Y. XU, “The Effect of Curving on Flow Characteristics in Rectangular Turbine Stator Cascades With Different Incidences,” ASME Paper No.91-GT-60

[10] A. L. YANG, Z. YAO, Q. L. WU, G. Y. ZHUN, “Numerical Study of Flows in the curved-blade stage and Its Redesign for a steam turbine”, *Journal of Aerospace Power, Vol19, No1, Sep, 2004*

[11] Z. H. GU, G. T. FENG, S. T. WANG, Z. Q. WANG, “Analysis of curved rotot in gas turbine with numerical simulation”, *Journal of Engineering Thermophysics, Vol22, No.5, Sep, 2001*

[12] Y. P. SONG, N. LI, S. T. WANG, Z. Q. WANG, “effect of curved rotor on the performance of axial flow transonic compressor”, *Journal of Engineering Thermophysics, Vol25, No.4, Jul, 2004*

[13] AxSTREAM User manual , SoftInWay Company, 2006

[14] FINE/TURBO User manual, Numeca International Company, 2006

[15] L. Moroz and Y. Govoruschenko and P. Pagur, “Axial turbine stages design: 1D/2D/3D simulation, experiment, optimization,” *Proceeding of ASME Turbo Expo 2005, Power for Land, Sea and Air,* June 6-9, 2005 Nevada, USA