

DEVELOPMENT OF ADVANCED VORTEX BOW BLADES FOR TURBINES

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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DEVELOPMENT OF ADVANCED VORTEX BOW BLADES FOR TURBINES

by

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Submitted

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to the



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**DEDICATED TO
MY PARENTS, MY FAMILY AND
MY LAB MATES**

CERTIFICATE

This is to certify that the thesis entitled, “**Development of Advanced Vortex Bow Blades For Turbines**”, being submitted by **Mr. Devershi Mourya** to the Indian Institute of Technology Delhi, India, for award of degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard.

The results contained in the thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma.

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ABSTRACT

Steam and gas turbines comprise a major part of power generation which influence human energy requirements. Thus, the performance of the turbine is critical to enhance the overall efficiency of power-generation plants and propulsion devices. With advancement, there is consensus that a reduction in the number of blades is an effective way of reducing the weight of the turbine to improve its thrust-to-weight ratio. However, the reduction in the number of blades leads to reduction of performance of the turbine due to high blade loading. Geometrical modification of turbine blade design is one of the ways to reduce the weight of the turbine and improve its efficiency. To achieve the same performance with reduced weight, a high-loaded blade can fulfil this, but this leads to an increase in end wall flow. Two efficient methods to reduce enwall loss is sweeping and bowing. In this work, a combined experimental and computational analysis has been developed to understand the clues to reduce the generation of end wall loss in front of the leading edge by using a modified sweep blade. The modified sweep profile has been incorporated at the junction of the leading-edge and hub end wall. To obtain a modified sweep profile six different sweep curves which were created by varying the control points of the Bezier curve are used to fabricate the blades. Thereafter, these blade designs were compared for finding lower end wall losses using total pressure loss, vorticity magnitude and turbulent kinetic energy at the leading edge using computational fluid dynamics analysis. The results suggest that the size of the horseshoe vortex and corner vortex are reduced, which leads to the overall reduction of the vortex-affected region at the leading edge of a second order sweep blade. The reduction of the vortex-affected region further resulted in the disappearance of the secondary and tertiary vortices. The optimized sweep blade profile with the lowest values for all three parameters has been chosen for fabrication using the 3D printing technique. The

fabricated 3D printed blade with the modified sweep profile was tested experimentally in an in-house fabricated wind tunnel. During experiments, the distribution of static pressure was measured around the blade surface near the end wall and total pressure was measured downstream of the cascade at 50% of the axial cord from the trailing edge. The experimental and computational results are found to be in close agreement. It is observed that the simulation can predict the real field performance with an acceptable accuracy. Similar investigations were performed on optimized bow blades for reduction of endwall flow loss within the cascade channel using the same methodology. For optimized bow blade design, bowing improved the static pressure loading locally, which helps to transfer low momentum fluid of endwall towards midspan which leads to cross-flow movement case. Due to this, an improved fluid flow behaviour is observed at the pressure side only. Whereas, on the suction side, due to the increase of low momentum fluid from midspan to endwall, there is an increase in the end wall loss. Therefore, an overall reduction in loss is found to be minimal for bow blades. Finally, an advanced blade profile is obtained by combining both optimized sweep and optimized bow profile to harness the advantages of both designs to obtain improved performance. The advanced turbine blade is tested using the previous methodology for its performance characteristics. It was observed that a high static pressure zone generates between LE & hub endwall. This accelerates the fluid upward and creates faded curls such as HSV and CV after that weak HSV separates out into two components. When the pressure side component of HSV reached inside the cascade passage due to the unavailability of cross-flow, it does not convert into PV and fails to travel inside the passage significantly. Also, the component of HSV on the suction side was weaker thus would travel a shorter distance and being difficult to detect. This advanced blade showed a reduction of ~16 % in total pressure loss coefficient and ~16 % in the vorticity magnitude due to the combination of the optimal shape of a bow with a sweep

profile in the blade cascade. Throughout the investigations, the CFD analysis helped to develop an understanding of the generation and location of vortices, their turbulent kinetic energy value and the distribution of streamline in the fluid. Simulations trajectories were beneficial to gaining insights into complex 3-D flow and the dependence of end wall losses on different parameters including blade design. Overall, the results of this investigation showed that the developed methodology was able to capture the flow behaviour and study the phenomenon of loss generation in front of the leading-edge and inside the cascade near the hub endwall of turbines. It was also found that modification between the junction of leading-edge and endwall able to reduce the generation of vortices in front of leading-edge and also reduce the generation of the cross and down flow, pitch-wise when the spanwise profile of the blade is improved within the cascade channel. the use of simulation data is to capture the generated secondary vortex at the leading edge and within the cascade and after the trailing edge the magnitude of formed vortices and secondary kinetic energy was captured.

संक्षेप

भाप और गैस टर्बाइन बिजली उत्पादन का एक बड़ा हिस्सा होते हैं जो मानव ऊर्जा आवश्यकताओं को प्रभावित करते हैं। इस प्रकार, बिजली पैदा करने वाले उपकरणों की समग्र दक्षता बढ़ाने के लिए टरबाइन का प्रदर्शन महत्वपूर्ण है। प्रगति के साथ, आम सहमति है कि ब्लेड की संख्या में कमी टरबाइन के वजन को कम करने का एक प्रभावी तरीका है ताकि इसके जोर-से-भार अनुपात में सुधार हो सके। हालांकि ब्लेड की संख्या में कमी के साथ टरबाइन का प्रदर्शन कम हो जाता है। और ब्लेड डिजाइन को संशोधित करना टरबाइन के वजन को कम करने और इसकी दक्षता में सुधार करने के तरीकों में से एक है। कम वजन के साथ समान प्रदर्शन प्राप्त करने के लिए, एक उच्च भार वाला ब्लेड इसे पूरा कर सकता है, लेकिन इससे अंत दीवार प्रवाह में वृद्धि होती है। दीवार के नुकसान को कम करने के लिए दो प्रभावी तरीके व्यापक और झुकना है। इस काम में, एक संशोधित स्वीप ब्लेड का उपयोग करके अग्रणी किनारे के सामने अंत दीवार के नुकसान की पीढ़ी को कम करने के लिए एक संयुक्त प्रयोगात्मक और कम्प्यूटेशनल पद्धति विकसित की गई है। संशोधित स्वीप प्रोफाइल को लीडिंग-एज और हब एंड वॉल के जंक्शन पर शामिल किया गया है। एक संशोधित स्वीप प्रोफाइल प्राप्त करने के लिए छह अलग-अलग स्वीप वक्र जो बेज़ियर वक्र के नियंत्रण बिंदुओं को बदलकर बनाए गए थे, ब्लेड बनाने के लिए उपयोग किए जाते हैं। इसके बाद, इन ब्लेड डिजाइनों की तुलना कम्प्यूटेशनल तरल गतिकी विश्लेषण का उपयोग करते हुए कुल दबाव हानि, भ्रमिलता परिमाण और अग्रणी किनारे पर अशांत गतिज ऊर्जा का उपयोग करके अंत दीवार के नुकसान के लिए की गई थी। परिणाम बताते हैं कि घोड़े की नाल के भंवर और कोने के भंवर का आकार कम हो जाता है, जिससे ब्लेड के अग्रणी किनारे पर भंवर प्रभावित क्षेत्र की समग्र कमी हो जाती है। भंवर प्रभावित क्षेत्र में कमी के परिणामस्वरूप द्वितीयक और तृतीयक भंवर गायब हो गए। सभी तीन मापदंडों के लिए न्यूनतम मूल्यों के साथ अनुकूलित स्वीप ब्लेड प्रोफाइल को 3डी प्रिंटिंग तकनीक का उपयोग करके निर्माण के लिए चुना गया है। संशोधित स्वीप प्रोफाइल के साथ निर्मित 3डी प्रिंटेड ब्लेड का प्रयोगात्मक रूप से इन-हाउस निर्मित पवन सुरंग में परीक्षण किया गया था। प्रयोगों के दौरान, स्थिर दबाव के वितरण को अंतिम दीवार के पास ब्लेड की सतह के आसपास मापा गया था और कुल दबाव को कैस्केड के अनुप्रवाह किनारे से अक्षीय कॉर्ड के 50% पर मापा गया था। प्रयोगात्मक और कम्प्यूटेशनल परिणाम निकट समझौते में पाए जाते हैं। यह देखा गया है कि सिमुलेशन स्वीकार्य विचलन के साथ वास्तविक क्षेत्र के प्रदर्शन की भविष्यवाणी कर सकता है। विकसित संयुक्त पद्धति का उपयोग करके कैस्केड चैनल के भीतर एंडवॉल प्रवाह हानि को कम करने के लिए अनुकूलित धनुष ब्लेड पर इसी तरह की जांच की गई थी। अनुकूलित धनुष ब्लेड डिजाइन के लिए, झुकने से स्थानीय स्तर पर स्थिर दबाव लोडिंग में सुधार हुआ, जो एंडवॉल के कम गति वाले द्रव को मिडस्पैन की ओर स्थानांतरित करने में मदद करता है जिससे क्रॉस-फ्लो मूवमेंट केस होता है। इसके कारण बेहतर द्रव प्रवाह व्यवहार केवल दाब पक्ष पर देखा जाता है। जबकि, सक्शन की तरफ, मिडस्पैन से एंडवॉल तक

कम गति वाले तरल पदार्थ की वृद्धि के कारण, अंत की दीवार के नुकसान में वृद्धि होती है। इसलिए, धनुष ब्लेड के लिए नुकसान में समग्र कमी न्यूनतम पाई गई है। अंत में, बेहतर प्रदर्शन प्राप्त करने के लिए दोनों डिजाइनों के लाभों का उपयोग करने के लिए अनुकूलित स्वीप और अनुकूलित धनुष प्रोफाइल दोनों को मिलाकर एक उन्नत ब्लेड प्रोफाइल प्राप्त की जाती है। उन्नत टरबाइन ब्लेड का परीक्षण इसकी प्रदर्शन विशेषताओं के लिए पिछली पद्धति का उपयोग करके किया जाता है। यह देखा गया कि एलई और हब एंडवॉल के बीच एक उच्च स्थैतिक दबाव क्षेत्र उत्पन्न होता है। यह द्रव को ऊपर की ओर तेज करता है और एचएसवी और सीवी जैसे फीका कर्ल बनाता है जिसके बाद कमजोर एचएसवी दो घटकों में अलग हो जाता है। जब क्रॉस-फ्लो की अनुपलब्धता के कारण एचएसवी का दबाव पक्ष घटक कैस्केड मार्ग के अंदर पहुंच जाता है, तो यह पीवी में परिवर्तित नहीं होता है और मार्ग के अंदर महत्वपूर्ण रूप से यात्रा करने में विफल रहता है। इसके अलावा, चूषण पक्ष पर एचएसवी का घटक कमजोर था इसलिए कम दूरी की यात्रा करेगा और पता लगाना मुश्किल होगा। ब्लेड कैस्केड में स्वीप प्रोफाइल के साथ धनुष के इष्टतम आकार के संयोजन के कारण इस उन्नत ब्लेड ने कुल दबाव हानि गुणांक में ~ 16% और भंवर परिमाण में ~ 16% की कमी दिखाई। जांच के दौरान, सीएफडी विश्लेषण ने भंवरों की पीढ़ी और स्थान, उनके अशांत गतिज ऊर्जा मूल्य और द्रव में सुव्यवस्थित के वितरण की समझ विकसित करने में मदद की। सिमुलेशन प्रक्षेपवक्र जटिल 3-डी प्रवाह में अंतर्दृष्टि प्राप्त करने और ब्लेड डिजाइन सहित विभिन्न मापदंडों पर अंत दीवार के नुकसान की निर्भरता के लिए फायदेमंद थे। कुल मिलाकर, इस जांच के परिणामों से पता चला कि विकसित कार्यप्रणाली प्रवाह व्यवहार को पकड़ने और टर्बाइनों के हब एंडवॉल के पास कैस्केड के अंदर और अग्रणी किनारे के सामने हानि उत्पादन की घटना का अध्ययन करने में सक्षम थी। यह भी पाया गया कि अग्रणी-किनारे और एंडवॉल के जंक्शन के बीच संशोधन अग्रणी-किनारे के सामने भंवरों की पीढ़ी को कम करने में सक्षम है और क्रॉस और डाउन फ्लो की पीढ़ी को भी कम करता है, जब ब्लेड की स्पैनवाइज प्रोफाइल पिच-वार होती है कैस्केड चैनल के भीतर सुधार हुआ है। सिमुलेशन डेटा का उपयोग उत्पन्न माध्यमिक भंवर को अग्रणी किनारे पर और कैस्केड के भीतर कैप्चर करना है और अनुगामी किनारे के बाद गठित भंवरों और माध्यमिक गतिज ऊर्जा के परिमाण पर कब्जा कर लिया गया था।

CONTENTS

S.No.	Details	Page No.
	CERTIFICATE	i
	ACKNOWLEDGEMENT	ii
	ABSTRACT	IV
	CONTENTS	IX
	LIST OF TABLES	XIX
	NOMENCLATURES	XX
	CHAPTER - 1	1
1.1	BACKGROUND	1
1.2	MOTIVATION	2
1.3	CHARACTERISTICS OF FLUID FLOW WITHIN THE TURBINE BLADE CASCADE	3
1.4	FEATURES OF THE GENERATED LOSSES IN TURBINE BLADE CASCADE	5
1.4.1	<i>Profile loss</i>	5
1.4.2	<i>Tip leakage loss</i>	6
1.4.3	<i>Endwall loss</i>	7
1.4.4	<i>Need for advanced techniques to control endwall flows</i>	8
1.5	ORGANIZATION OF THESIS	10
	CHAPTER - 2	12
2.1	INTRODUCTION	12
2.2	ENDWALL LOSS STRUCTURE	12
2.2.1	<i>Horseshoe vortex</i>	13
2.2.2	<i>Corner vortex</i>	13
2.2.3	<i>Crossflow</i>	14
2.2.4	<i>Passage vortex</i>	15

2.2.5	<i>Counter vortex</i>	15
2.2.6	<i>Trailing edge vortex</i>	16
2.3	ENDWALL FLOW MODELS	16
2.4	TECHNIQUES TO CONTROL ENDWALL FLOW LOSS	20
2.4.1	<i>Blade Leaning</i>	20
2.4.2	<i>Blade bowing</i>	21
2.4.3	<i>Endwall Contouring</i>	27
2.4.4	<i>Endwall fencing and spitter</i>	28
2.4.5	<i>Endwall slot</i>	29
2.4.6	<i>Leading Edge Sweep</i>	30
2.4.7	<i>Vortex generators</i>	34
2.4.8	<i>Purge flow or synthetic jets</i>	35
2.5	CONCLUSIONS FROM LITERATURE REVIEW	36
2.5.1	<i>Work already accomplished</i>	36
2.5.2	<i>Partially accomplished work</i>	36
2.5.3	<i>Work not attempted (Basis for Novel part of the present work)</i>	37
2.6	OBJECTIVES OF THE PRESENT RESEARCH	38
CHAPTER - 3		39
3.1	INTRODUCTION	39
3.2	CONSTRUCTION OF DATUM TURBINE CASCADE	39
3.2.1	<i>Geometry description of blade profile (E423)</i>	39
3.2.2	<i>Construction of cascade with datum blades</i>	40
3.3	GEOMETRICAL DETAILS OF SWEEP BLADES AND CONSTRUCTION OF CASCADE WITH SWEEP BLADES	42
3.3.1	<i>Geometrical details of sweep profile and sweep blade</i>	43
3.3.2	<i>Linear cascade with sweep blades</i>	44
3.4	GEOMETRICAL DETAILS OF BOW BLADES AND CONSTRUCTION OF CASCADES WITH BOW BLADES	44
3.4.1	<i>Geometrical details of bow shape and bow blade</i>	44

3.4.2	<i>Linear cascade with bow blades</i>	45
3.5	CONSTRUCTION OF A NOVEL LINEAR CASCADE WITH ADVANCED BLADES	46
3.6	DESCRIPTION OF VARIOUS PARAMETERS FOR THE PERFORMANCE ANALYSIS OF TURBINE BLADE:	47
3.7	COMPUTATIONAL FLOW DOMAIN AND GRID GENERATION	47
3.8	MESH GENERATION	49
3.9	TWO EQUATION TURBULENCE MODELS.....	53
3.10	SELECTION OF TURBULENCE MODEL	55
3.11	GRID CONVERGENCE TEST AND SELECTION OF OPTIMAL GRID	58
CHAPTER - 4		61
4.1	INTRODUCTION	61
4.2	LOW-SPEED WIND TUNNEL FACILITY	61
4.2.1	<i>Main Features of the Wind Tunnel</i>	61
4.2.2	<i>Wind Tunnel Test Section</i>	64
4.3	RESEARCH CASCADES	65
4.4	DETAILS OF EQUIPMENT AND INSTRUMENTATION	67
4.4.1	<i>Axial fan run by a variable speed motor</i>	67
4.4.2	<i>Pressure Measuring Probes</i>	67
4.4.3	<i>Digital thermometer</i>	69
4.4.4	<i>Measuring scale, Needle, Syringe with needle and tube</i>	70
4.4.5	<i>Low range digital pressure gauge</i>	71
4.5	METHODOLOGY OF EXPERIMENTATION AND DATA COLLECTION.....	72
4.5.1	<i>Methodology of Experimentation</i>	72
4.5.2	<i>Data Collection and Processing</i>	73
4.5.3	<i>Uncertainty analysis</i>	73
4.6	SUMMARY	74
CHAPTER - 5		76
5.1	INTRODUCTORY REMARKS	76

5.2	SIMULATION OF FLOW THROUGH A LINEAR CASCADE WITH DATUM BLADES	76
5.2.1	<i>Analysis of flow at the foot of central blade Leading edge</i>	<i>76</i>
5.2.2	<i>Study of pressure side flow field of central blade</i>	<i>78</i>
5.2.3	<i>Study of suction side flow field of central blade</i>	<i>79</i>
5.3	STUDY OF THE EFFECT OF SWEEPING ON DATUM BLADES	80
5.3.1	<i>Introduction</i>	<i>80</i>
5.3.2	<i>Sweep curve.....</i>	<i>80</i>
5.3.3	<i>Study of fluid flow filed generated by linear cascade of sweep blades</i>	<i>85</i>
5.3.4	<i>Performance evaluation of optimized sweep blade</i>	<i>97</i>
5.3.5	<i>Experimental verification-</i>	<i>99</i>
CHAPTER - 6		102
6.1	INTRODUCTION	102
6.2	PERFORMANCE ANALYSIS OF BOW BLADES	102
6.2.1	<i>Development of optimal shape model for bow curve.....</i>	<i>103</i>
6.2.2	<i>Selection of Bow angle for second order bow blade.....</i>	<i>104</i>
6.2.3	<i>Bow curve length</i>	<i>105</i>
6.3	DEVELOPMENT OF ADVANCED TURBINE BLADE WITH BOW AND SWEEP	105
6.3.1	<i>Comparative study of fluid flow field generated by three linear cascades.....</i>	<i>106</i>
6.4	EXPERIMENTAL VERIFICATION	120
CHAPTER - 7		122
7.1	MAIN ACHIEVEMENTS.....	122
7.2	MAJOR FINDINGS AND CONCLUSIONS.....	123
7.3	SUGGESTIONS FOR FUTURE WORK	125
Reference.....		126

References

LIST OF FIGURES

Figure 1.1 Role of turbine blade in jet engines	1
Figure 1.2(a) Blade Efficiency for the different blade profiles; (b) Evolution of blade shape	3
Figure 1.3 Characteristics of fluid flow in turbine blade cascade	4
Figure 1.4 Profile loss	6
Figure 1.5 Tip leakage loss	6
Figure 1.6 Schematic description of major features of endwall flow system	8
Figure 1.7 Techniques of reducing Endwall flow	9
Figure 1.8 Brief description of present research work	10
Figure 2.1 Structure of endwall loss	13
Figure 2.3 Endwall cross flow	15
Figure 2.4 Formation of Trailing edge vortex	16
Figure 2.5 Model of Hawthorne for endwall flows	17
Figure 2.6 Endwall flow model of Langton	17
Figure 2.7 Secondary flow models according to (a) Wang (b) Sharma and butler	18
Figure 2.8 Secondary flow model according to Goldstein and Spores	18
Figure 2.9 Endwall flow model of Doerffer and Amecke	19
Figure 2.10 (a) Positive lean blade; (b) Negative lean blade	21
Figure 2.11 (a) Positive bow blade; (b) Negative bow blade	22
Figure 2.12 Endwall Contouring in turbine blade	27
Figure 2.13 Fencing at endwall of turbine blade; (b) Blade with splitters	29
Figure 2.14 (a) Cross section configurations of endwall slotted blade geometry; (b) 3D Model of the End slotted blade	30

Figure 2.15 Leading Edge Sweeping	30
Figure 2.16 (a) Vortex generators on airfoil	34
Figure 2.17 Purge flow in cascade	35
Figure 3.1 Velocity diagram of Datum blade	40
Figure 3.2 (a) Definitions of Datum blade, (b) Schematic representation of Datum blade cascade set up	41
Figure 3.3(a) Definitions of Datum and sweep blade, (b) Schematic representation of sweep blade cascade set up	43
Figure 3.4 (a) Definitions of Bow blade, (b) Schematic representation of Bow blade cascade set up	45
Figure 3.5(a) Definitions of advanced blade, (b) Schematic representation of advanced blade cascade set up	46
Figure 3.6 Computational domain with Boundary conditions	48
Figure 3.7 Datum blade cascade model with block topology	49
Figure 3.9 Comparison between different turbulence models and experimental results of static pressure at blade surface near the hub	58
Figure 3.10. Grid invariance test for (a) The lift to drag ratio predicted for datum blade (b) Total pressure loss coefficient along the spanwise direction at 56% C_{ax} plane. (Re-27106, M-0.015)	59
Figure 4.1(a) Schematic diagram of the experimental set-up, (b) Installed experimental set-up	62
Figure 4.2(a) Schematic diagram of the test section, (b) Photograph of the test section set-up	64
Figure 4.4 Photographs of 9(a) Axial fan and motor, (b) Motor regulator	67

Figure 4.5 Photograph of Pitot tube	68
Figure 4.6 Photograph of Single hole Pitot tube with traversing mechanism	69
Figure 4.7(a) Data logger; (b) thermocouple wire	70
Figure 4.8 miscellaneous tools	71
Figure 4.9 Digital pressure gauge	71
Figure 5.1 Spanwise distribution of streamlines formed by the secondary velocity vector of flow at the foot of the leading edge of datum blade; (a) $Re = 32527$ & $M=0.018$), (b) $Re = 271061$ & $M = 0.15$ and (c) 542122 & $M-0.3$.	77
Figure 5.2 Spanwise distribution of streamline formed by secondary velocity vector on pressure side of datum blade; (a) $Re = 32527$ & $M=0.018$), (b) $Re = 271061$ & $M = 0.15$ and (c) 542122 & $M-0.3$.	78
Figure 5.3 Spanwise distribution of streamline formed by secondary velocity vectors on suction side of datum blade; (a) $Re = 32527$ & $M=0.018$), (b) $Re = 271061$ & $M = 0.15$ and (c) 542122 & $M-0.3$.	79
Figure 5.4. Comparison of different sweep profiles, A-10%, B-15%, C-20%, and D-25% height of the blade	81
Figure 5.5. Performance of various Sweep profiles. Spanwise distribution of (a) TPLC, (b) VM, (c) Tke and (d) TI at 0 % of C_{ax} plane ($Re-27106$, $M-0.015$)	83
Figure 5.6 Spanwise distribution of static of pressure of flow in front of LE: (a) Datum Blade, (b) Optimized sweep blade, ($Re-27106$, $M-0.015$)	86
Figure 5.7 Spanwise distribution of streamline with the secondary velocity vector of flow in front of LE: (a) Datum blade (close picture of CV, SV and TV at Zoom-in section), (b) Optimized sweep blade, ($Re-27106$, $M- 0.015$)	87

Figure 5.8 Span-wise distribution of streamline the secondary velocity vector at different axial plane (a) DP at 23% C_{ax} , (b) DP at 28% C_{ax} , (c) DP at 99% C_{ax} ; (d) OSB at 23% C_{ax} , (e) OSB at 28% C_{ax} , (f) OSB at 99% C_{ax} ; (Re-27106, M-0.015)	89
Figure 5.9 Spanwise distribution of Tke of flow in front of at leading edge (a) Datum Blade, (b) Optimized sweep blade, (Re-27106, M-0.015)	90
Figure 5.10 Spanwise distribution of VM of flow in front of at leading edge: (a) Datum Blade, (b) Optimized sweep blade, (Re-27106, M-0.015)	91
Figure 5.11 Span-wise contour of TPLC at leading edge: (a) Datum Blade, (b) Optimized Sweep Blade, (c) Numerical comparison through graph (Re-27106, M-0.015)	92
Figure 5.12 Span-wise contour of (i) Tke and (ii) VM, at leading edge: (a) Datum Blade, (b) Optimized Sweep Blade, (c) Numerical comparison through graph (Re-27106, M-0.015)	93
Figure 5.13 Span-wise contour of TPLC at 107 % C_{ax} downstream: (a) Datum Blade, (b) Optimized Sweep Blade (Re-27106, M-0.015)	94
Figure 5.14 FigurSpan-wise contour of turbulent kinetic energy at 107 % C_{ax} downstream: (a) Datum blade, (b) Optimized sweep blade, (Re-27106, M-0.015)	95
Figure 5.15 Span-wise contour of Vorticity magnitude at 107 % C_{ax} downstream: (a) Datum blade, (b) Optimized sweep blade, (Re-27106, M-0.015)	96
Figure 5.16 The contour of Vorticity Magnitude at Hub: (a) Datum Blade, (b) Optimized sweep blade, (Re-27106, M-0.015)	96
Figure 5.19 Static pressure distribution on the surface and spanwise variation of TPLC of (a) Datum blade, (b) Optimized sweep blade: (i) 3.33 % of Span (ii) 10 % of Span,	

(iii) TPLC with the height of the span at 121 percent axial chord measured at Re-27106, M-0.015	100
Figure 6.2 Effect of bow angle on performance of second order bow blade	104
Figure 6.3 (a) Effect of bow curve length on performance of second order bow blade with 25° bow angle and (b) Geometry of the optimal bow blade.	105
Figure 6.4 Geometry advanced turbine blade	106
Figure 6.5 Spanwise distribution of (i) Static of pressure, (ii) Streamline and secondary velocity vector of flow in front of LE: (a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep (Re-27106, M-0.015), (close picture of CV, SV and TV at Zoom-in section)	108
Figure 6.6 Span-wise distribution of streamline with the secondary velocity vector at 17% of axial plane; (a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep (Re- 27106, M-0.015	109
Figure 6.7 Span-wise distribution of streamline with the secondary velocity vector at 27% of axial plane; (a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep (Re- 27106, M-0.015	109
Figure 6.8 Spanwise distribution of Tke of flow in front of LE: a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep (Re-27106, M-0.015)	110
Figure 6.9 Spanwise distribution of VM of flow in front of LE: (a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep (Re-27106, M-0.015)	111
Figure 6.10 Span-wise contour of TPLC at leading edge: (a) Datum Blade, (b) Bow blade, (d) Bow blade with sweep, (d) Numerical comparison through graph (Re-27106, M-0.015)	112

Figure 6.11 Span-wise contour of Tke at leading edge: (a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep, (d) Numerical comparison through graph (Re-27106, M-0.015)	113
Figure 6.12 Span-wise contour of Vorticity Magnitude at the leading edge: (a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep, (d) Numerical comparison through graph (Re-27106, M-0.015)	115
Figure 6.13 Span-wise contour of Vorticity Magnitude at leading edge: (a) Datum Blade, (b) Bow blade, (c) Bow blade with sweep, (d) Numerical comparison through graph (Re-27106, M-0.015)	116
Figure 6.16 Evolution of pitch-wise average vorticity magnitude (Re-27106, M-0.015)	119
Figure 6.17 Static pressure distribution on the surface and spanwise variation of TPLC of (a) Bow blade, (b) Bow blade with sweep: (i) 3.33 % of Span (ii) 10 % of Span, (iii) TPLC with the height of the span at 150 percent axial chord measured at (Re-27106, M-0.015)	121

LIST OF TABLES

Table 2.1 Review for bow blades	23
Table 2.2 Review for Leading Edge Sweep	31
Table 3.1 Geometrical specifications of the blades	42
Table 3.2 Details of applied boundary conditions	53
Table 4.1 Reference properties at Upstream of experiment channel	63
Table 4.2 Uncertainty estimates	74
Table 5.1 Comparison of parameters between blades of different sweep profiles measured at the Leading edge or 0% of C_{ax} plane (Re-27106, M-0.015)	84
Table 5.2 Comparison of the overall mass averaged parameters between datum blade and optimum sweep blade	99
Table 6.1 Comparison of overall mass averaged parameters between datum blade, bow blade and Bow blade with sweep	120

NOMENCLATURES

Abbreviation

LEF	Leading Edge sweep
EW	Endwall
HSV	Horseshoe Vortex
LEHSV	Leading Edge Horseshoe Vortex
SSHSV	Suction Side Horseshoe Vortex
PSHSV	Pressure Side Horseshoe Vortex
CFD	Computational Fluid Dynamics
FVM	Finite Volume Method
TM	Turbulence Modelling
EWT	Endwall Treatment
REW	Realizable Endwall
Uref	Reference Free velocity
To,in	Reference Pressure
Pt,ref	Reference Stagnation Pressure
Cpt	Coefficient of total pressure
Pt	Stagnation Pressure

C _{pt} ,	Total pressure loss coefficient
BL	Boundary Layer
AWA	Area weighted averaged
u,v,w	Mean local velocity in the local coordinate system
C _f	Skin friction Coefficient

Greek Symbols

α	Blade angle
ρ	Density
τ_w	Wall shear stress (WSS)