공학석사학위논문

Effects of Large Tip Clearance and Turbulence Intensity on Aerodynamic Performance in a Turbine Cascade

터빈 캐스케이드에서 큰 팁간극과 난류강도가 공력성능에 미치는 영향

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장 원 준

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지도교수 송 성 진

이 논문을 공학석사 학위논문으로 제출함

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장 원 준

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위 원 장 : 최 해 천 (인)

부위원장 : 송 성 진 (인)

위 원 : 박 형 민 (인)

Abstract

Effects of Large Tip Clearance and Turbulence Intensity on Aerodynamic Performance in a Turbine Cascade

Won Joon Jang

School of Mechanical and Aerospace Engineering

The Graduate School

Seoul National University

Turbomachines have been widely used from power generation to aero-naval propulsion. Therefore, numerous studies have been devoted to improve their performance by reducing losses. Especially for aerodynamic performance, numerous efforts have been made to understand aerodynamic loss generation mechanisms in various types of such turbomachines.

Geometric and flow parameters are known to affect the aerodynamic losses. The geometric parameters such as blade configurations include tip clearance (TC), aspect ratio, and roughness. The flow parameters such as inlet flow conditions include turbulence intensity (Tu), incidence angle, Reynolds number, and Mach number.

Tip clearance (TC) is an evitable gap between rotating (rotors) and stationary (casing) components. The typical tip clearance of a turbine in aero engines is roughly 1% of its blade chord length. However, in smaller turbines e.g., turbopumps, the tip clearance becomes larger than 10% of the blade chord length. In a gas turbine, an incoming flow from a combustor is highly turbulent. Effects of the turbulence of the incoming flow past a turbine blade row having large (realistic) tip clearance on aerodynamic performance e.g., loss generation and deviation have not been reported hitherto.

This study, therefore, aims to identify experimentally how the turbulent intensity of the incoming flow influences loss and deviation at a turbine rotor row (in a linear cascade) with a large tip clearance. To this end, three selected turbulence intensity values, 0.6%, 3.3% and 5.3% for four selected tip clearances, 1%, 3%, 10% and 15% of the blade chord were considered at a fixed Reynolds number of 200,000.

Keywords: Large Tip Clearance, Turbulence intensity, Turbine Cascade, Mass-averaged Loss Coefficient

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Nomenclature

C	chord length, m
C_x	axial chord length, m
C_p	static pressure coefficient
H	passage height, m
LE	blade leading edge
PS	pressure side
P_s	static pressure, Pa
P_t	total pressure, Pa
Rms	root mean square
S	pitch, m
$S\ S$	suction side
TC	tip clearance based on chord length, %
Tu	turbulence intensity, %
U	axial velocity, m/s
V	velocity, m/s
X	axial location from the leading edge, m
Y	pitch-wise location, m
$\mathrm{Y_p}$	loss coefficient
Z	span-wise location from the hub endwall, m
β_1	inlet flow angle, ° (degree)
β_2	outlet flow angle, ° (degree)
λ	stagger angle, ° (degree)

Superscript

$-m$	mass averaged value

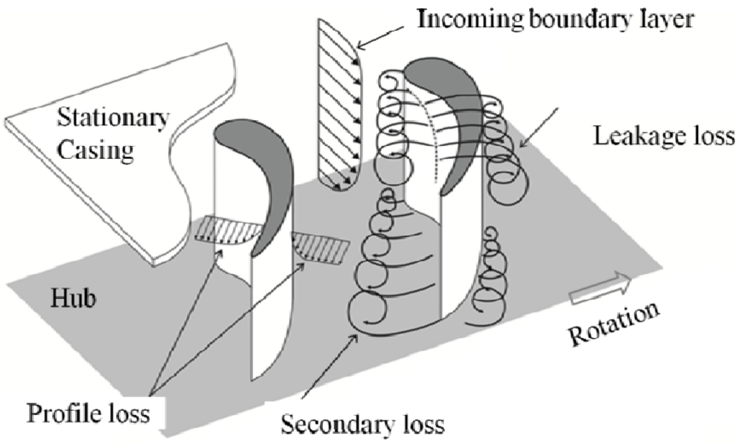
1. Introduction

1.1. Back ground and Motivation

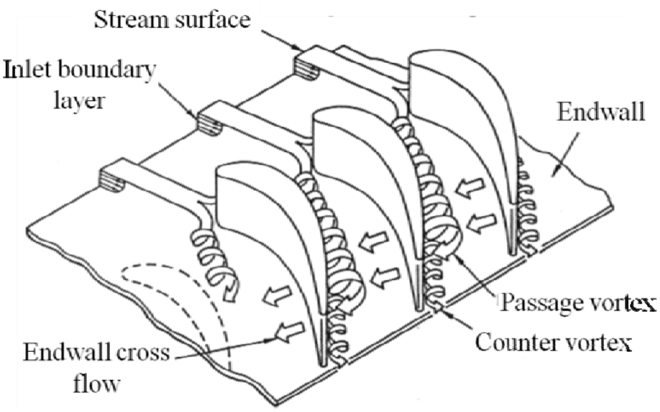
Turbomachines have been widely used from power generation to aero-naval propulsion. Therefore, numerous studies have been devoted to improve their performance by reducing losses. Especially for aerodynamic performance, numerous efforts have been made to understand loss generation mechanisms in various types of such turbomachines.

According to Denton [1], the overall loss consists broadly of profile loss, endwall loss and tip leakage loss. Profile loss is generated in the boundary layers on the blade surface away from the endwalls. Endwall loss is referred to as “secondary” loss because it arises from the secondary flows generated when the boundary layers on the end wall pass through blade rows. Tip leakage loss arises from the leakage flow over the tip of rotor blades and the hub clearance of stator blades. However, it has been argued that these losses are not independent and the interaction, for example, between the leakage loss and the endwall loss may be very strong especially for unshrouded blades.

Sjolander [2] schematically illustrates the mechanisms of loss generation in Fig. 1(a). Explain briefly what he observed in Fig. 1(a) similar to what you did for Fig. 1(b,c).



(a)



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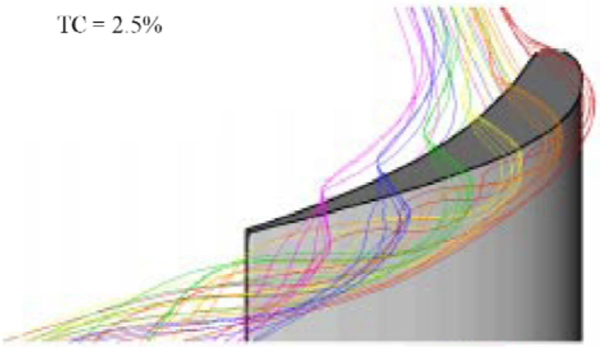


(c)

Figure 1. Loss mechanism and secondary flows formed in turbine rotors;(a) illustrated by Sjolander[2]; (b) by Langston [3]; (c) by Tall-man and Lakshminarayana [6].

Langston [3] reviewed secondary flows in axial turbines and presented their mechanism as illustrated in Fig. 1(b). The inlet boundary layer separates at a saddle point and forms a horseshoe vortex. One leg of this vortex (sometimes called the pressure side leg of the horseshow vortex), drawn into a cascade passage, is fed by the passage pressure towards suction endwall flow and becomes the passage vortex. The other leg (called the suction side leg) is drawn into an adjacent passage and has an opposite sense of rotation to the larger passage vortex. This smaller vortex is labeled as a counter vortex in Fig. 1(b). Sharma and Butler [4] proposed a slightly different version of the vortex pattern to Langston's with the counter vortex wrapping around the passage vortex.

Tip clearance in a turbine induces leakage flow, which arises due to the pressure difference between the pressure side and the suction side of the blade [14]. Sjolander and Amrud [5] performed flow visualization and pressure measurements on the tip gap flow. They proposed that rather than a single tip leakage vortex, there are three different vortices at various chord-wise locations. All of the observed vortices rotated in the same direction, and merged downstream. Tallman and Lakshminarayana [6] performed a numerical simulation of the tip gap flow and observed the flow at variety points. They classified the tip gap flow according to pitch wise location of inlet flow and Fig. 1(c) shows fluid path lines which make up tip leakage vortex.

Geometric and flow parameters are known to affect the above-mentioned aerodynamic losses. The geometric parameters such as blade configurations include tip clearance (TC), aspect ratio, and roughness. The flow parameters such as inlet flow conditions include turbulence intensity (Tu), incidence angle, Reynolds number, and Mach number.

To understand the mechanisms of such losses, this study focuses on the effects of tip clearance, especially a large tip clearance and turbulence intensity on aerodynamic loss and flow turning in a turbine blade cascade.

1.2. Literature Survey

In turbomachines e.g., compressors, turbines, and turbopumps, tip clearance (TC) is an evitable gap between rotating (rotors) and stationary (casing) components. The typical tip clearance of a turbine in aero engines is roughly 1% of its blade chord length. However, in smaller turbines e.g., turbopumps, the tip clearance becomes larger than 10% of the blade chord length. Most of previous studies dealing with the effects of the tip clearance on aerodynamic performance have considered small tip clearances e.g., less than 3% of the blade chord.

Yamamoto [7] studied loss generation in turbine rotor passages due to tip leakage flow where measurements were conducted in a low speed linear cascade for various tip clearances. In this study, three tip clearances, 0.013*C*, 0.021*C* and 0.027*C* as well as no tip clearance case as reference were considered where *C* is the turbine blade's true chord. It has been observed that with small tip clearances, the leakage and passage vortices co-exist without any interaction. This is because the distance of these vortices is far enough apart, compared to the size of the leakage vortex. As tip clearance was increased from TC = 0.013*C* to TC = 0.021*C* and 0.027*C*, the leakage vortex was observed to increase. The interaction became stronger, making the wake region wider. The amount of endwall fluid that is sucked into the tip clearance is increased with an increase in a gap size and so the leakage vortex becomes stronger, while the passage vortex becomes weak.

Few studies have investigated the effects of large tip clearance on aerodynamic performance in turbines. Among these few studies, Lee [8] and Shon [9] considered relatively large tip clearances ranging from 0.01*C* to 0.2*C* where *C* is the turbine blade's true chord. It has been observed that as the tip clearance is increased, the size of the tip passage vortex becomes smaller and the tip passage vortex eventually disappears at TC = 0.075*C* because the tip endwall boundary layer flow gains momentum from the leakage vortex.

With increasing the tip clearance up to 0.1*C*, the tip leakage vortex is increased in size and strength. However, as increasing the tip clearance further (larger than TC = 0.1*C*), the tip leakage vortex does not increase but detaches from the tip endwall.

With the tip clearance less than 0.1C, the fluid could not pass freely through the gap which is between the endwall and the leakage vortex because of the blockage from the tip leakage vortex. But with the tip clearance larger than 0.1*C*, tip leakage vortex detaches from the tip endwall, so the fluid could pass through the gap. The flow through the gap, which is unturned flow, reduces the loss from mixing of leakage flow with passage flow, but decreases aerodynamic performance of turbine. Therefore, mass averaged loss increased up to 0.1*C* of the tip clearance, and then decreased. Aerodynamic performance was decreased for the increased tip clearance.

The flow in a gas turbine is highly turbulent due to the wakes, blade row interaction and jet mixing in combustion chamber. The level of turbulence i.e., turbulence intensity of the incoming flow ranges typically from 3% to 5% in compressors, from 7% to 30% at the exit of combustion chambers, and from 3% to 28% in turbines [10]. Gregory-Smith and Cleak [11] studied the case without a tip clearance and 5% of turbulence intensity adopting parallel arrays of a round rod type turbulence generator. Increasing turbulence intensity was found to decrease boundary layer thickness and secondary loss. Zhang and Hodson [12] studied the case without tip clearance and 4% of turbulence intensity. Reynolds number was varied from 100,000 to 260,000. Increasing turbulence intensity decreased total pressure loss, because high turbulence intensity reduced separation bubble size and the effect of rollup vortex (passage vortex) in the boundary layer. Ciorciari et al. [13] validated experiment data which was conducted without tip clearance and 5.3% of turbulence intensity in a linear turbine cascade. They found that increasing turbulence intensity decreased the strength of passage vortex.

Matsunuma [14] studied turbulence intensity effects with and without tip clearance. Tip clearance was 0.007C, and turbulence intensity was varied between 0.5% and 4.1%. Experiments conducted in annular turbine cascade. At the Reynolds number of 134,000, under high turbulence intensity, the passage vortices at the tip and hub endwall were weakened and pushed towards the endwall.

1.3. Objectives

Despite many researches, the effects of turbulence intensity and large tip clearance on the aerodynamic performance of turbomachines are not understood. Therefore, the present study aims to investigate effects of turbulence intensity (Tu) on performance in a linear turbine cascade with large tip clearance (TC). To this end, aerodynamic performance e.g., loss and deviation is evaluated by measuring total pressure distribution at the downstream of a turbine rotor blade row in a linear cascade. Four tip clearances, 0.01*C*, 0.03*C*, 0.10*C* and 0.15*C* where *C* is the turbine blade's true chord and three turbulence intensities 0.6%, 3.3% and 5.3% were selected. The Reynolds number was fixed at 200,000 during the entire study.

In particular, this study characterizes,

(a) The effects of tip clearance (from 0.01*C* to 0.15*C*) on loss and deviation angle.

(b) The effects of turbulence intensity in each tip clearance on loss and deviation angle.

(c) The combined effects of tip clearance and turbulence intensity on loss and deviation angle.

2. Test Facility and Instrumentation

2.1. Test Facility

Figure 2 schematically shows a test facility, consisting of (a) an AC motor and centrifugal fan, (b) a diffuser, (c) a settling chamber, (d) a contraction section, (e) a flow developing section, and (f) a test section. The air at ambient conditions is supplied at the fixed volume flow rate of 300 m^3/min powered by 15 kW motor.

The settling section contains four mesh screens and a honey comb. Outlet size of contraction section is 200 mm width and 500 mm height. Flow developing section is changeable according to test section and connects wind tunnel and test section. Outlet size of flow developing section is 200 mm width and 476 mm height. In this study, perforate plate type Tu generators are installed in transition section. Test section is a linear turbine cascade type with 8 blades and 7 passages, and equipped tail boards to adjust periodicity. Measurement was conducted in the 0.7 axial chord length upstream of 4^{th} passage and in the 0.2 axial chord length downstream between 4^{th} and 5^{th} blade. Traverse system have 2-axis traversing with yaw angle adjust. All data acquiring procedures using LabVIEW™ are automated. The traverse system is equipped with cobra type 5-hole probe from United Sensor Corp., with this system Pt, Ps, V and flow angle were obtained at 1.2 axial chord length downstream.

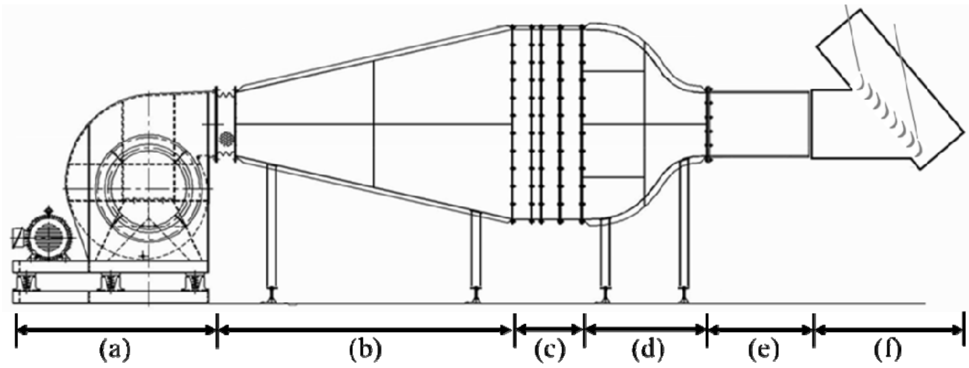


Figure 2. Schematic of test facility showing a test section accommodating a linear cascade.

2.2. Blade Geometry

The blade geometry was referred to LSRR (Large Scale Rotating Rig) at United Technologies Research Center [15]. Details of blade are shown in Fig. 3 and table 1. Chord length of blade is 109.58mm and axial chord length is 93.41mm. Stagger angle, the angle from axial chord direction to chord direction, is 32.12°. Span length, distance between hub endwall and tip endwall, is fixed to 200mm. Pitch length, distance between blades, is 92.34mm, so solidity, chord over pitch, is 1.19. Inlet flow angle is 42.18°, and outlet flow angle is 64.03°.

In this study, tip clearances were 0.01*C*, 0.03*C*, 0.10*C* and 0.15*C*, where *C* is the turbine blade’s true chord. To control tip clearance, blade span length was varied by attaching of detaching additional pieces on the blade tip. Details of tip clearances are shown in table 2.

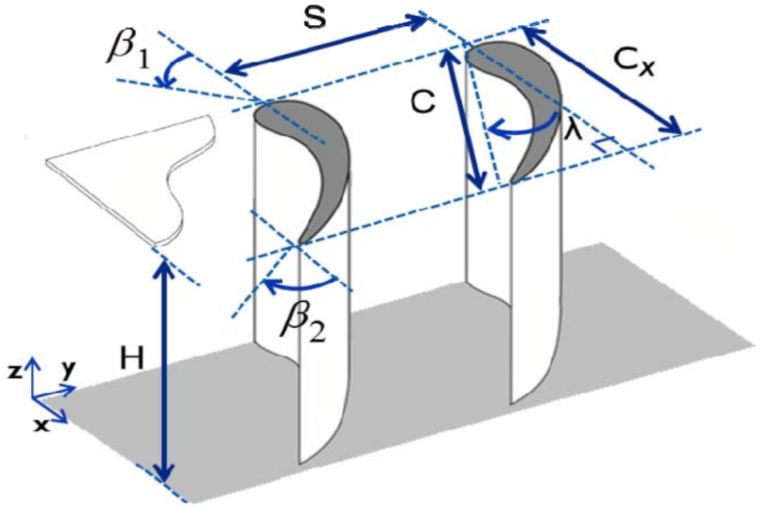


Figure 3. Schematic of the blade geometry used in the present study.

Table 1. Geometric parameters of the blades used in the present study.

Chord length, C	109.58 mm
Axial Chord length, C_x	93.41 mm
Stagger angle, λ	32.12º
Span, H	200 mm
Pitch, S	92.34 mm
Solidity, C/S	1.19
Inlet flow angle, β_1	42.18º
Outlet flow angle, β_2	64.03º

Table 2. Tip clearance setup in the present study.

	1%	3%	10%	15%
Span, H [mm]	198.90	196.71	189.04	183.56
TC [mm]	1.10	3.29	10.96	16.44
Normalized TC/H [mm]	0.55%	1.65%	5.48%	8.22%

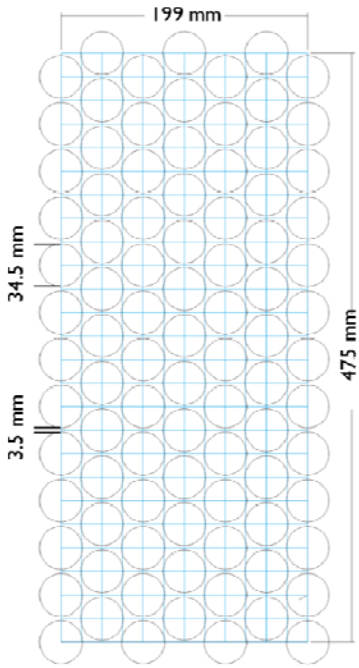
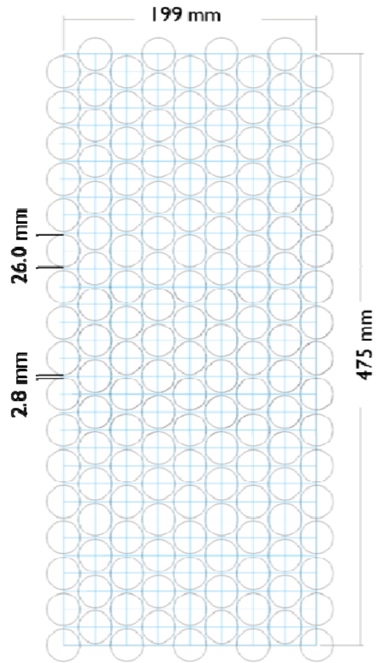
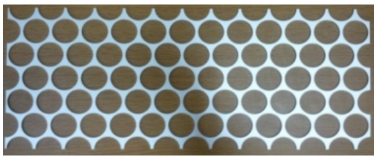
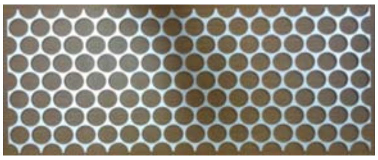
2.3. Turbulence Generator

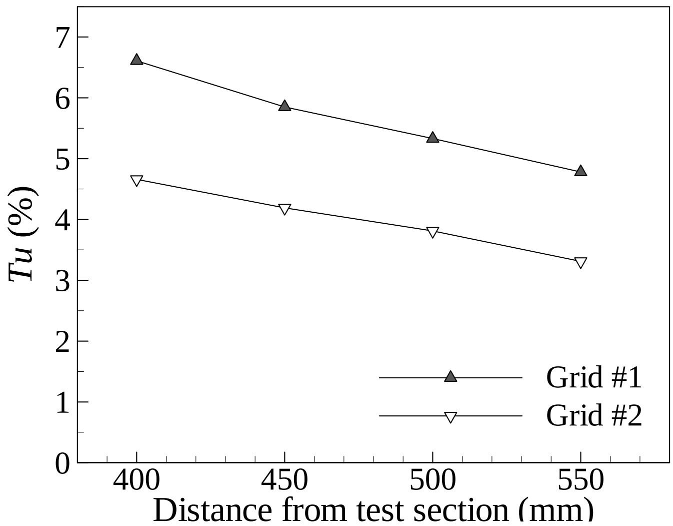
Grids have been used as a means of generating nearly isotropic turbulence [17]. There are many types of grid, square-mesh arrays of round rods, square-mesh arrays of square bars, parallel arrays of round rods, parallel arrays of square bars and perforated plates. In this study perforated plate type turbulence generator was used, because they enable to generate a turbulence approximating a homogeneous and isotropic turbulence, even for a high level of turbulence intensity [18].

Two kinds of perforate plates were designed to make different turbulence intensity. The plate total area was 199 mm width and 475 mm height. The diameters of perforated hole were 34.5 mm and 26 mm, respectively. The open area ratio, which defined as area of perforated holes over total area, of perforated plates were nearly same as 0.741. The plates thickness were 3mm. Perforate plate type Tu generators have installed in flow developing section

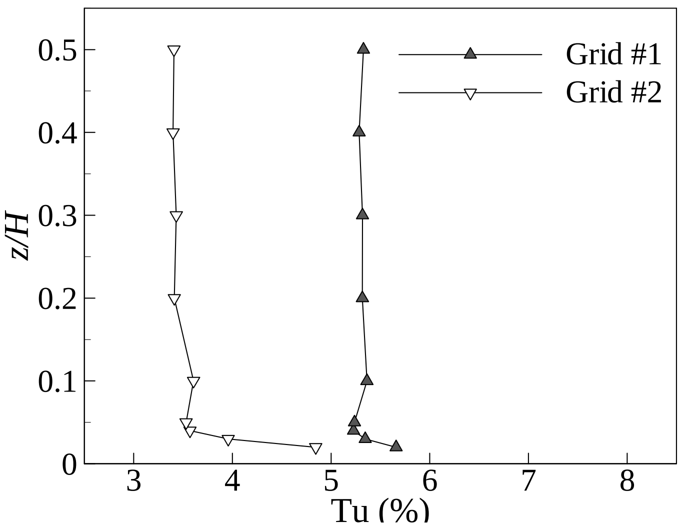
To get turbulence intensity data at various locations of perforate plates in flow developing section were tested. The location ranged from 400 mm to 550 mm upstream of test section. Considered the value of turbulence intensity and the distribution of turbulence intensity for span wise direction, grid #1 located 500 mm upstream of test section and turbulence intensity was 5.3%, grid #2 located 550 mm upstream of test section and turbulence intensity was 3.3%. Fig. 4 shows the results of test.

Table 3. Details of two turbulence generators, employing a perforated plate type grid.

	Grid #1	Grid #2
Design		
Products		
Hole Diameter	34.5 mm	26.0 mm
Number of perforated holes	75	132
Thickness	3 mm	3 mm
Total Area	9.4525×10^{-2} m^2	9.4525×10^{-2} m^2
Open Area	7.0076×10^{-2} m^2	7.0047×10^{-2} m^2
Open Area ratio	0.7413	0.7410



(a)



(b)

Figure 4. Measured turbulence intensities: (a) varied distance; (b) selected turbulence intensity in present study.

2.4. Cascade and Measuring Points

The schematic of cascade and measuring points are shown in Fig.5.

At 0.7 C_x upstream from leading edge, upstream flow condition and Tu were measured using pitot tube (United Sensor™) and 55P11 type hot-wire probe (Dantec Dynamics™), respectively.

At 1.1 C_x downstream from leading edge, Periodicity was measured through hub endwall static pressure tap. The results of periodicity are shown in Fig. 6. Periodicity was controlled by tail board. The peak value difference of C_p was controlled in the range of 3%.

At 1.2 C_x downstream from leading edge, downstream condition was measured using the 5-hole probe. As shown in Fig. 7, measurement positions were pitch-wise 39 points, span-wise 39 points (from 11.62% to 99.25% of span) total 1,521 points. To obtain detailed loss mechanism, measuring points were set denser at tip region.

Pressure Systems Inc. Net Scanner™ was used for both static pressure and 5-hole probe data, as differential pressure transducer. The specification of the sensor range was ±2.5kPa and uncertainty was ±0.5% of full scale. Uncertainties [19] associated with loss coefficient and flow angles were evaluated to be within ±0.003 and ±1.0 degree, respectively.

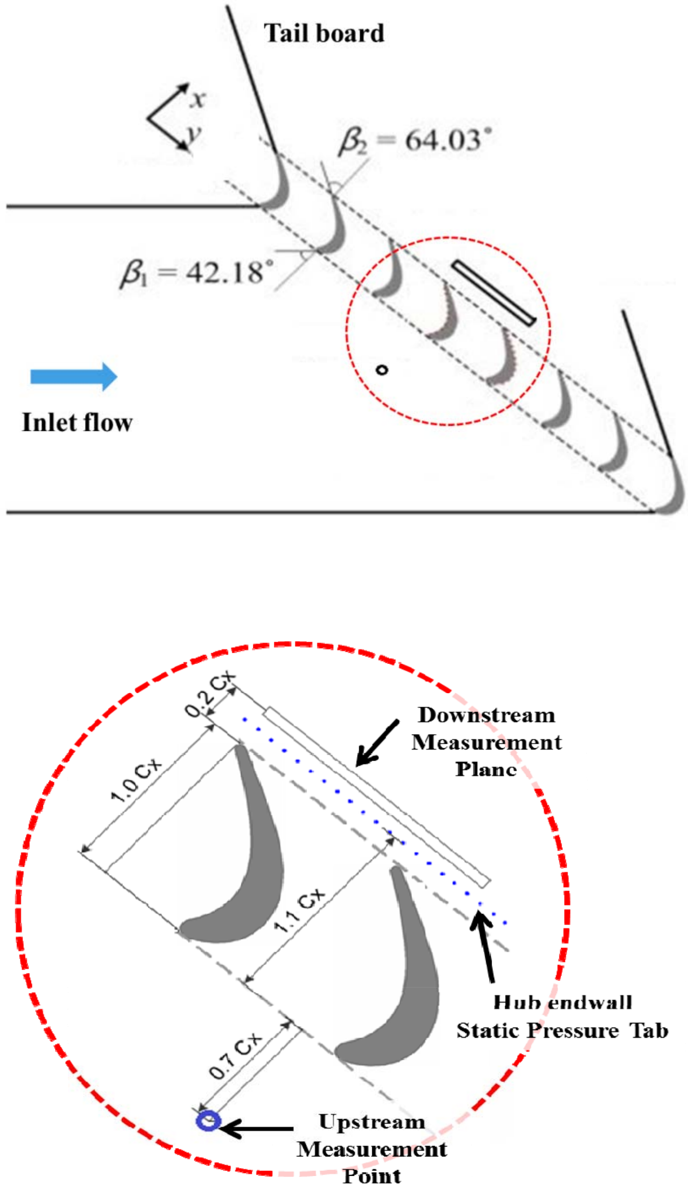


Figure 5. Schematic of turbine cascade measuring points.

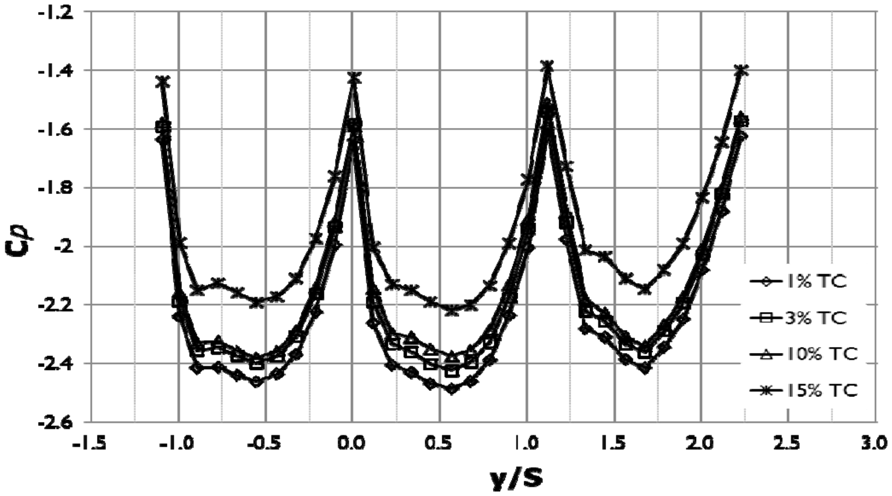


Figure 6. Periodicity varying tip clearance from 1% to 15% (Tu=0.6%).

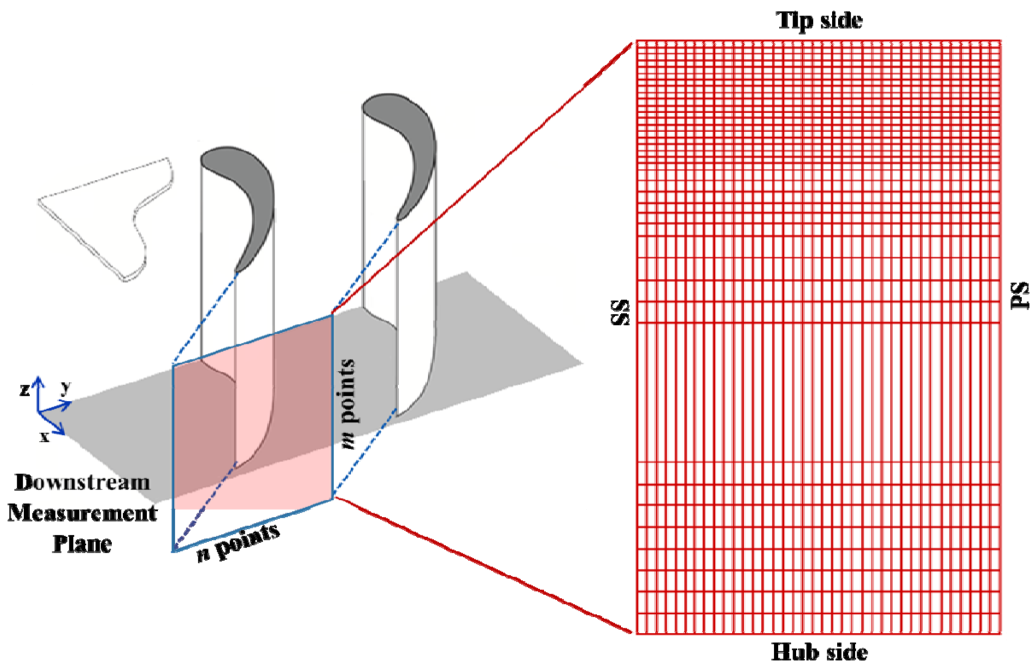


Figure 7. Schematic of linear turbine cascade

(where m = 39, n = 39, SS = suction side, PS = pressure side).

2.5. Data Reduction Parameters

2.5.1. Turbulence intensity (Tu)

The nature of the turbulence in a wind tunnel of conventional design can be expected to be homogeneous and nearly isotropic states [16]. Tu is defined as Equation 1.

$$\mathrm{Tu} = \frac{\sqrt{u_{rms}^2}}{V} \qquad (1)$$

2.5.2. Loss coefficient (Y_p)

Loss coefficient ($\mathrm{Y_p}$) is defined as Equation 2. Difference between $0.7C_x$ upstream and $1.2C_x$ downstream total pressure is non-dimensionalized based on mixed out velocity dynamic head.

$$Y_p = \frac{P_{t,inlet} - P_{t,exit}}{\frac{1}{2}\rho V_{mixedout}^2} \qquad (2)$$

2.5.3. Mass-averaged loss coefficient (Y_p^m)

Overall loss level can be evaluated using mass-averaged loss coefficient. Mass averaged loss coefficient is defined as Equation 3.

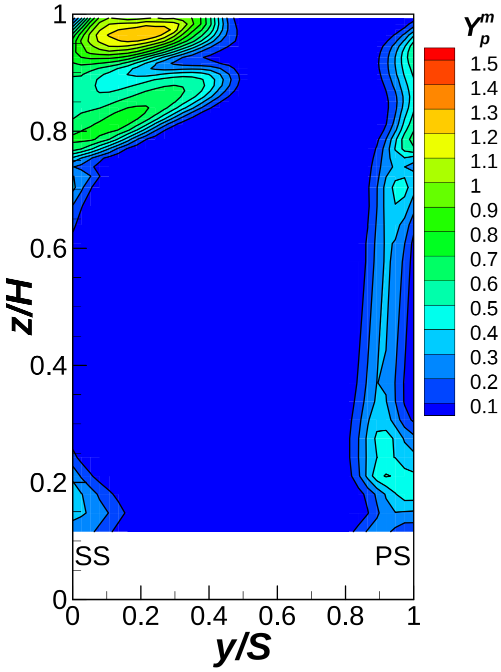
$$\overline{Y}_p^m = \frac{P_{t,inlet} - \overline{P}_t^m}{\frac{1}{2}\rho V_{mixedout}^2} \qquad (3)$$

3. Discussion of Results

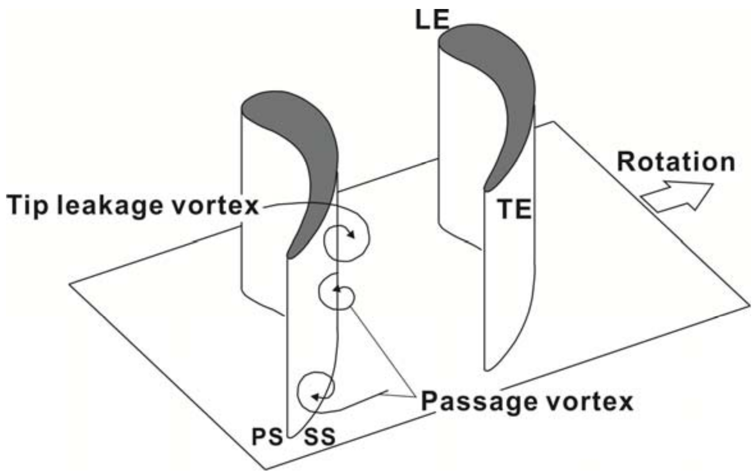
3.1. Local coefficient distribution at low turbulence level (Tu =0.6%)

Loss generation at the immediate downstream of the turbine rotor blade row for a small tip clearance (TC = 0.01*C*) and a low turbulence level (Tu = 0.6%) is considered first as reference where *C* is the true chord of turbine blades. Figure 8 shows the loss coefficient contour at the downstream traverse plane ($0.2C_x$) from the trailing edge. Here, C_x is the axial chord. Two high loss regions are formed near the tip region (*z/H*=1.0) at *y/S*=0.2 as shown in Fig. 8(a). Another high loss region but not as high as those formed near the tip region in magnitude is also formed at the corner of the hub endwall (*z/H*=0.0) and the blade suction side (*y/S*=0.0).

As the mainstream near the tip region leaks through the tip clearance, it rolls up to form a tip leakage vortex (having a clock-wise circulation when viewed from downstream) as indicated in Fig. 8(b), which is responsible for the high loss region formed in the vicinity of the blade tip. The second high loss is generated slightly below the high loss region caused by the tip leakage vortex (having a counter-clock-wise circulation), which forms due to the passage vortex that is convected from the pressure side of the neighboring turbine blade tip (see Fig. 8(b)).



(a)



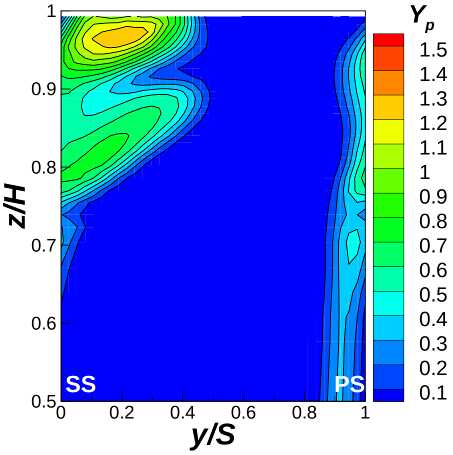
(b)

Figure 8. Loss generation at the downstream of a turbine rotor blade row for TC = 0.01*C* (C=chord length) and Tu = 0.6%; (a) Down-stream loss coefficient (Y_p) contour; (b) Identified high loss sources.

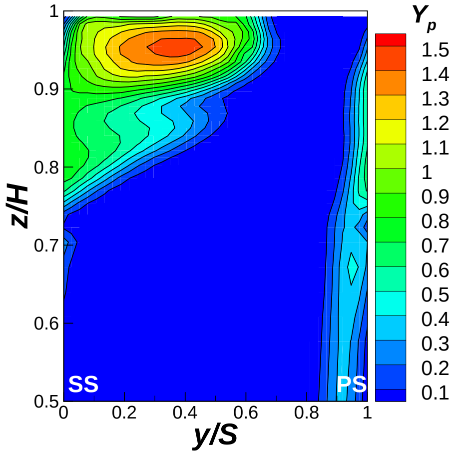
The high loss region that formed at the corner of the endwall (*z/H*=0.0) and blade suction side (*y/S*=0.0) results from the passage vortex that is convected from the pressure side of the neighboring turbine blade hub. The intensity of this passage vortex seems to be weaker than that formed near the tip region, causing the lower loss.A narrow and span-wisely long high loss region is formed at *y/S* = 0.9. This results from boundary layer separation from the turbine blade surfaces – the profile loss.

Now it is of interest to examine how an increase in tip clearance influences the loss in terms of distribution and magnitude. The tip clearance (TC) is increased from TC=0.01*C* up to TC=0.15*C* whilst the turbulence level remains unchanged i.e., Tu=0.6%. Results in Fig. 9 where only an upper half span is considered i.e., $z/H \geq 0.5$, depict that the high loss region caused by the tip leakage vortex is moved towards the mid-passage and becomes stronger in magnitude until TC=0.10*C*. After which, the increased tip clearance conversely but slightly reduces the size of the high loss region, consistent with the findings reported in Refs. [12,13]. The high loss region appears to be squeezed or concentrated.

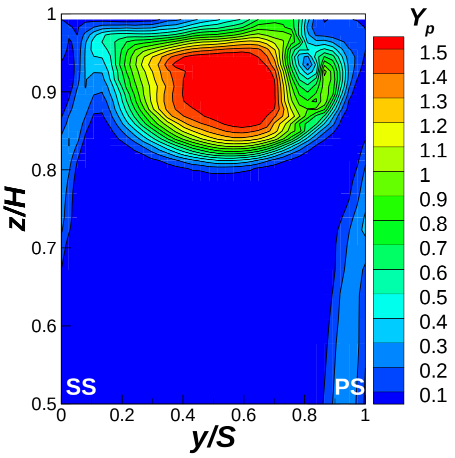
On the other hand, another high loss region caused by the passage vortex is reduced in size and eventually disappears, consistent with the findings reported in Ref. [11].



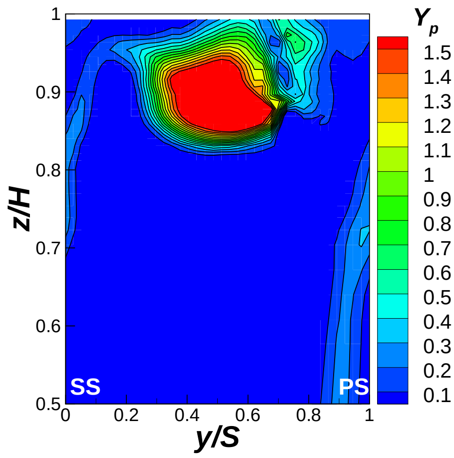
(a) TC = 0.01*C*



(b) TC = 0.03*C*



(c) TC = 0.10*C*



(d) TC = 0.15*C*

Figure 9. Effect of the tip clearance on loss generation with a low turbulence level, Tu=0.6%; (a) TC=0.01*C*; (b) TC=0.03*C*; (c) TC=0.1*C*; (d) TC=0.15*C*.

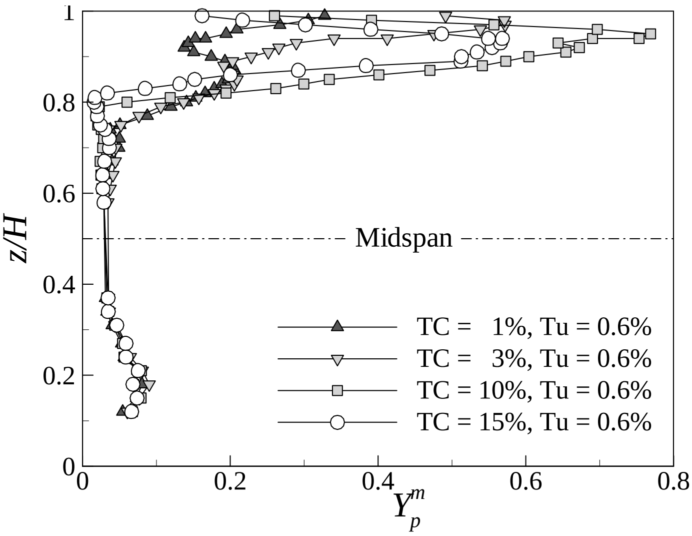


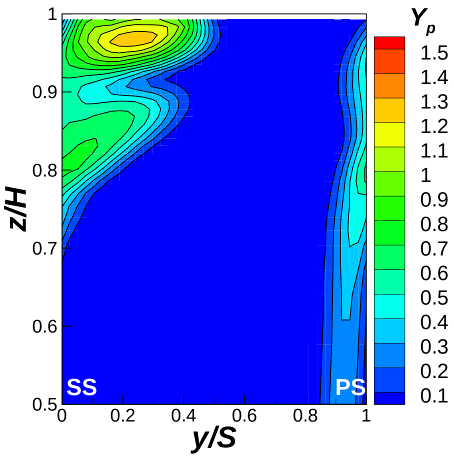
Figure 10. Span-wise distribution of pitch-wise mass averaged loss coefficients (Y_p^m) for a fixed low turbulence level, Tu=0.6%.

To quantify the effect of the tip clearance on loss distribution along the blade span (*z/H*) at the low turbulence level (Tu=0.6%), the data of the loss contours in Figs. 7 and 8 was mass-averaged pitch-wisely. Results in Fig. 10 exhibit that the flow in the hub region ($z/H \leq 0.5$) is unaffected by the varied tip clearance. For example with TC≦0.03*C* (or 3% of the blade chord), the high loss indicated in the range from *z/H*= 0.7 to 0.9 is caused by the passage vortex and another high loss exists at *z/H*= 0.9 results from the tip leakage vortex. The passage vortex influences the loss, Y_p^m significantly and can be distinguished from the tip leakage vortex. However, with larger tip clearances e.g., TC≧0.10*C* (or 10% of the blade chord), only a single peak (or high loss region) is visible, resulting from the tip leakage vortex.

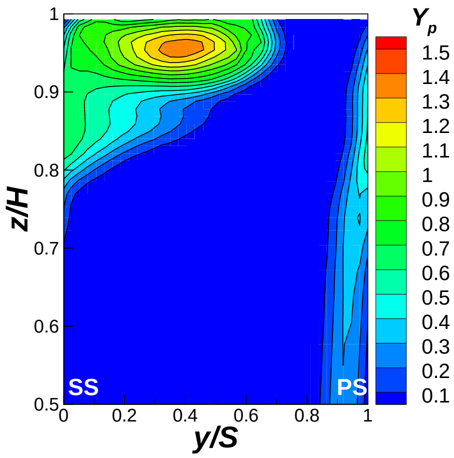
3.2. Variation of loss distribution with tip clearance at high turbulence level (Tu=5.3%)

Now, the variation of loss distribution at the highly turbulent mainstream i.e., Tu = 5.3% is considered while the tip clearance (TC) is varied from TC=0.01*C* (1% of the blade chord) up to TC=0.15*C* (15% of the blade chord). Results in Fig. 11 where only an upper half of the turbine blade span is considered i.e., $z/H \geq 0.5$ show that the loss distribution at high turbulence level (Tu=5.3%) responds to the tip clearance variation in a similar manner to that with the low turbulence level (Tu=0.6). The high loss region caused by the tip leakage vortex is moved towards the mid-passage and becomes stronger in magnitude up to TC=0.10*C*. However, after which, the tip leakage vortex becomes weaker e.g., at TC=0.15*C*, consistent with the findings reported in Refs. [12, 13]. Furthermore, the high loss region caused by the passage vortex is reduced in size and eventually disappears, also consistent with the findings reported in Ref. [11].

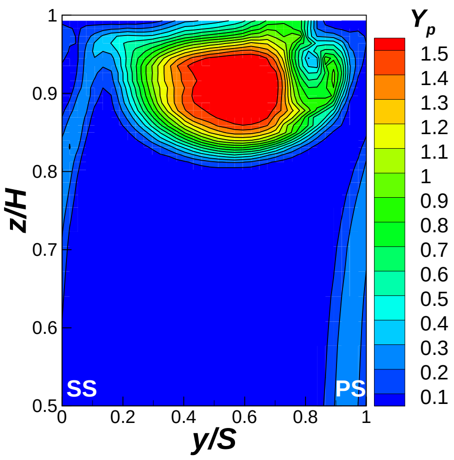
To better understand how the turbulence intensity (Tu) affect the loss, a comparison between the two turbulence intensities (Tu=0.6% and Tu=5.3%) is made for the four selected tip clearance cases in Fig. 12. The span-wise distributions of the pitch-wise mass averaged loss coefficient show that the high loss region caused by the tip leakage vortex is independent of the turbulence intensity in strength and larger in size. However, the loss resulting from the passage vortex near the tip region becomes slightly weaker only at smaller tip clearances such as TC=0.01C and 0.03C. At larger tip clearances such as TC=0.1C and 0.15C, no visible effect is seen, consistent with the findings reported in Refs. [12-14].



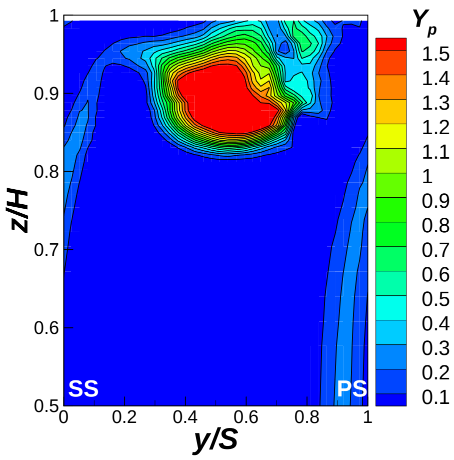
(a) TC = 0.01*C*



(b) TC = 0.03*C*

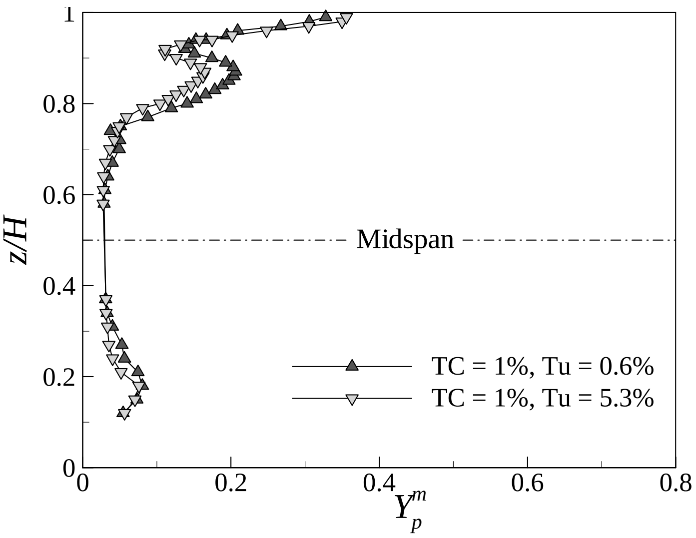


(c) TC = 0.10*C*

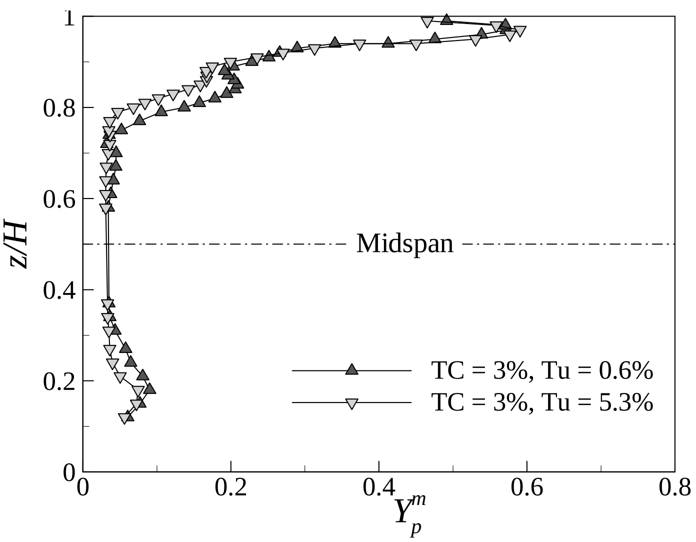


(d) TC = 0.15*C*

Figure 11. Effect of the tip clearance on loss generation with a high turbulence level, Tu=5.3%; (a) TC=0.01*C*; (b) TC=0.03*C*; (c) TC=0.1*C*; (d) TC=0.15*C*.

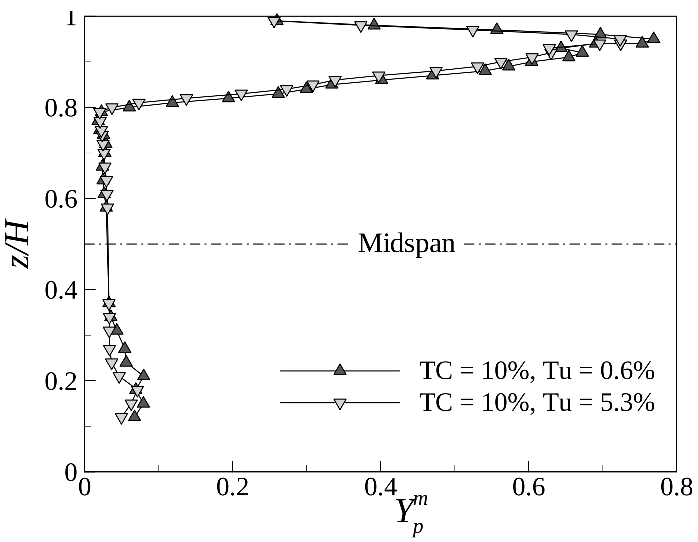


(a)

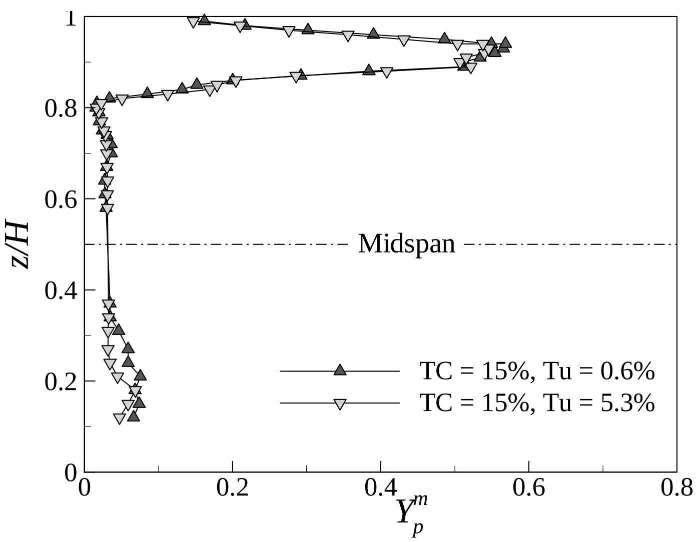


(b)

Figure 12. Span-wise distributions of pitch-wise mass averaged loss coefficient; (a) TC=0.01*C*; (b) TC=0.03*C*; (c) TC=0.1*C*; (d) TC=0.15*C*.



(c)



(d)

Figure 12. Span-wise distributions of pitch-wise mass averaged loss coefficient; (a) TC=0.01*C*; (b) TC=0.03*C*; (c) TC=0.1*C*; (d) TC=0.15*C*.

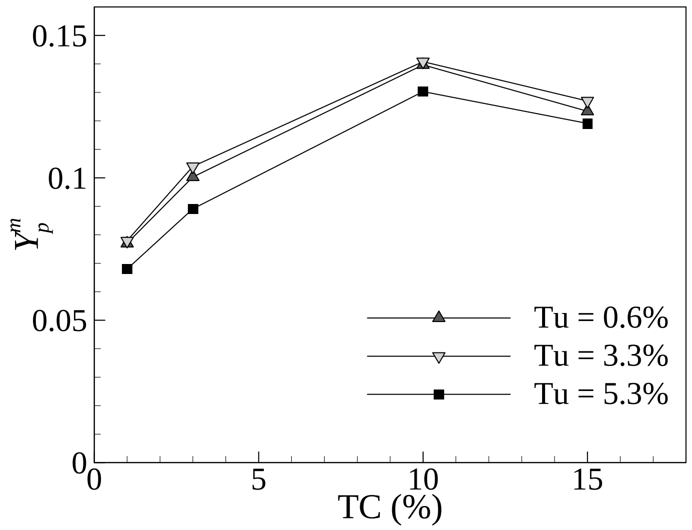
3.3. Mass-averaged Overall Loss

Overall loss generated through a turbine blade row is evaluated by the mass averaged loss coefficient, Y^m_p. In Fig. 13(a), the smaller tip clearance than 10% of the blade chord causes a monotonic increase in the overall loss as increasing the tip clearance. However, a further increase in the tip clearance from which, conversely leads to a decrease in the overall loss.

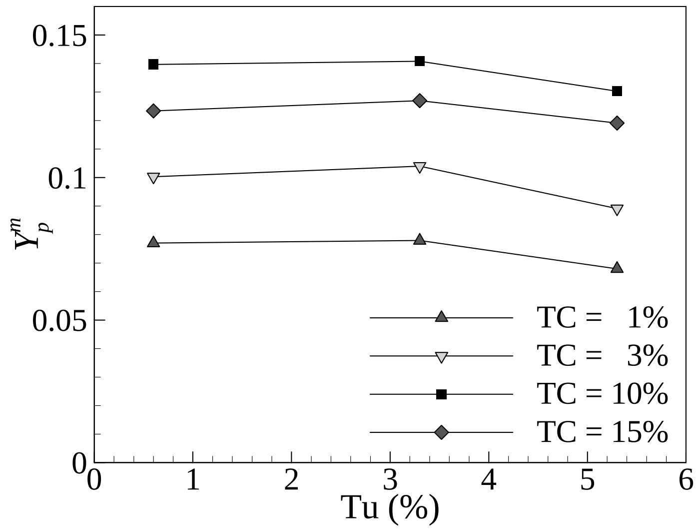
To quantify how the level of turbulence i.e., turbulence intensity affects the overall loss for a given tip clearance, the data in Fig. 13(a) is extracted and results are re-plotted in Fig. 13(b) as a function of turbulence intensity. The mass-averaged loss is almost independent of the turbulence intensity when it is low e.g., up to Tu=3.3%. However, it becomes higher e.g., Tu=5.3%. The increased Tu is observed to reduce slightly the loss regardless of the tip clearance considered in ths present study as also tabulated in Table 4.

Table 4. Mass averaged loss coefficient data for the presently considered cases.

Tu	TC			
	1%	3%	10%	15%
0.6 %	0.0770	0.1003	0.1397	0.1234
5.3 %	0.0680	0.0891	0.1303	0.1191
Reduction rate	11.77 %	11.12 %	6.72 %	3.52 %



(a)



(b)

Figure 13. Dependence of the mass averaged loss ($Y_p{}^m$) on (a) Tip clearance (TC) and (b) Turbulence intensity (Tu).

3.4. Flow Turning Characteristics

Fig. 14 shows the span-wise distribution of pitch-wise mass averaged deviation measured at $0.2\,C_x$ downstream from the trailing edge with the tip clearance varying from TC=0.01*C* to TC=0.15*C* and Tu=0.06% fixed. The deviation is a difference between the exit flow angle and the exit blade angle. Positive deviation means that the flow exiting the turbine blade row is under-turned.

Below *z/H*=0.5 (from hub to mid-span), the increased tip clearance does not affect the deviation at all. There is a local peak of the deviation at about *z/H*=0.2, resulting from the passage vortex.

Another local peak of the deviation at about z/H=0.8 also results from the passage vortex. However, the deviation here is decreased suddenly after TC=0.03*C* and eventually the local peak formed due to the passage vortex disappears.

A substantial response of the deviation to the tip clearance can be observed near the tip endwall. As the tip clearance is increased, the extent of the flow under-turning (or the increase in the deviation) becomes significant. This means that the tip leakage flow becomes more axial. However, a stronger flow mixing with the mainstream that exits the blade passage with a smaller deviation. The difference of the deviation between the tip leakage flow and the mainstream is larger for the larger tip clearance. However, for large tip clearances e.g., TC=0.10*C* and 0.15*C*, the deviation difference between the two appears to be marginal.

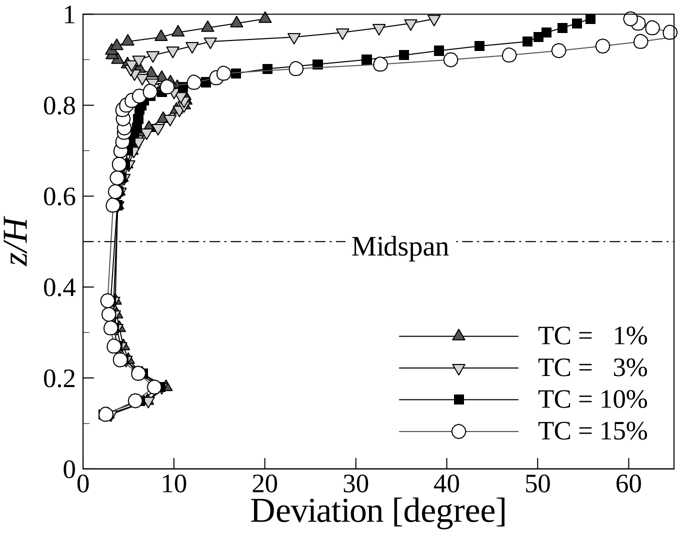
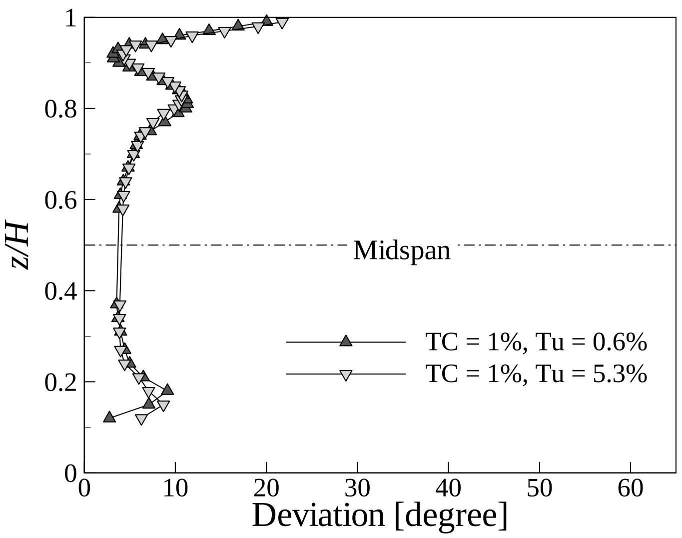
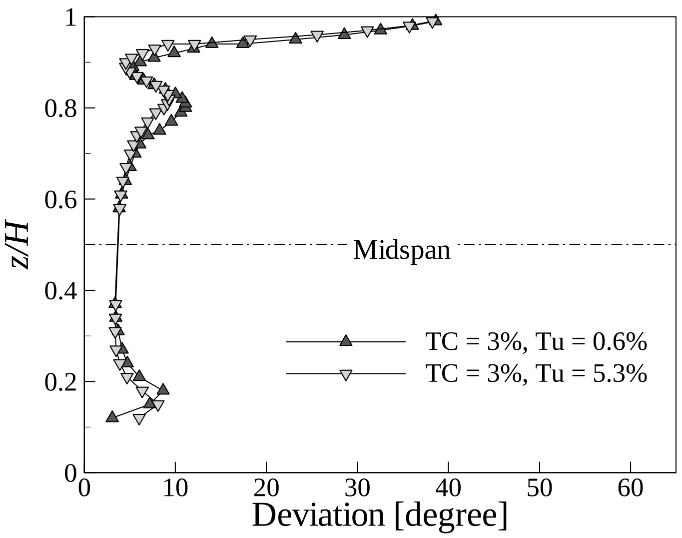


Figure 14. Span-wise distributions of pitch-wise mass averaged deviation an gle with TC from 1% to 15% (Tu = 0.6%).

Now, it is of interest to examine the role of turbulence intensity in affecting the observed deviation considered in Fig. 14 whilst varying the tip clearance. Figure 15 shows the span-wise distribution of pitch-wise mass averaged deviation for the four selected tip clearances. In all the tip clearances considered in the present study, there is no visible influence of the turbulence intensity on the deviation.

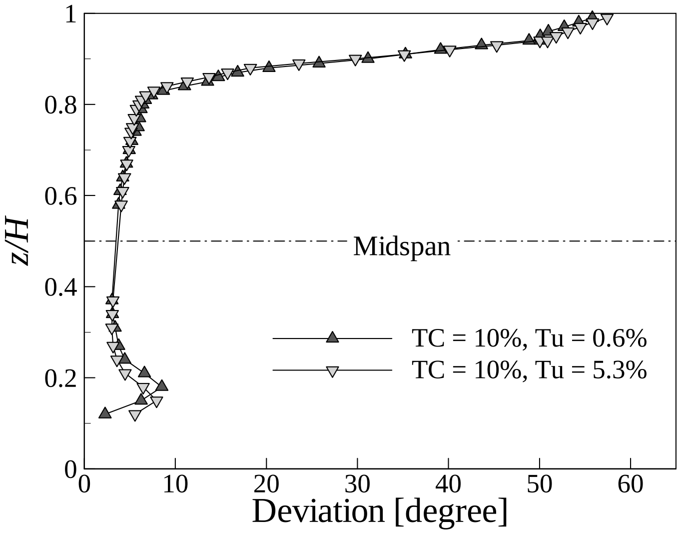


(a) TC = 0.01C

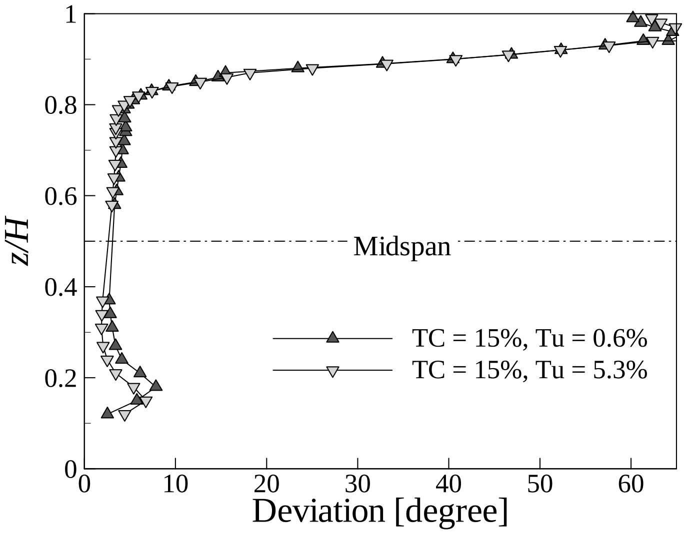


(b) TC = 0.03C

Figure 15. Span-wise distributions of pitch-wise mass averaged deviation angle ; (a) TC=0.01*C*; (b) TC=0.03*C*; (c) TC=0.10*C*; (d) TC=0.15*C*.



(c) TC = 0.10*C*



(d) TC = 0.15*C*

Figure 15. Span-wise distributions of pitch-wise mass averaged deviation ang le ; (a) TC=0.01*C*; (b) TC=0.03*C*; (c) TC=0.10*C*; (d) TC=0.15*C*.

4. Conclusions

Increasing tip clearance from TC=0.01*C* to TC=0.03*C* increases the tip leakage vortex and reduces the passage vortex. It also increases the overall loss. However, for large tip clearances such as TC=0.10*C* and 0.15*C*, the observed two high loss regions are merged, showing a single high loss region, mainly caused by the tip leakage vortex. At TC=0.10*C*, the mass averaged loss is the highest and at TC=0.15*C* the mass averaged loss becomes slightly lowered.

In Tu=5.3% at TC=0.01*C* and TC=0.03*C*, the strength and the area of the passage vortex near the tip are decreased. The strength of the leakage vortex is decreased and the area of leakage vortex is increased. However, at TC=0.10*C* and TC=0.15*C*, the merged vortex does not show the dependence on Tu.

For the combined effect of tip clearance and turbulence intensity on the overall loss, the high turbulence intensity (Tu=5.3%) reduces the overall loss whereas the rate of its reduction is decreased with increasing tip clearance since the tip-side passage vortex is affected by tip clearance and turbulence intensity. Increasing tip clearance and high turbulence intensity acts to decrease the tip-side passage vortex. However, the effect of tip clearance is more significant than turbulence intensity. Therefore, increasing tip clearance decreases or diminishes the passage vortex, so the effect of turbulence intensity is decreased.

The conclusions of the research are listed as follows.

1. For tip clearances smaller than 10% of the blade chord, the overall loss is increased as the tip clearance increases. However, for tip clearance larger than 10%, the tip clearance effect decreases for all of the turbulence intensity tested in the present study.
2. In comparison to Tu=0.6%, the high turbulence level (Tu=5.3%) decreases the overall loss for 1%, 3%, 10% and 15% of the tip clearance.
3. The reduction rate of overall loss by increasing turbulence intensity from 0.6% to 5.3% was reduced with increasing the tip clearance.
4. In large tip clearances, the tip-side passage vortex is decreased so the effect of the high turbulence intensity that decreases the overall loss is reduced.

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요약(국문초록)

터빈캐스케이드에서 큰 팁간극과 난류강도가 공력성능에 미치는 영향

큰 팁간극과 난류강도가 공력성능에 미치는 영향을 연구하기 위해 팁간극은 1%, 3%, 10% 그리고 15%를 적용하였고, 난류강도는 0.6%, 3.3% 그리고 5.3%를 적용하였다. 공력성능에 미치는 영향은손실계수, 질량평균 손실계수 그리고 블레이드 출구에서 유동각의 받음각으로 판단하였다. 실험결과 모든 난류 강도에서 팁간극이 10%까지 증가하는 동안 질량평균 손실계수는 증가하였고, 10%이상의 팁간극에서 질량평균 손실계수는 감소하였다. 모든 팁간극에서 0.6% 난류강도 대비 5.3% 난류강도에서 질량평균 손실계수는 감소하였으며, 3.3% 난류강도에서는 효과가 미미하였다. 난류강도 증가에 따른 질량평균 손실계수의 감소율은 팁간극이 증가함에 따라 감소하였다.

주요어 :큰 팁간극, 난류 강도, 터빈케스케이드, 질량평균 손실계수

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