공학석사학위논문

CFD를 통한 부분 슈라우드형 축류 터빈의 공력 성능 평가 및 유동장 분석

Numerical Investigation of Flow Characteristics in Full and Partial Shrouded Axial Turbines using CFD

2020 년 8 월

서울대학교 대학원

기계공학부

유지상

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Numerical Investigation of Flow Characteristics in Full and Partial Shrouded Axial Turbines using CFD

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Tip leakage flow loss is a main aerodynamic loss source in operating a turbine. To reduce the tip leakage flow loss, shrouded turbine is used in modern turbomachinery industry. Shrouded turbine exhibits the improved aerodynamic performance, but it has structural problem related to increased weight and high stress on rotating parts. The concept of partial shroud arises for the purpose of reducing weight with maintaining high efficiency. Some researchers have studied several types of shroud applied in low pressure axial turbine both experimentally and numerically. Based on former studies, the new geometry of partial shroud is invented. In this paper, the aerodynamic performance and flow structures of new partial shrouded turbine is numerically investigated.

Keyword : Axial Turbine, Partial Shroud, CFD, Flow Structure

Student Number : 2018-26631

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Chapter 1. Introduction

1.1. Background

The tip leakage flow loss is a main source accounting for 30% of total loss in operation of a turbine. Tip leakage flow generates due to the presence of small gap between rotating blade and stationary casing endwall. A portion of main flow pass through the gap, which is leading to turbine power reduction due to reduced mass flow. Also, the vortex is developed when the leakage flow pass through the clearance. It is called the tip leakage vortex as shown in Figure 1.1 [1]. Because of the tip leakage vortex, total pressure loss core has occurred near tip region.

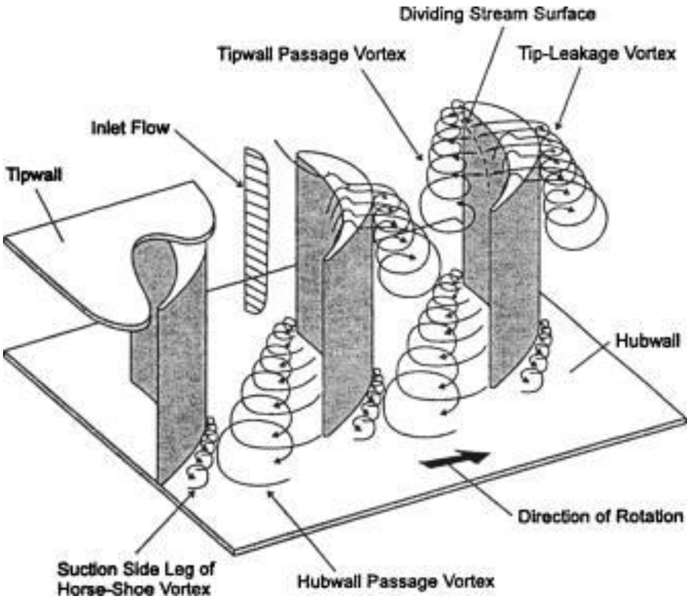


Figure 1.1. Flow field in the turbine blade passage [1]

The tip leakage flow loss can be reduced in a shrouded turbine. Shrouded turbine has a shroud, which is an axisymmetric annular ring covering the rotor blade. Since shroud prevents flow from crossing the tip clearance, the growth of tip leakage vortex is suppressed. Therefore, aerodynamic performance enhanced in a shrouded turbine compared to unshrouded turbine.

Yoon et al. [2] examined the effect of clearance on the aerodynamic performance of shrouded and unshrouded turbine experimentally. The result shows the presence of a break-even clearance. Above the break-even clearance, the shrouded turbine has higher efficiency than the unshrouded turbine. It is accordance with that the gradient of efficiency with respect to clearance is gradual in the shrouded turbine.

Although shrouded turbine has benefit in aerodynamic performance, it has disadvantage in structure due to increased weight and stress on rotor disk. From this reason, some researchers investigate the effects of partial shroud.

1.2. Previous Researches

Several researches have been studied the aerodynamic performance of partial shrouded turbine and investigated the flow structure numerically or experimentally.

In 2005, Porreca et al. [3] investigated the aerodynamics of axial turbines with partial shroud (PS) and full shroud (FS). (Figure 1.2.) They conducted both the experiment and the computational simulation. The experimental results show that the flow near the tip is underturned at the rotor exit in PS case. Also, the tip leakage flow is generated in PS case due to the absence of the shroud platform. This feature caused a underloading of the tip rotor blade region, and the underloading results in a negative incidence at downstream stator blade. Performance measurements show 1.1% higher second stage efficiency for FS case than PS case. However, the losses in the second stator is decreased by almost 1% in the PS case, since the decrease of secondary loss associated with reduced tip passage vortex is larger than the increase of profile loss due to the negative incidence.

Afterwards, Porreca et al. [4] compared three different shrouds; a full shroud (FS), partial shroud (PS), and enhanced partial shroud (EPS). The main difference of PS and EPS is the presence of the shroud platform which covers the blade passage at trailing edge. (Figure 1.3.) The presence of the shroud platform prevents the main flow from expanding in the exit cavity. Porreca et al. [4] identified that the flow field of EPS case is altered to the intended feature of FS case. The second stage efficiency is improved by about 0.6% respect to FS case. This study suggested the developed shroud design for enhancing aerodynamic efficiency.

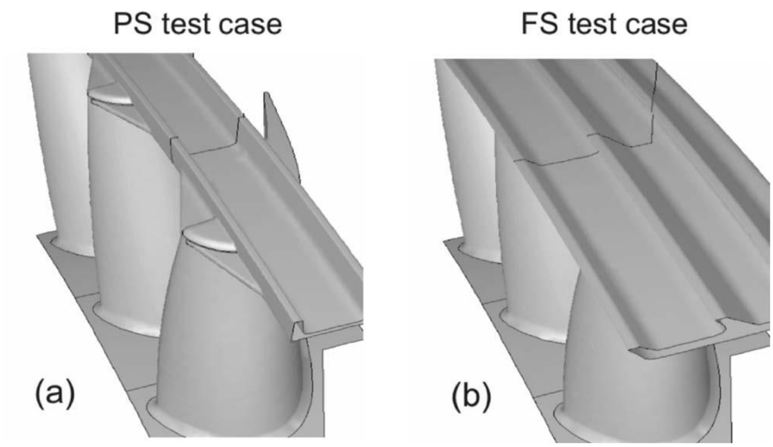


Figure 1.2. Schematic of the shroud configuration : (a) partial shroud, (b) full shroud [3]

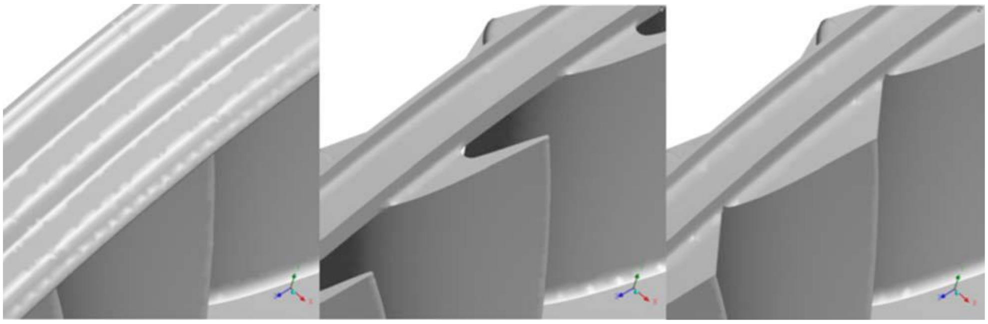
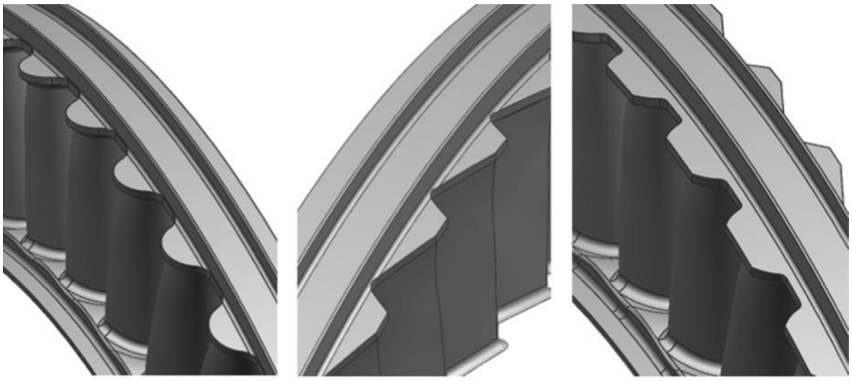


Figure 1.3. Schematic of the shroud geometry : FS (left), PS(middle), EPS(right) [4]

Rebholz et al. [5] conducted an experimental and computational study of the effect of various shroud cutbacks on turbine aerodynamics. The LE cut-back yields the lowest efficiency drop under the high mass reduction of shroud. They suggested that shroud should be removed from the leading part to maintain high aerodynamic performance.



a) b) c)

Figure 1.4. Schematic of the shroud geometry : FS (left), PS(middle), EPS(right) [5]

Palmer et al. [6] calculated a loss coefficient of a full shroud turbine by numerical simulations, both steady and unsteady. Steady calculation shows that the shroud cavity leads to about 1% debit in efficiency per 1% of the total mass flow passing through the cavity. The total loss due to the cavity is equally divided into the free expansion loss of leakage jet and mixing loss between the cavity flow and the main flow. Unsteady calculation reveals the unsteady loss associated with the inlet toroidal vortex, which contributes to the viscous dissipation and the recirculating flow.

Additionally, Palmer et al. [7] investigated the effects of shroud asymmetry on cavity loss generation by numerical computations. The result shows that the shroud asymmetry does not change the free expansion loss a lot, however it increased the mixing loss. The quantity of unsteady loss at the inlet cavity is comparable to the generic shroud case, but the details of loss generation are modified such that the redistributed small vortex cores, in contrast with a large, single toroidal vortex, generate viscous losses in the scalloped shroud.

1.3. Research Objective

Some researches about partial shrouded turbine have been studied. However, just few types of partial shrouds have been investigated. In this study, the newly designed partial shrouded turbine has been investigated numerically. This partial shroud has no shroud cover on the leading edge as shown in Figure 1.5.

The objective of this study is as follow. First, the aerodynamic performance of the new partial shrouded turbine is evaluated by CFD. Second, the flow structure inside the turbine will be discussed.

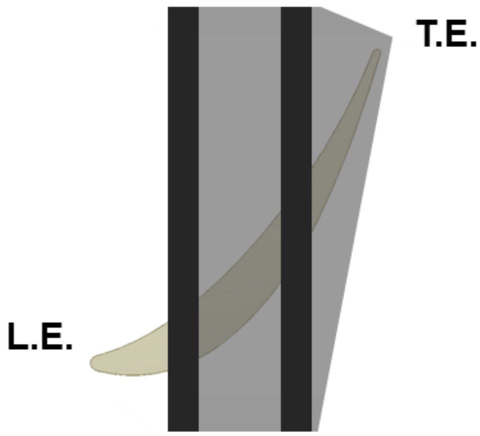


Figure 1.5. Concept of the new partial shroud

Chapter 2. Numerical Model

2.1. Test Turbine

In this study, LISA turbine model is used for the numerical simulation. LISA turbine is an 1.5 stage axial turbine, which was mounted on the LEC (Laboratory for Energy Conversion) in ETH Zurich. Behr [8] opened information about LISA turbine to the public in his Ph.D. thesis. The blade profile data can be acquired from that paper. Based on the data be created the analysis model of LISA turbine as shown in Figure 2.1.

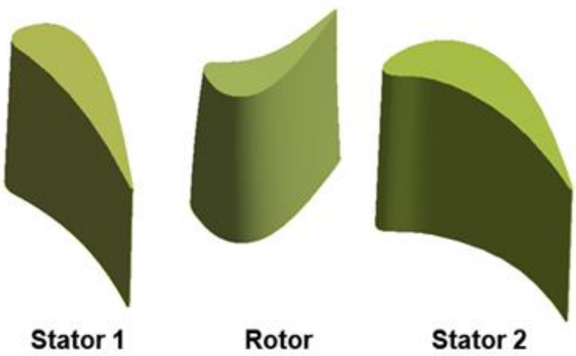


Figure 2.1. CFD analysis model of the LISA turbine

Blade information and main parameters are listed in the Table 2.1 and 2.2. Tip clearance of the rotor is 1% of blade span length, which is 0.7mm. This value will be applied to shrouded turbine model identically.

Table 2.1. Blade information of the LISA turbine [8]

	Stator 1	Rotor	Stator 2
Number of blades	36	54	36
Aspect ratio	0.87	1.17	0.82

Table 2.2. Main parameters of the LISA turbine at design operating point [8]

Parameter	Value
Rotor speed	2700 rpm
Pressure ratio (total-to-static)	1.60
Inlet total pressure	1.4 bar
Inlet total temperature	55℃
Mass flow rate	11.70 kg/s
Shaft power	292 kW
Hub/Tip diameter	660/800 mm

2.2. Shroud Design

Three different shapes of shroud are taken in consideration in this research. The first case is an axisymmetric full shroud (FS) typical in turbomachine industry. From now, FS will be considered as a baseline model. The second case is partial shroud (PS1), which has shroud cutback on the both leading and trailing edge. The third case is a newly designed partial shroud, which has never been investigated. This partial shroud (PS2) is similar to PS1, but without shroud cover on the leading part. Figure 2.2. shows 3D CAD model of three different shrouds: FS, PS1 and PS2. All these shrouds are mounted on the rotor blade tip only and have two vertical fins.

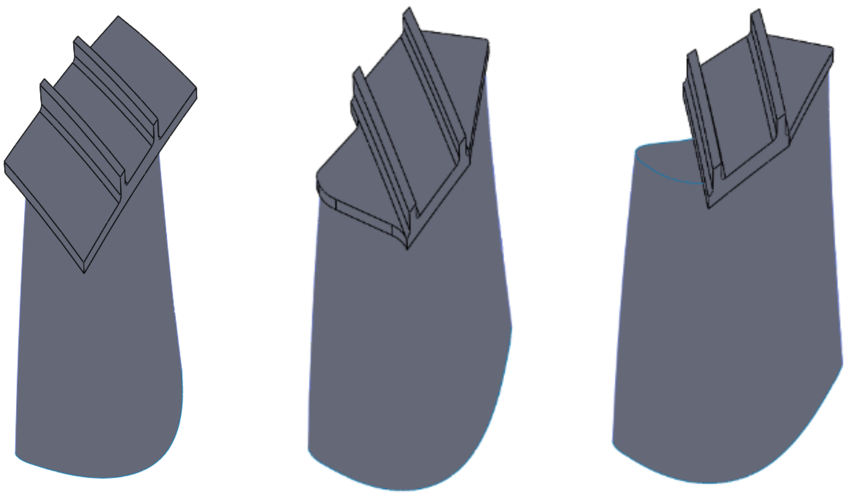


Figure 2.2. Three different shroud geometry on the rotor blade : FS(left), PS1(middle), and PS2(right)

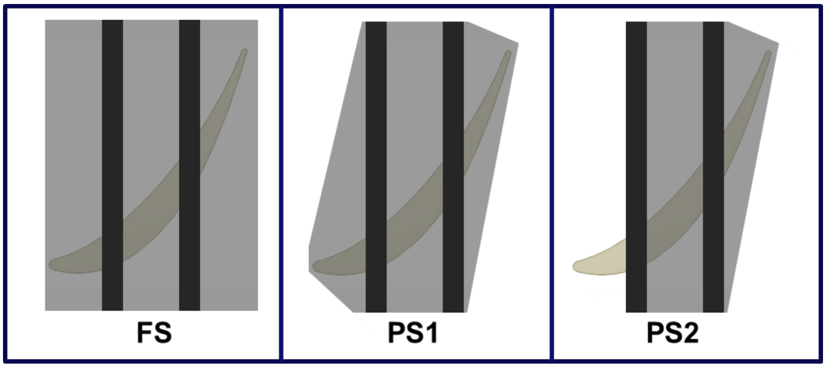


Figure 2.3. Schematic of test shrouds from top view : FS(left), PS1(middle), and PS2(right)

Figure 2.4. shows the schematic of shroud and casing endwall from meridional view. And geometric parameters are listed in the Table 2.3.

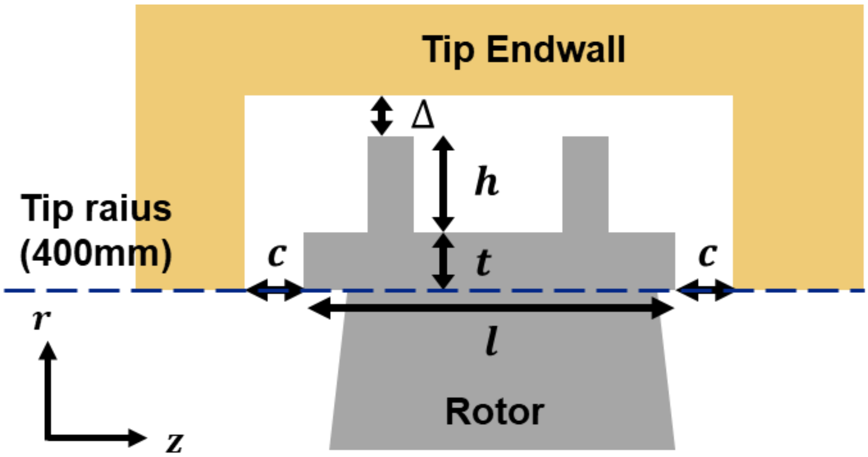


Figure 2.4. Schematic of shroud and tip endwall from meridional view

Table 2.3. Geometric parameters in Figure 2.4.

Parameter	Value
Tip clearance (Δ)	0.7mm
Inlet / Exit axial gap (c)	3mm
Shroud length (l)	47mm
Shroud thickness (t)	2.7mm
Fin height (h)	4.6mm

Chapter 3. Numerical Method

3.1. Numerical Setup

Numerical simulation has been performed with ANSYS CFX 2019 R1. The simulation method is steady calculation. CFD domain is a single passage for each blade row and the periodic boundary condition is imposed on the side surface. At the interface between stator and rotor, the mixing plane method is applied under the constraint that the average velocity is conserved.

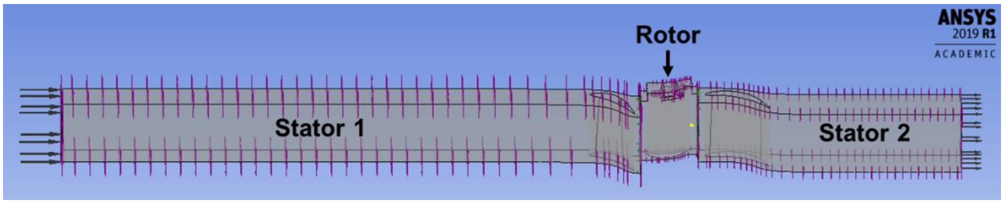


Figure 3.1. Numerical simulation model in ANSYS CFX

Figure 3.1. shows the numerical simulation model in ANSYS CFX pre. The model is consisted of three different parts : stator1, rotor, and stator 2. Total pressure and total temperature is applied to the inlet boundary condition and the flow direction is set to normal to boundary. Average static pressure is applied to the outlet boundary condition. All the wall including blade and shroud is set to smooth and adiabatic wall. The flow is modelled as a fully turbulent flow and shear stress transport turbulence (SST) model is applied.

Mesh generation is performed with ANSYS TurboGrid 2019 R1 and ANSYS ICEM 2019 R1. The structured hexahedral mesh is applied to two stator regions. On the other hand, the unstructured tetrahedral mesh with prism layer is applied to the shrouded rotor regions due to complex shroud geometries. Mesh elements in stator 1, rotor, and stator 2 are 1.5 million, over 30 million, and 1.5 million respectively. Finally, the maximum y+ value is about 1.8 for SST turbulence model being used properly.

Chapter 4. Results

In this chapter, the numerical simulation results for three cases of shrouded axial turbines will be introduced. Furthermore, discussion will be described based on the results.

As introduced in the Chapter 2, inlet total pressure and inlet total temperature is 103.7kPa and 55℃. The rotation speed is 20000 rpm. Outlet static pressure is determined to the pressure drop across the whole turbine stage be same for all three cases. The pressure drop is 50.687kPa, which is estimated from the simulation of unshrouded turbine model.

4.1. Turbine Performance

In this section, aerodynamic performance of turbine such as flow capacity, efficiency and blade loading will be evaluated from CFD result.

4.1.1. Mass Flow Rate

Mass flow rate is calculated at the inlet boundary surface. Mass flow rate for FS case is 11.77 kg/s, which is the highest among all cases. The drop in mass flow rate is 0.02 kg/s for PS1. For PS2, mass flow rate decreases 0.04 kg/s compared to FS. Mass flow rate decreases when the shroud cover on the leading edge region is disappeared. It means that the flow capacity is affected by the presence of the shroud cover. From experiment and CFD, Porreca [4] also indicated that mass flow rate of partial shrouded turbine lowers than full shrouded turbine.

Table 4.1. Mass flow rate of FS, PS1 and PS2 case

Parameter	FS	PS1	PS2
Mass Flow Rate [kg/s]	11.77	11.75	11.73

4.1.2. Efficiency

Aerodynamic performance of turbines can be evaluated by the total-to-total efficiency, which is defined as the ratio of real turbine work to ideal work. Torque based total-to-total efficiency is described as (4.1).

$$\eta_{tt} = \frac{\text{Power}}{\dot{m} \cdot c_p \cdot T_{t,in} \cdot \left(1 - \left(\frac{P_{t,out}}{P_{t,in}}\right)^{\frac{\gamma-1}{\gamma}}\right)} \tag{4.1}$$

Calculated 1st stage efficiency and other parameters for FS, PS1 and PS2 are listed in Table 3.2. 1st stage efficiency is higher in FS case than other PS cases. PS1 case shows about 1% efficiency drop. Another 1% efficiency penalty is observed for PS2 case, which has no shroud cover on the leading edge region. Based on this result, the shroud cover plays an important role on the aerodynamic performance of turbines.

Likewise, mass averaged total pressure at the rotor exit decreases in PS cases compared to FS case. It means that the total pressure loss generates when a part of shroud is eliminated. Detailed flow structure, which affects the total pressure field, will be discussed later.

Table 4.2. Estimated efficiency and other parameters of FS, PS1 and PS2 case

Parameter	FS	PS1	PS2
Mass Flow Rate [kg/s]	11.77	11.75	11.73
Power [kW]	283.96	280.97	277.91
Exit Total Pressure [kPa]	104.11	104.07	104.03
Efficiency [%]	90.21	89.25	88.35

4.1.3. Blade Loading

Blade loading refers to force from the pressure difference between pressure and suction side of blade. Fig. 4-1 shows the blade loading at 90% span of rotor blade. A horizontal axis represents the streamwise location. A vertical axis represents the static pressure coefficient defined as (4.2). In this equation, $P_{t,in}$ and $P_{s,in}$ refers to mass averaged total pressure and area averaged static pressure at the turbine inlet. And $P_{s,out}$ means area averaged static pressure at the rotor exit.

$$C_p = \frac{P_s - P_{s,out}}{P_{t,in} - P_{s,in}} \quad (4.2)$$

At pressure side, the pressure difference among three cases is small. However, the pressure changes a lot at suction side. Static pressure in PS cases rises on the front region of suction side compared to FS case. In addition, PS2 has higher pressure that PS1 due to strong ingress effect near suction side. As a result, specific work of turbine is the largest in FS. Then comes PS1 and PS2 in that order.

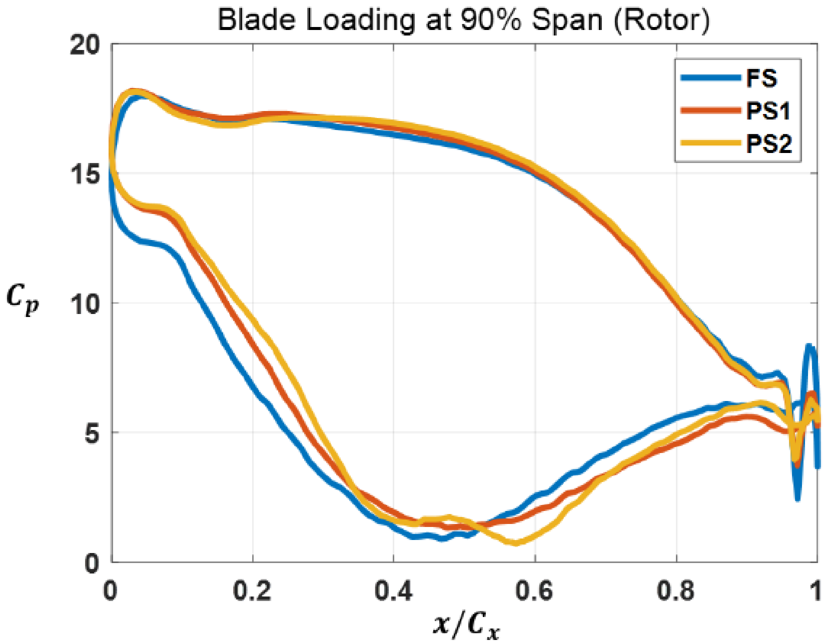


Figure 4.1. Blade loading at 90% span of the rotor blade

4.2. Entropy Generation

$$e = \exp\left(\frac{s - s_{inlet}}{R}\right) \tag{4.3}$$

Fig. 4-2 shows the entropy generation contour in the shrouded rotor region. This contour is plotted using entropy function (4-3). The definition of entropy function is described in (4.3). $e = 1$ means that no entropy change occurs, while $e < 1$ represents entropy generates due to the flow interaction.

For all three cases, entropy increases at the trailing edge near tip region. Because the flow direction of the shroud leakage flow and the main flow is different each other, the mixing process is enhanced. Therefore, the entropy rise has occurred remarkably at that region. When a partial shroud is applied, the region where the entropy increases is expanded from 90% to 85% span at the rotor exit as shown in Figure 4.3 and 4.4. It represents that the mixing process is intensified due to enlarged shroud exit cavity area.

Shroud cutback on the leading edge region also affects the entropy generation. For PS1 case, entropy increases dramatically at the shroud leading part. And entropy also rises at the rotor exit region due to this effect. When the shroud cover is removed, entropy rise at the shroud leading edge is enhanced. (Figure 4.4.)

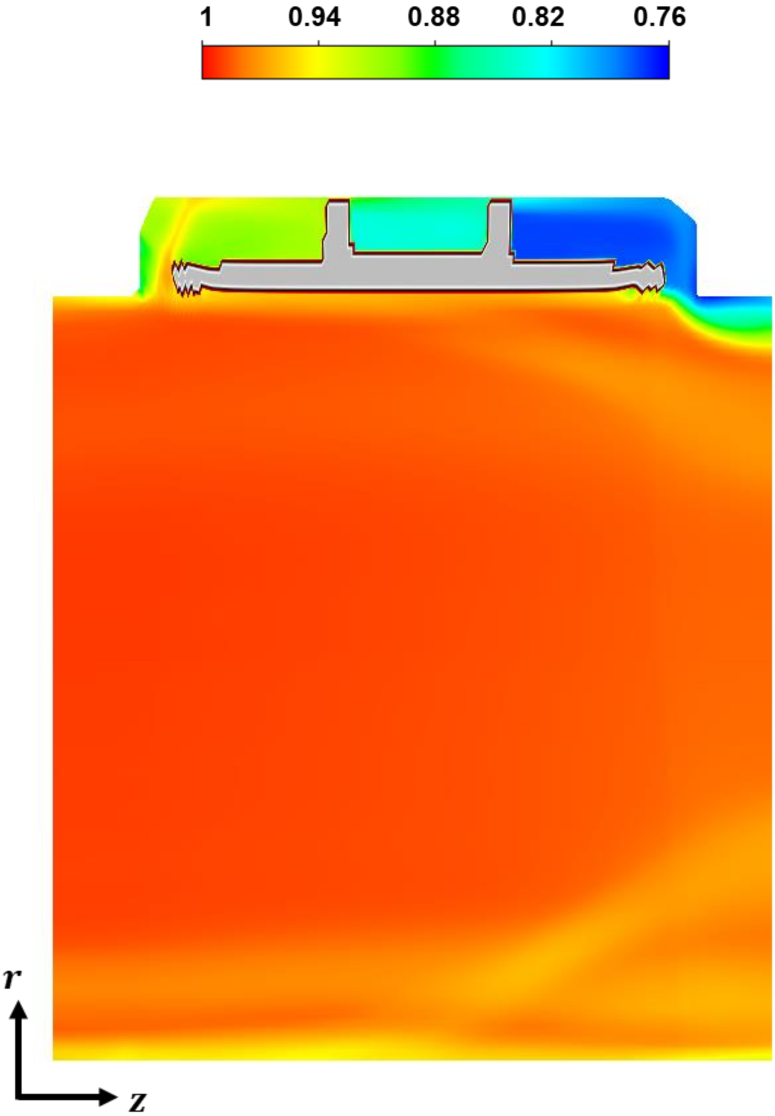


Figure 4.2. Entropy function at the rotor region of FS case

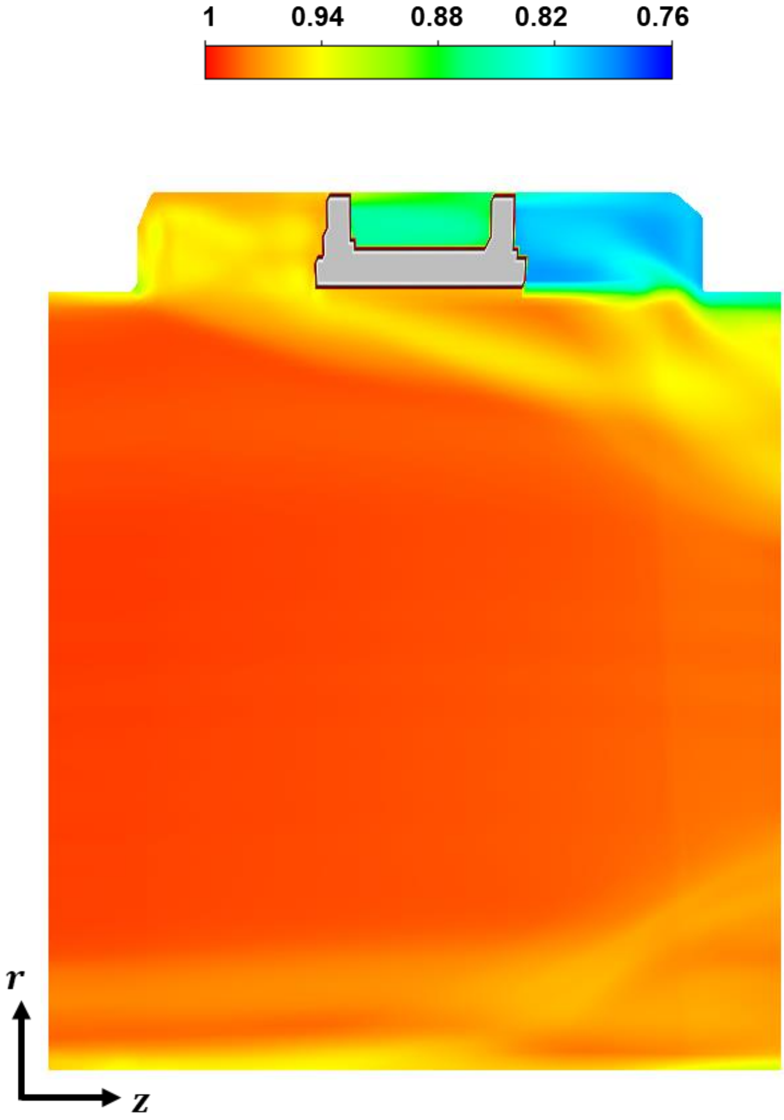


Figure 4.3. Entropy function at the rotor region of PS1 case

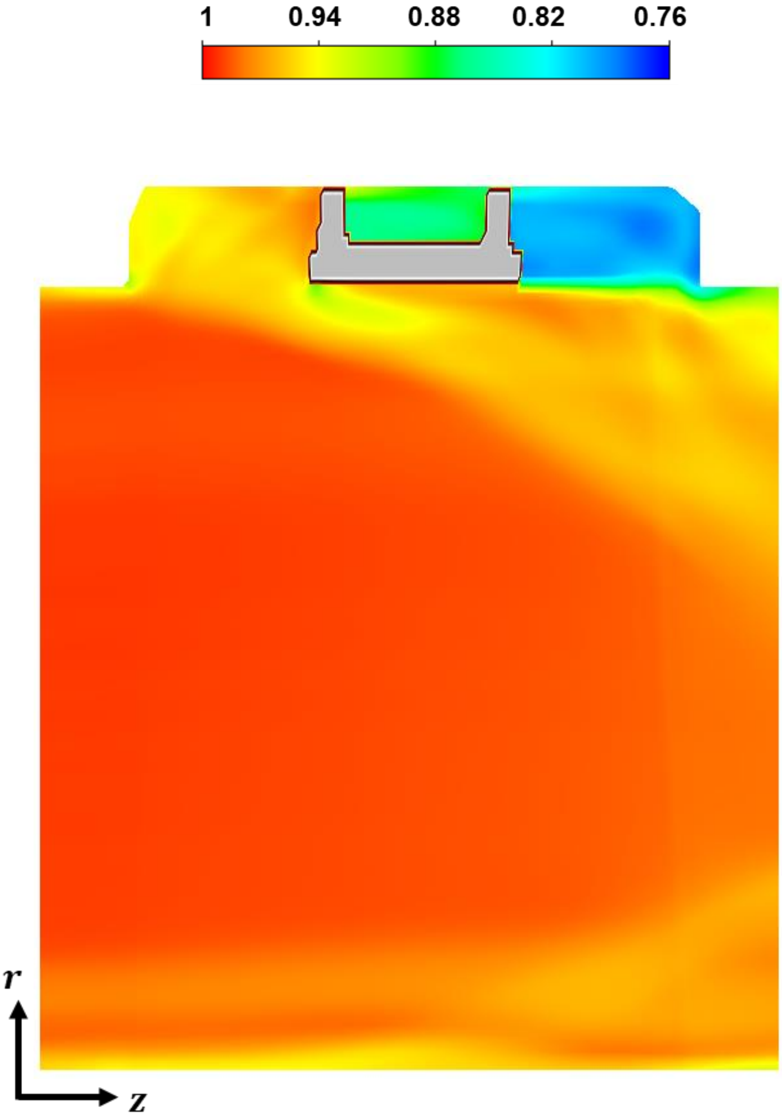


Figure 4.4. Entropy function at the rotor region of PS2 case

4.3. Total Pressure Loss

Total pressure loss coefficient is an indicator that quantifies the total pressure loss through the turbine blade. It is defined as the ratio of total pressure drop to dynamic pressure.

$$Y_p = \frac{P_{t,in} - P_t}{P_{t,in} - P_{s,in}} \tag{4.4}$$

$P_{t,in}$ represents the mass averaged relative total pressure at rotor inlet and $P_{s,in}$ represents the area averaged static pressure at rotor inlet. Therefore, the numerator means the relative total pressure drop across the rotor blade. The denominator refers to the relative dynamic pressure at the rotor inlet. Figure 4.5. – 4.7. show the total pressure loss coefficient contour at the rotor exit of FS, PS1, and PS2 case respectively.

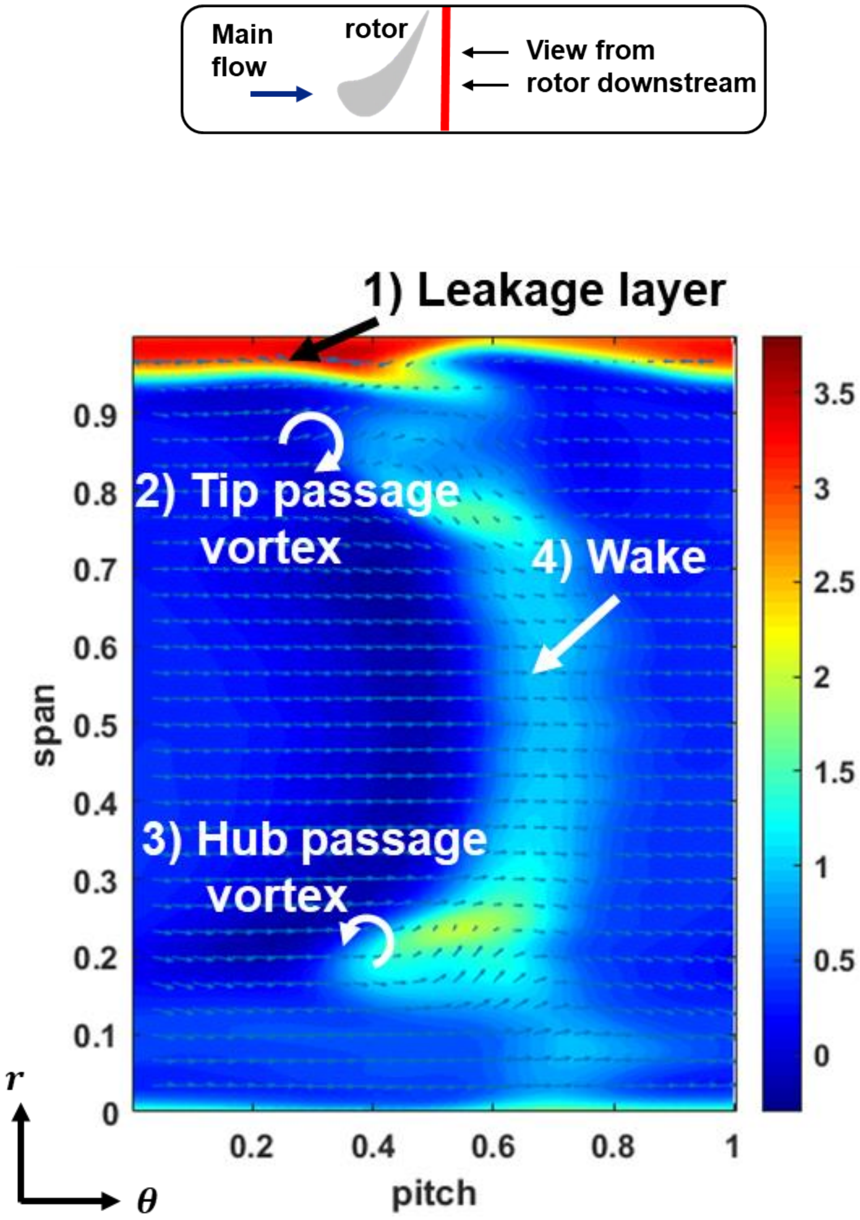
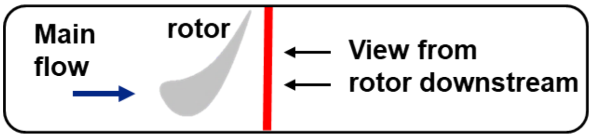


Figure 4.5. Total pressure loss coefficient contour at the rotor exit of FS case



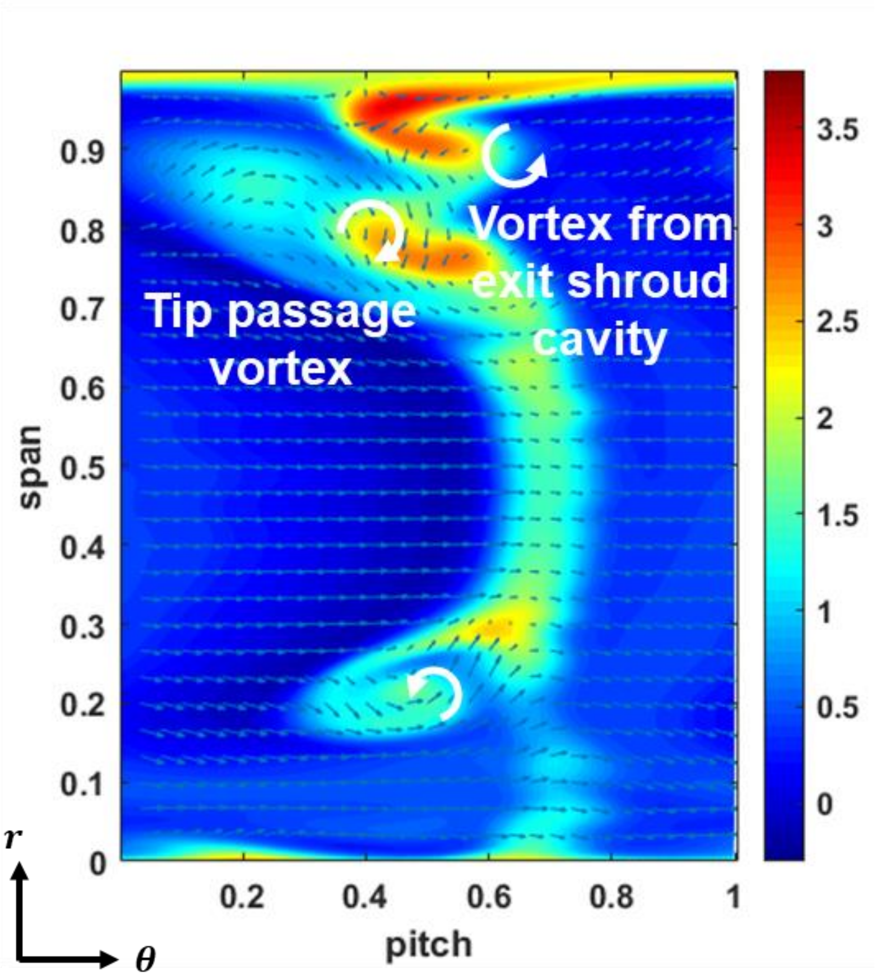


Figure 4.6. Total pressure loss coefficient contour at the rotor exit of PS1 case

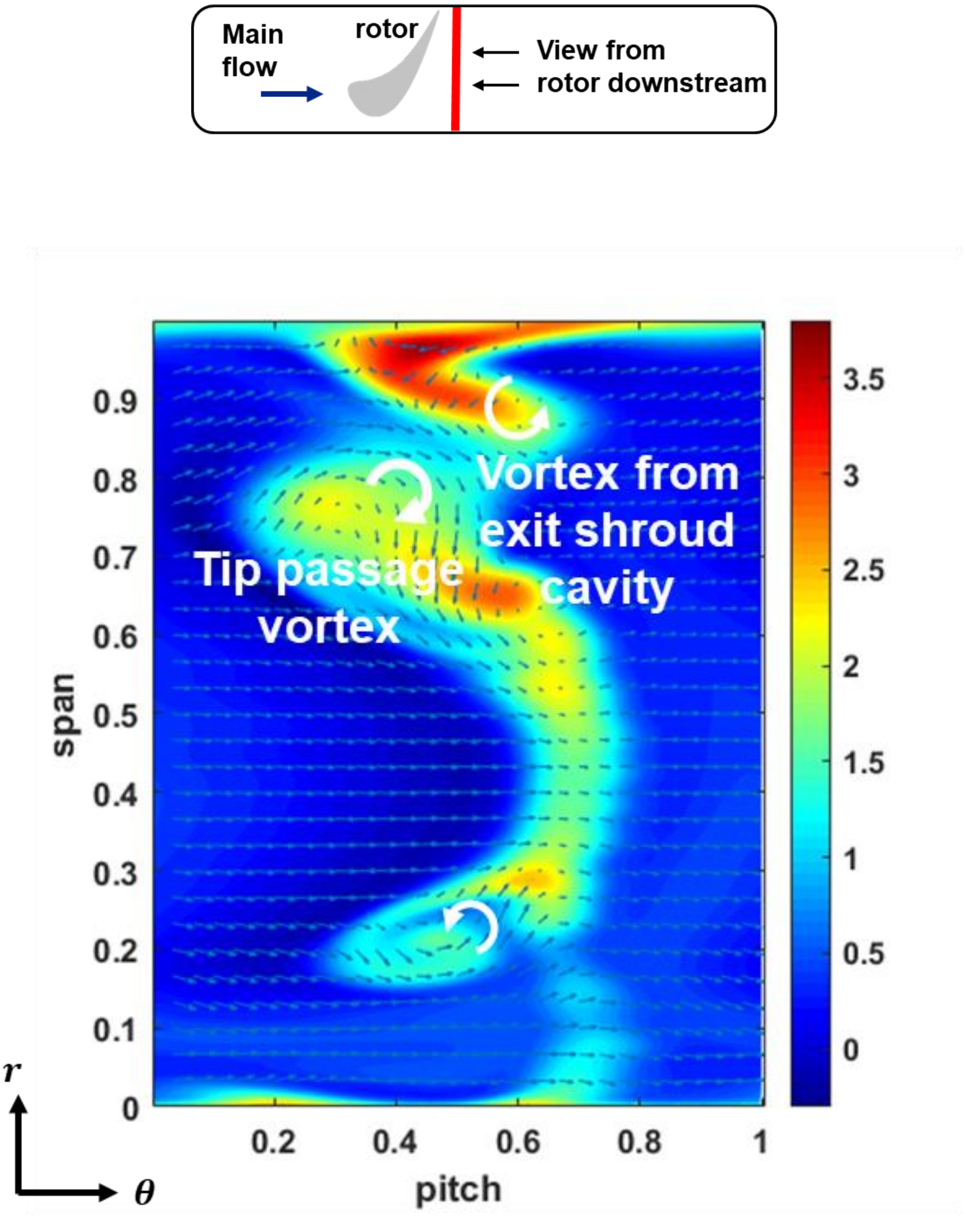


Figure 4.7. Total pressure loss coefficient contour at the rotor exit of PS2 case

For FS case, hub passage vortex can be observed at 20% span. Also, the wake structure due to boundary layer development is formatted along the 0.7 pitch. These two flow structures can be observed in PS1 and PS2 cases. However, there is a strong leakage layer near tip region only founded in FS case. This is due to narrow flow area between shroud exit cavity and main passage. Only the low momentum fluid can pass through this area, so that the leakage layer is developed near tip region.

The big difference between FS and PS case is the tip passage vortex and the vortex from exit shroud cavity. First, the strength of tip passage vortex in FS case is very weak. On the other hand, the tip passage vortex is developed in PS case. The reason is that the strong incoming flow from the shroud inlet cavity generates vortex, so called the tip passage vortex. This flow structure went through the blade suction surface, and finally made vortex core at the rotor exit. When the shroud cover is eliminated for PS2 case, the tip passage vortex is enhanced due to strong inflow through expanded shroud inlet cavity area. Therefore, the total pressure loss reduction is bigger in PS2 case than PS1 case.

Second is the formation of vortex from shroud exit cavity. For FS case, the vortex is generated from the backflow which is bumped against the tip endwall. This vortex is just captured into the shroud inlet cavity, because the axial clearance between shroud and tip endwall is too small. Therefore, only tip leakage layer due to low momentum fluid is developed at the rotor exit. On the other hand, the vortex developed in the shroud exit cavity moves to main passage. This vortex is located at 95% span at the rotor exit as shown in Figure 4.6.-4.7. Because the shroud shape at the trailing edge is the same for PS1 and PS2 case, the strength of vortex from shroud exit cavity is comparable. The principle of this vortex formation is explained by Yun et al. [9]. Simply speaking, this vortex is developed due to vortex tilting effect.

Chapter 5. Conclusion

The new partial shrouded turbine has been investigated numerically in this study. This partial shroud has ordinary cutback on the trailing part, whereas has no shroud cover on the leading edge. So the effect of shroud cover on the leading edge is first introduced.

The partial shroud with shroud cover on the leading edge shows efficiency drop of 1% comparted to full shroud, while 1.9% for partial shroud without shroud cover. The shroud cover on the leading edge affects the aerodynamic performance of turbine.

Without shroud cover, entropy increases dramatically near the shroud leading edge. As a result, it leads to entropy generation and total pressure loss at the rotor exit. The reason why the loss increases in the rotor passage is the vortex generation in the shroud inlet cavity region. Without the shroud cover, the tip passage vortex is strengthened due to strong inflow from inlet shroud cavity to main passage, resulting to make total pressure loss core at the rotor exit. The turbine efficiency is lowered due to this flow structure.

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초 록

팁 누설 유동에 의한 손실은 터빈에서 발생하는 손실의 약 1/3을 차지하고 있는 주요 공력손실원이다. 이러한 팁 누설 유동 손실을 줄이기 위해 로터 블레이드의 팁에 슈라우드를 달아 팁 누설 유동을 억제시키는 방법이 있다. 슈라우드 형 터빈은 팁 누설 유동에 의한 손실을 줄여 터빈 공력 효율을 높이는 장점이 있는 반면, 슈라우드로 인해 단 무게와 회전 부품에 가해지는 응력이 증가하는 단점이 있다.

부분 슈라우드는 터빈의 무게를 줄이면서 높은 공력 효율을 유지하기 위해 고안된 개념이다. 부분 슈라우드 형 터빈의 공력 성능에 대한 선행 연구가 있지만, 다양한 부분 슈라우드 형상에 대해서 연구가 이루어지지 않았다. 본 논문에서는 leading edge 위에 슈라우드 덮개가 없는 새로운 형태의 부분 슈라우드 형 터빈을 직접 설계하고, CFD 유동해석을 수행하였다. CFD 결과, 완전 슈라우드 형 터빈에 비해 동익 블레이드 출구에서의 전압력 손실이 증가하였고, 이로 인해 공력 효율이 감소하였다. 유동장 분석을 통해 슈라우드 덮개를 제거함으로서 tip passage vortex가 발달하여 전압력 손실이 증대되는 것을 확인하였다.

핵 심 어 : 축류 터빈, 부분 슈라우드, 유동해석, 유동 구조

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