Influences of Groove Type Casing Treatment on Tip Leakage Flow Behavior in Linear Compressor Cascade at Different Tip Clearances (Influence of Single Groove at Mid-chord)

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Abstract: In this study, the influences of the single groove installed at the mid-chord, which is known as to have large expansion effect on the stable operating flow range of low speed axial compressor, on the flow behavior and the loss generation in a linear compressor cascade were investigated numerically at different tip clearances. The computed results clarified the following remarkable phenomena in common to both small and large tip clearance cases. The single groove locally weakens the tip leakage flow by the decrease of the blade loading and the flowing of the flow near the blade pressure side into the groove, and consequently reduces the distance of the tip leakage vortex from the blade suction surface. Meanwhile, although the groove decreases the loss due to the tip leakage vortex generated from the blade leading edge, the loss generation in the entire cascade passage is almost the same as that in the cascade without the groove because the additional loss generation due to the presence of groove.

1. INTRODUCTION

The improvements of aviation and industrial gas turbine performances such as the efficiency have been demanded seriously because of worsening global environmental problems and concern for the depletion of fossil fuel. Due to these social demands, many studies for an axial compressor constituting gas turbine have been carried out in order to particularly increase the efficiency and the pressure ratio per a single stage and extend the stable operating flow range.

In the axial compressor constituting gas turbine, an open impeller is generally used as the rotor impeller. In such compressor, the clearances inevitably presence between the rotating blade tips and the stationary shroud casing wall. As a consequence, flow through the tip clearance is generated by the pressure difference between the blade pressure and suction surfaces and then influences the loss generation significantly by the generation of the tip leakage vortex [1]. Moreover, the interface between the tip leakage flow and the main flow is moved toward the upstream as the flow rate decreases. When this interface reaches the cascade inlet, the blockage due to the tip leakage flow influences the inception of rotating stall which is known as the one of factor for restricting the operating flow range [2, 3].

A circumferential groove casing treatment (CGCT) is a one of the technique to improve the compressor aerodynamic performance. The CGCT controls the tip leakage flow behavior by the single or multi groove installed on the shroud casing wall and consequently shifts minimum stable flow rate toward lower flow rate. The influences of the groove location and the number of grooves on the expansion effect on the stable operating range have been investigated by many researchers [4, 5]. However, although there is a report that the CGCT declines the efficiency at some operating points [4], this mechanism has not been investigated. On the other hand, the axial compressor constituting gas turbine is generally constituted by the several pairs of rotor and stator which are referred to as stage. In such compressor, the blade high is gradually reduced toward the final stage. As a result, in the rear stage, because the tip clearance size for the rotor blade height relatively increases compared with that in the front stage, the influence of the tip leakage flow on the aerodynamic performance is increased. Therefore, in order to intensify the improvement effect of CGCT on the aerodynamic performance of rear compressor stage, it is also required to clarify the influence of the tip clearance size on the flow phenomena generated by CGCT.

The purpose of this study is to obtain knowledge to maximize the expansion effect of CGCT on the stable operating flow range of the rear compressor stage without the trade-off such as the efficiency penalty. As an early study, the influences of the single groove installed at the mid-chord, which is known to have large expansion effect on the stable operating flow range of low speed axial compressor [5], on the flow behavior and the loss generation in a linear compressor cascade were investigated at different tip clearances.

2. TEST CASCADE

The configuration and the specification of test compressor cascade are shown in Fig. 1 and Table 1, respectively. This test cascade is a linear compressor cascade which has two-dimensional blades imitated the

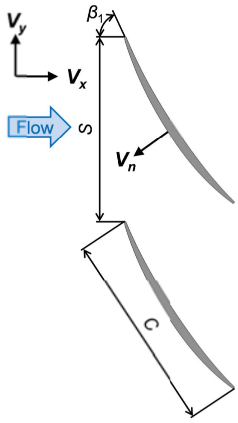


Fig. 1 Test cascade

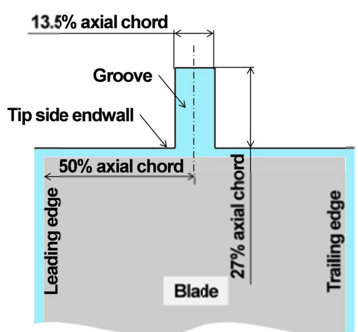


Fig. 2 Groove shape

Table 1 Specification of test cascade

Chord C	254 mm
Pitch S	236 mm
Span H_b	249.8 mm
Inlet angle (Measured from axial direction) β_1	65.1 deg.
Stagger angle (Measured from axial direction)	56.9 deg.
Solidity C/S	1.08

blade tip shape of the GE Rotor B Section Blade and has the tip clearances. In the present study, the flows in the two type cascades were analyzed numerically at different tip clearances. The first cascade has the smooth wall as the tip side endwall (SW), and another one has the endwall in which the single groove is installed (GW). The tip clearance sizes were set to 4.2 mm (1.65% of C) and 1.27 mm (0.5% of C). The groove shape was designed by reference to [5].

3. NUMERICAL ANALYSIS

3.1 Computational method

In this study, the computations were performed by using the open source CFD code OpenFoam with the assumption that the flow in cascade is steady state incompressible flow. The solution algorithm was the SIMPLE method. The convection term was estimated by the MUSCL scheme. The low-Reynolds type of SST k-ω model was chosen as the turbulence model.

3.2 Computational condition

In order to reduce the computational resource, the computational domain was set to the tip side endwall from the midspan in the single passage. The inlet and outlet boundary planes were arranged at 1C upstream of the cascade inlet and 2C downstream of the exit, respectively. The computational grids were generated by using the H and C type structured grids. The total number of cell of SW was approximately 5.5 million and that of GW was approximately 6.8 million.

As boundary conditions, the inlet velocity V_1 and the inlet flow angle α_1 were applied uniformly at inlet boundary. By reference to the experimental condition in [6], the V_1 and the α_1 were set to 25.5 m/s and 65.1 deg., respectively. The free-stream boundary was used at the outlet boundary. The cyclic boundary condition was applied at the pitchwise boundary plane. In order to reveal the basic flow phenomena generated by the single groove, the relative motion of the tip side endwall against the blade row was not considered in this study.

4. RESUITS AND DISCASSIONS

In this section, the influences of the single groove on the flow behavior and the loss generation in the cascade will be investigated at the small and the large tip clearance cases. Figure 3 shows the axialwise distribution of the static pressure coefficient C_{ps} on the blade surface near the blade tip. In this figure, the X/C_a is the axialwise length normalized by the blade axial chord length, and it takes 0 at the leading edge and 1.0 at the trailing edge, respectively. The C_{ps} is defined by the following equation.

$$C_{ps} = (P_s - P_{s1})/(P_{t1} - P_{s1}) \tag{1}$$

where the P_s is the static pressure, and the P_{s1} and the P_{t1} are the cross-sectional mass averaged values of the static and the total pressures at X/C_a=-1.3, respectively. Figure 4 gives the streamlines with the origin near the mid-gap at the blade suction side in the tip clearance. In this figure, the streamline colors are varied depending on the locations of origins (Upstream of groove : Red, Groove location : Black, Downstream of groove : Blue). Figure 5 shows the trajectory of the tip leakage vortex core generated from the blade leading edge. Figure 6 indicates the axialwise and the pitchwise momentums ψ_x^* and ψ_y^* of the tip leakage flow through the surface S_{tc} which is the blade suction surface extended from the blade tip to the tip side endwall. The ψ_x^* and ψ_y^* are defined by the following equations and indicate the non-dimensional axialwise and pitchwise momentums per unit length at each axialwise location, respectively [7].

$$\Psi_x{}^* = \int_{\text{Blade tip}}^{\text{Endwall}} \Psi_x \, dz/S_1 \tag{2}$$

$$\Psi_y{}^* = \int_{\text{Blade tip}}^{\text{Endwall}} \Psi_y \, dz/S_1 \tag{3}$$

where the ψ_x is $\rho V_n V_x/\rho V_1 V_1$ and the ψ_y is $\rho V_n V_y/\rho V_1 V_1$. As shown in Fig. 1, the V_n is the velocity component normal to the S_{tc}, and the V_x and the V_y are the axialwise and the pitchwise velocity components, respectively. The ρ is the density and the S_1 is the cross-sectional area at the cascade inlet. Figure 7 shows the tip leakage flow rate through the surface S_g indicated in this figure. Figure 8 gives the spanwise velocity V_z, which is normalized by the V_1, distribution on the interface between the groove and the blade-to-blade passage. Figure 9 indicates the total pressure loss coefficient C_{pt} distribution on the planes normal to the blade chord line and the streamlines with the origin around the high loss regions (LR). The C_{pt} is defined by following:

$$C_{pt} = (P_{t1} - P_t)/P_{t1} \tag{4}$$

where the P_t is the total pressure. Table 2 gives the mixed-out averaged total pressure loss coefficient $C_{pt2,m}$ downstream the cascade. The $C_{pt2,m}$ is defined by

$$C_{pt2,m} = (P_{t1} - P_{t2,m})/P_{t1} \tag{5}$$

where the $P_{t2,m}$ is the mixed-out averaged total pressure at X/C_a = 1.3.

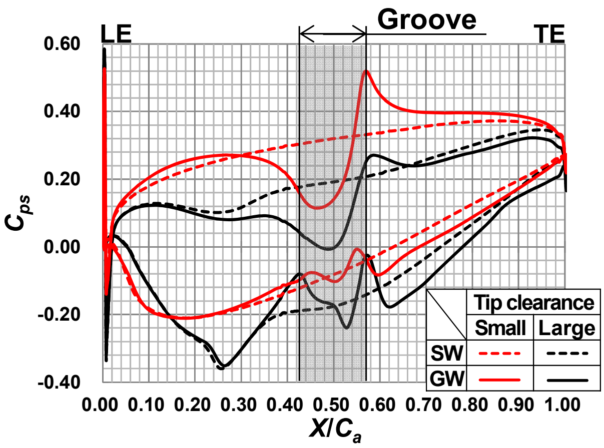
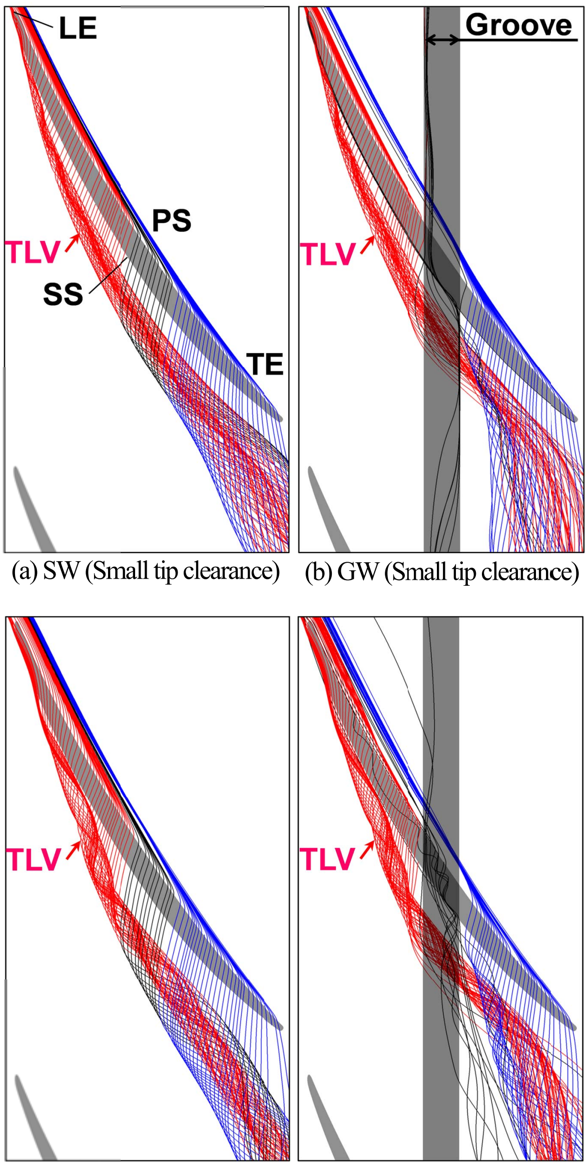


Fig. 3 Blade surface static pressure distribution near blade tip



(a) SW (Small tip clearance) (b) GW (Small tip clearance)

(c) SW (Large tip clearance) (d) GW (Large tip clearance)

Fig. 4 Behavior of tip leakage flow

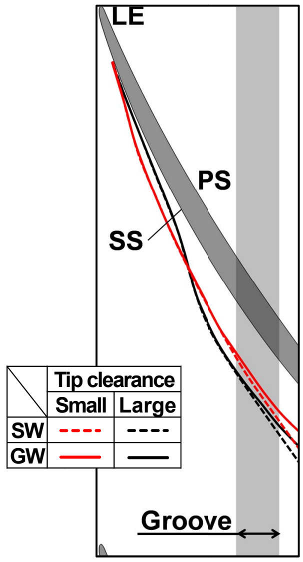


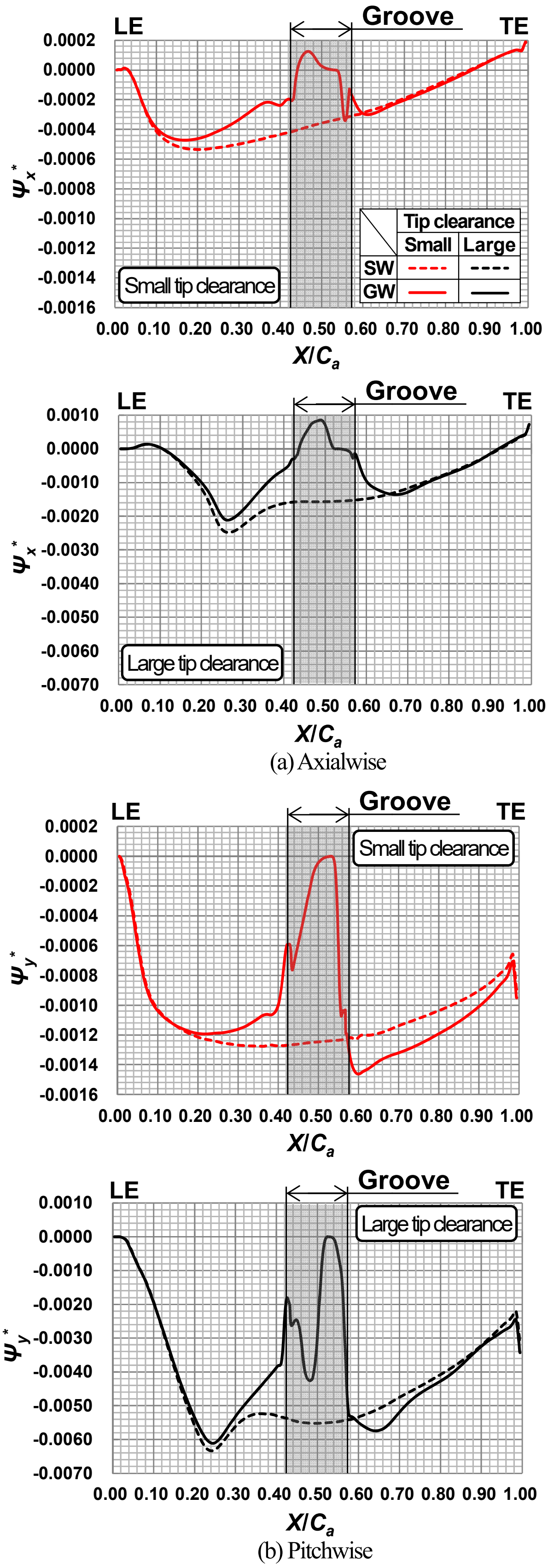
Fig. 5 Trajectory of TLV core

4.1 Small tip clearance

The influences of the groove on the flow behavior and loss generation in the cascade with the small tip clearance will be discussed.

In the SW, the flow through the tip clearance due to the pressure difference between blade pressure and suction surfaces generates the leakage vortex from the blade leading edge "TLV" as shown in Figs. 3 and 4(a). This vortex is generated also in the GW as in Fig. 4(b). However, around the groove location, the distance of TLV core from the blade suction surface is reduced compared with that in the SW as observed in Fig. 5. The distance of TLV core from the blade suction surface depends on not only the momentum of the main flow but also that of the tip leakage flow. So, the influence of the groove on the momentum of the tip leakage flow will be investigated in the following. The negative ψ_x^* and ψ_y^* around the groove location are increased compared with those in the SW as in Fig. 6, and then these phenomena are considered to reduce the distance of TLV core from the blade suction surface. These increases of ψ_x^* and ψ_y^* are considered to be due to the fact that the blade loading near the blade tip is decreased around the groove location and consequently reduces the Q_g compared with that in the SW as seen in Figs. 3 and 7. Moreover, the flow around the blade pressure side flows into the groove as observed in Fig. 8(a) and then this phenomenon also decreases the Q_g. The influence of the groove on the TLV behavior is summarized as follows: The groove weakens the flow indicated by the black streamlines in the SW in Fig. 4(a) by the decrease of the blade loading around the groove location and the flowing of the flow near the blade pressure side into the groove and then inclines its flow direction to the main flow one. As a result, the distance of TLV core from the blade suction surface is decreased.

Next, the influence of the single groove on the loss generation will be investigated. In the SW, the high loss region distributes around the trajectory of TLV core as



(a) Axialwise

(b) Pitchwise

Fig. 6 Momentum components of tip leakage flow

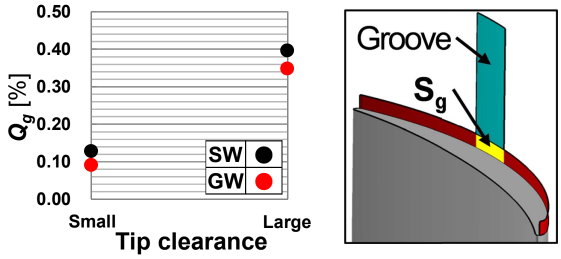
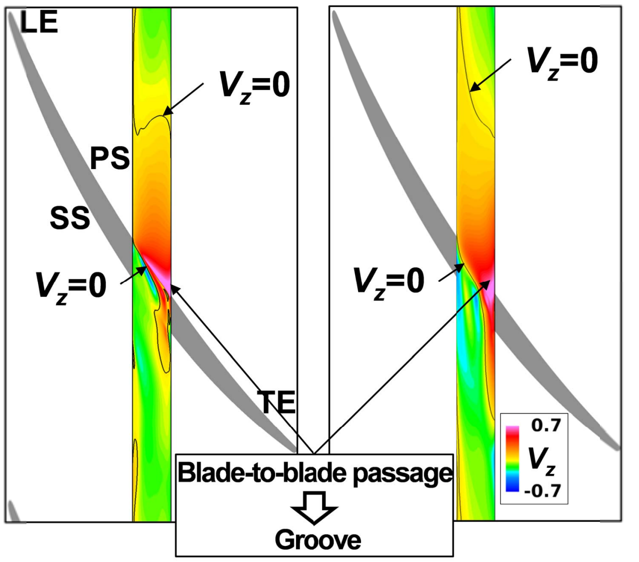


Fig. 7 Flow rate through S_g



(a) GW (Small tip clearance) (b) GW (Large tip clearance)

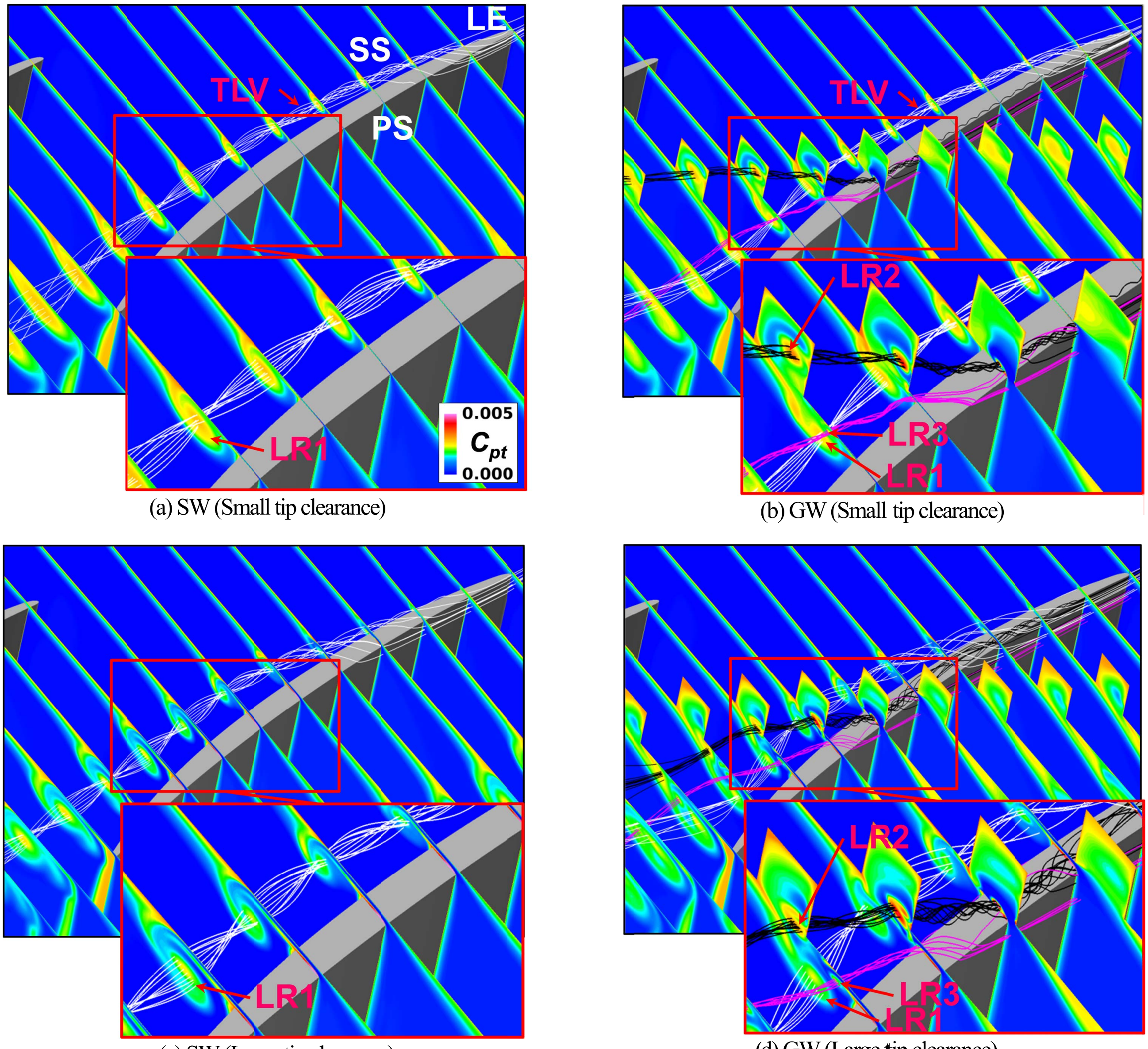
Fig. 8 Spanwise velocity distribution on interface between groove and blade-to-blade passage

shown in Fig. 9(a). The similar phenomenon is observed also in the GW. However, downstream the groove location, the high loss region due to TLV is slightly reduced compared with that in the SW as observed in the comparison of Fig. 9(a) with Fig. 9(b). On the other hand, as seen in Fig. 9(b), the separation bubble generated on the blade tip surface flows along the downstream sidewall of groove (black streamlines) and consequently generates the high loss region “LR2”. Moreover, the blade loading near the blade tip suddenly increases downstream the groove as observed in Fig. 3. This phenomenon induces the additional tip leakage vortex and consequently generates the high loss region “LR3” (purple streamlines in Fig. 9(b)). Although the loss generation due to TLV is decreased in the GW, the $C_{pt2,m}$ is almost the same value to that in the SW as in Table 2. This is considered to be due to the generations of the LR2 and the LR3.

4.2 Large tip clearance

The influences of the groove on the flow behavior and the loss generation at the large tip clearance will be investigated by comparing with those at the small tip clearance.

In the SW, the TLV is observed also in the large tip clearance case as in Fig. 4(c). However, towered the downstream of the cascade, the distance of TLV core from the blade suction surface is further increased



(a) SW (Small tip clearance) (b) GW (Small tip clearance)

(c) SW (Large tip clearance) (d) GW (Large tip clearance)

Fig. 9 Total pressure loss coefficient distribution

Table 2 Mixed-out averaged total pressure loss

Tip clearance	SW(×10^{-4})	GW(×10^{-4})	100×(GW-SW)/SW [%]
Small	172.999	172.995	-0.002
Large	173.398	173.380	-0.011

compared with that in the small tip clearance case as seen in Fig. 5. In the large tip clearance case, the TLV is generated also in the GW as in Fig. 4(d). Around the groove location, the single groove reduces the distance of TLV core from the blade suction surface compared with that in the SW as observed in Fig. 5. The comparisons of the momentum components of the tip leakage flow and the Q_g in GW with those in SW show qualitatively similar tendencies to those in the small tip clearance as seen in Figs. 3 and 6. Moreover, also in the GW with the large tip clearance, the blade loading around the groove location is decreased compared with that in the SW and the flow near the blade pressure side flows into the groove. Therefore, in the same manner as at the small tip clearance case, the single groove locally increases the negative axialwise and pitchwise momentum components of the tip leakage flow by the reduction of the blade loading and the flowing of the flow near the blade pressure side into the groove. And consequently, the groove reduces the distance of TLV core from the blade suction surface.

Concerning the loss generation in the SW, as shown in Figs. 9(a) and 9(c), the high loss region distributes around the trajectory of TLV core also in the large tip clearance case. Meanwhile, the $C_{pt2,m}$ in the large tip clearance case is higher than that in the small tip clearance case as in Table 2. This is considered to be due to the fact that the loss generation caused by the TLV is increased according to the increase of the tip clearance. In the comparison of the GW with the SW in the large tip clearance case, the single groove decreases the loss generation due to TLV downstream the groove but generates the LR2 and the LR3 in the same manner as in the small tip clearance case as observed in Figs. 9(c) and 9(d). As a consequence, the $C_{pt2,m}$ in the GW shows similar value to that in the SW also at the large tip clearance case as in Table 2. Therefore, the influence of the single groove on the loss generation in the large tip clearance case is considered to be almost the same as that in the small tip clearance case.

5. CONCLUSIONS

In this study, the influences of the single groove on the flow behavior and the loss generation in the linear compressor cascade were investigated in the small and the large tip clearance cases. The conclusions derived from the present study were summarized as follows:

(1) In the cascade which has the smooth tip side endwall, the tip leakage vortex is generated from the blade leading edge commonly in the small and the large tip clearance cases. This vortex generates the loss and it is increased according to the increase of the tip clearance size.

(2) The single groove installed at the mid-chord locally weakens the tip leakage flow by the reduction of the blade loading and the flowing of the flow near the blade pressure side into the groove, and consequently reduces the distance of tip leakage vortex from the blade suction surface. Moreover, the groove has the effect to decrease the loss due to the tip leakage vortex generated from the blade leading edge. However, the loss generation in the entire cascade passage is almost the same as that in the cascade without groove because the additional loss generation due to the presence of groove. These phenomena are observed commonly in the small and the large tip clearance cases.

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