

## Numerical Study of Improving Aerodynamic Performance of Low Solidity LPT Cascade through Increasing Trailing Edge Thickness (Postprint)

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### Abstract

Film cooling technology represents one of the most significant developments in air cooling for hot-section components of aero-engines and has been widely applied. However, film cooling hole structures in high-temperature regions often suffer from non-uniform cooling effectiveness during actual operation. The first-stage turbine vanes consume the largest portion of cooling air in aero-engines; therefore, research aimed at reducing cooling air consumption offers the greatest potential. This study investigates a novel stepped-slot film-cooled vane designed to achieve high cooling effectiveness and uniformity. Numerical methods were employed to investigate the factors affecting the cooling effectiveness of the stepped-slot film-cooled vane. This paper focuses on cooling effectiveness and pressure loss under various blowing ratio conditions to determine the optimal structural parameters through analysis of the results. The results demonstrate that an optimum slot width of 1.0 mm and a blowing ratio of 10.0 yield the best performance. Under these conditions, the vane achieves optimal cooling performance with high cooling effectiveness while maintaining low pressure loss.

### Full Text

#### Preamble

This paper presents a novel approach to reduce the solidity of low-pressure turbine (LPT) blade cascades while maintaining structural integrity. Aerodynamic performance of a low-solidity LPT cascade was improved by increasing blade trailing edge thickness (TET). The solidity of the LPT cascade blade can be reduced by approximately 12.5% through increasing the TET without a significant drop in energy efficiency. For the low-solidity LPT cascade, increasing the TET can decrease energy loss by 23.30% and increase the flow turning angle by 1.86% at a Reynolds number (Re) of 25,000 and freestream turbulence intensity

(FSTI) of 2.35%. The flow control mechanism governing behavior around the trailing edge of an LPT cascade is also presented. The results demonstrate that appropriate TET is important for the optimal design of high-lift-load LPT blade cascades.

**Keywords:** Aircraft engine, low pressure turbine, trailing edge thickness, profile loss, flow control

## Introduction

Optimization of turbomachinery design requires minimizing manufacturing and operating costs while maintaining high system efficiency. In low-pressure turbines (LPTs), this can be achieved by reducing the number of blades per row; however, the reduction in blade number results in an increased load acting on each blade [1]. High-performance LPTs typically operate at low Reynolds numbers and often suffer from flow separation on the suction sides, decreasing efficiency and reducing blade performance [2]. One way to improve the aerodynamic performance of LPTs is to control flow separation [3,4].

Various flow control devices have been used in LPTs to control flow separation. Passive devices, such as those used by Lake et al. [5] and Rouser et al. [6], include dimples, grooves, and trips on the suction surface to control flow separation. In another study, Van Treuren et al. [7] used vortex generators to control flow separation, while Murawski and Vafai [8] considered changing the axial chord of the blade. Finally, Byerley et al. [9] considered Gurney flaps to control boundary layer separation. Active devices have also been developed to control flow separation. Huang et al. [10] utilized single plasma actuators placed at different chord locations to control boundary layer separation, while Liu et al. [11], Bons et al. [12-14], and Bernardini et al. [15] considered Vortex Generator Jets (VGJs).

The primary LPT blade profile loss is due to flow separation; however, wake loss is also important. Wake loss can be reduced by changing the trailing edge thickness or by altering the shape of the trailing edge [16,17]. Zhou et al. [18] improved aerodynamic performance of LPT blades by increasing the trailing edge thickness (TET) of the blade. For a higher-lift cascade, increasing TET can increase trailing edge static pressure and reduce wake loss.

Recently, there has been a focus on developing low-solidity and highly-loaded low-solidity LPT cascade blades. Sondergaard et al. [19] used VGJs to decrease the solidity of the LPT cascade Pack B, while Qiao et al. [4,20] used the jet-flap and Gurney-flap to decrease energy loss, which enabled a reduction in the solidity of the LPT cascade Pack B while maintaining high efficiency. In these studies, active devices (VGJs and jet flap) and passive devices (Gurney-flap) were applied to the blade to control flow separation in low-solidity LPT cascades, which increases manufacturing cost and compromises the structural integrity of the blade.

Inspired by the improvement in aerodynamic performance of LPT blades

achieved by increasing TET, we propose that solidity may be reduced by only increasing the TET of the blade, with the goal of reducing blade count while maintaining structural integrity. To the authors' knowledge, we are the first to study the feasibility of reducing the solidity of LPT blade cascades by increasing the TET of LPT blades. We present flow control effects resulting from increasing TET of LPT blades.

## Computation Model and Method

### Geometric Model

Figure 1 [Figure 1: see original paper] shows the geometry of the P&W Pack B. The chord length of the Pack B blade is  $C = 17.78$  cm. The pitch length is  $s = 14.12$  cm and the axial chord length is  $C_x = 15.95$  cm. The inlet flow angle ( $\beta_1$ ) and the designed exit flow angle ( $\beta_2$ ) for the blade are  $35^\circ$  and  $-60^\circ$ , respectively. The solidity  $\tau$  (defined as  $C/s$ ) of the cascade is 1.25, which is the optimum cascade solidity for conventional design.

Increasing the TET was accomplished by only changing the profile of the blade on the pressure side at approximately 95% chord of the airfoil, as shown in Figure 2 [Figure 2: see original paper]. The TET  $h$  is shown in Figure 2. The standard TET of Pack B is  $h/s = 1.7\%$ .

### Computation Mesh and Computation Methods

For numerical simulations, a multi-block structured grid was used. The blade was surrounded by an O-grid, with the first layer near the wall prescribed at 0.015 mm and a grid expansion ratio of 1.12. The  $y^+$  of the blades was less than 0.5. Figure 3 [Figure 3: see original paper] shows the computational grids for simulations.

Two-dimensional RANS equations were solved to describe flow around the LPT blade profile. Flow separation and transition were solved using the Langtry-Menter transition model [21,22].

The inlet total pressure, flow angle, eddy viscosity coefficient, and total temperature were specified at the inlet boundary. The outlet boundary specified static pressure. A periodic condition was used to simulate only one blade.

### Validation of the Numerical Method

To verify the numerical methods, the computational data were compared with experimental data [5,6,10].

The wall pressure coefficient  $C_p$  is defined as:

$$C_p = \frac{P_s - P_{inlet}}{0.5\rho U_{inlet}^2}$$

where  $\rho$  is the inlet air density,  $U_{inlet}$  is the inlet velocity,  $P_s$  is the static pressure on the blade surface, and  $P_{inlet}$  is inlet static pressure.

The energy loss coefficient  $\gamma$  based on the inlet velocity  $U_{inlet}$  is defined as:

$$\gamma = \frac{P_{0,inlet} - P_{0,outlet}}{0.5\rho U_{inlet}^2}$$

where  $P_{0,inlet}$  is inlet stagnation pressure and  $P_{0,outlet}$  is outlet stagnation pressure.

The energy loss coefficient  $\omega$  based on the outlet velocity  $U_{outlet}$  is defined as:

$$\omega = \frac{P_{0,inlet} - P_{0,outlet}}{0.5\rho U_{outlet}^2}$$

where  $U_{outlet}$  is the outlet velocity.

In Figure 4 [Figure 4: see original paper], the computed pressure coefficient distributions are shown along with experimental data. The computed  $C_p$  distributions on the blade show good agreement with experimental data. These results show that computational methods have the ability to predict flow separation and transition. At a given FSTI, decreasing the Re moves the location of separation upstream and the location of reattachment downstream. For a given Reynolds number, increasing the FSTI moves the location of separation downstream and the location of reattachment upstream.

A comparison of computed energy loss coefficients with experimental results is shown in Figure 5 [Figure 5: see original paper]. Computed data display good agreement with experimental data for  $Re = 86,000$  and  $Re = 172,000$ , as shown in Figure 5(a); however, the computed values overestimate experimental data for  $Re = 25,000$  and  $Re = 50,000$ . As shown in Figure 5(b), for  $Re = 25,000$ , the computed values were in good agreement with experimental values for  $FSTI = 1\%$ , but computed values were slightly lower than experimental data for  $FSTI = 4\%$ . At  $Re = 45,000$ , the computed data and the experimental data exhibited large differences when  $FSTI = 1\%$ , which may be caused by flow instability; however, the computed data and the experimental data showed good agreement when  $FSTI = 4\%$ . At  $Re = 100,000$ , the computed loss coefficient matched experimental values for both  $FSTI = 1\%$  and  $FSTI = 4\%$ . Based on fit to experimental data, the computation method used in this work is able to describe flow separation and transition in the turbine cascade.

## Effect of TET on the Low Solidity LPT Cascades

To decrease the blade count, the solidity of the LPT cascades was reduced by 12.5% and 25%, which were respectively referred to as Pack LB1 and Pack LB2.

The solidity of the LPT cascades was changed by only increasing the pitch of the cascade with the other airfoil parameters unchanged.

To improve aerodynamic performance of the low-solidity LPT, the TET of the blade was increased. Table 1 shows the changes in TET.

Figure 6 [Figure 6: see original paper] shows the effect of TET on the energy loss coefficient in the two low-solidity cascades. As shown, for Pack LB1, the energy loss coefficient first decreases and then increases at  $Re = 25,000$ ,  $FSTI = 2.35\%$  as the TET increases. The energy loss coefficient of Pack LB1 blades with TET of 4.0% decreases by 23.30% compared to the coefficient for a standard trailing edge at  $Re = 25,000$ ,  $FSTI = 2.35\%$ . The energy loss coefficient increases at higher Reynolds number and higher FSTI. However, increasing TET cannot reduce the energy loss coefficient in the lower-solidity cascade Pack LB2.

Figure 7 [Figure 7: see original paper] shows the effect of TET on the turning angle in the two low-solidity cascades. As shown in Figure 7, the turning angle of the two low-solidity cascades increases as TET increases. The turning angle increases by 1.86% at  $Re = 25,000$ ,  $FSTI = 2.35\%$  with a TET of 4.0% in the Pack LB1. Figure 6 and Figure 7 together show an interesting result: increased TET enhanced aerodynamic performance of low-solidity LPT cascade; however, increasing TET couldn't suppress flow separation when the solidity is too low.

Figure 8 shows aerodynamic performance of a blade cascade with trailing edge thickness 4.0% at  $Re = 25,000$ ,  $FSTI = 2.35\%$ . As shown in Figure 8: see original paper, the energy loss coefficient of a low-solidity Pack LB1 with a TET of 4.0% can be manipulated to be equivalent to that of a Pack B cascade. As shown in Figure 8(b), the turning angle of a low-solidity Pack LB1 cascade with a TET of 4.0% is about  $1^\circ$  lower than that of a Pack B cascade, which is about  $2^\circ$  higher than that of Pack LB1 cascade with standard TET. These results show that aerodynamic performance of a low-solidity Pack LB1 cascade can nearly match that of a Pack B cascade by increasing the TET.

The static pressure coefficient  $C_{pb}$  is defined as:

$$C_{pb} = \frac{P_p - P_{outlet}}{0.5\rho U_{inlet}^2}$$

where  $P_{outlet}$  is outlet static pressure and  $P_p$  is the blade trailing edge plane static pressure.

Figure 9 [Figure 9: see original paper] shows the static pressure coefficient  $C_{pb}$  at  $Re = 25,000$ ,  $FSTI = 2.35\%$ . As shown in Figure 9, the positive static pressure coefficient area of a low-solidity cascade with increased TET differs from the coefficient of a Pack B cascade, which is larger than the coefficient for a Pack LB1 cascade with standard TET. Increasing the positive static pressure coefficient  $C_{pb}$  area accelerates the trailing edge flow and reduces wake loss. However,

increasing TET enhances the trailing edge flow mixture, which increases the wake loss. The total wake loss results from the combination of these two effects.

Compared with the technologies in references [19-21], increasing TET doesn't require adding other devices to the blade, which decreases manufacturing cost and maintains the structural integrity of the LPT blade.

Figure 10 [Figure 10: see original paper] shows the pitch-wise energy loss coefficient distribution on a plane near the trailing edge at  $Re = 25,000$ ,  $FSTI = 2.35\%$ . The pitch-wise energy loss coefficient of the low-solidity cascade with a TET of 4% is slightly larger than that of a Pack B cascade, which is smaller than that of a Pack LB1 cascade with standard trailing edge. Increasing TET decreases the width and intensity of the wake. The center of the Pack LB1 cascade wake moves towards the pressure side as the TET increases.

Figures 11 and 12 respectively show streamline and velocity contours and turbulence kinetic energy contours in the low-solidity LPT cascades at  $Re = 25,000$ ,  $FSTI = 2.35\%$ . For a low-solidity cascade blade with standard TET, there is severe flow separation on the suction surface, as shown in Figure 11 [Figure 11: see original paper]. With TET of 4.0%, the flow separation is significantly reduced, as shown in Figure 11(b). As TET increases from 4.0% to 7.5%, the size of the separation bubble decreases slightly, as shown in Figure 11(c). As shown in Figure 12 [Figure 12: see original paper], increasing TET decreases the turbulence kinetic energy on the suction surface. However, the turbulence kinetic energy near the trailing edge increases when TET is very large.

The increase in trailing edge thickness deflects the main stream, which results in accelerating flow on the adjacent airfoil suction surface. This can increase energy in the boundary layer on the suction surface, which increases resistance to flow separation. As a result, the location of separation moves downstream and the boundary-layer separation zone becomes smaller.

## Conclusions

This work presents a new idea to decrease the solidity of LPT blade cascades by increasing the TET. In low-solidity LPT cascades, aerodynamic performance can be improved by increasing the thickness of the trailing edge.

With an increased TET, the solidity of the LPT cascade can be reduced by 12.5% without significant loss. When the solidity of the LPT cascade is reduced by about 12.5%, increasing the thickness of the trailing edge can decrease energy loss by 23.30% and increase turning angle by 1.86% at  $Re = 25,000$  and  $FSTI = 2.35\%$ .

There are three main effects of increasing the thickness of the trailing edge: (1) The main stream is deflected, which results in accelerating flow on the adjacent airfoil suction surface. This can increase energy in the boundary layer, which increases resistance to flow separation and decreases the boundary-layer loss. (2) The trailing edge plane static pressure increases, which reduces the wake

loss. (3) The trailing edge flow mixture is enhanced, which increases the wake loss. The profile loss results from the combination of these three effects.

It is generally thought that increasing airfoil lift and controlling flow separation require adding active or passive devices, while our work shows that the solidity of the LPT cascade can be reduced by only increasing the TET. Compared with previous technologies, the new idea presented in this work decreases manufacturing cost and maintains the structural integrity of the LPT blade.

This work provides new guidelines for the design of high-lift-load LPT blade cascades.

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