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STUDY OF THE SECONDARY FLOW STRUCTURES CAUSED THE ADDITION FORWARD FACING STEP TURBULENCE GENERATED

CASE STUDY: HORSESHOE VORTEX BETWEEN 9C7/32.5C50 BODY AND ENDWALL

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Abstract

Secondary flow is the most dominant hydraulic loss in axial compressor. If secondary flow is weak, it could improve the performance of axial compressor. One of the efforts to reduce the secondary flow is through giving the addition of leading edge fairing, but it is not effectively used at high angle of attack (AoA). Moreover, the information of the highly turbulent flow occurs, after crossing a forward facing step turbulence generated (FFST). Consequently, the addition FFST is predicted to reduce the occurrence of secondary flow.

This research was presented by means of experiments in the wind tunnel. The results of the experiment were exposed in the skin friction surfaced through the oil flow visualization. Then these results were

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confirmed by numerical simulations in the steady state conditions and free stream flows with $Re_d = 10^5$. Body profile issued by British 9C7/32.5C50 with chord length 120 mm. This analysis compared the result of the secondary flow character between without and with FFST.

Results of the addition FFST generated new theory of secondary flow characters. Meanwhile, the new theory stated that the end stagnation point is the determinant point the forward saddle point. As a result, the separation line 3D opened and kept away from the body contour. End stagnation point (ESP) was the source of attachment line in horseshoe vortex formations. Moreover, the blockage in horseshoe formations always caused by attachment line in horseshoe vortex. Whereas previous theories have always stated, determining the blockage occurs always based on the forward saddle point. Therefore, this theory states that the blockage depends on the ESP, it causes the high turbulent flows. This state gives additional information about the change of secondary flow characteristics. The highest performance FFST to reduce the blockage is at 4 degrees AoA by 21.9%.

1. Introduction

Since Lakshminarayana and Horlock [1] stated that the secondary flow is the dominant factor of energy loss in annular axial compressor, the researchers presented again the fundamental side on the phenomenon of secondary flow. The simplest secondary flow phenomenon happened among endwall with a body, it is often referred as the horseshoe vortex. While the structure of the more complex secondary flow occurs at the tip, occurrence of this incident usually referred as the tip vortex. The studies on the horseshoe vortex have been done by Merati et al. [2] and Abdulla et al. [3]. Their theory states that horseshoe vortex formation is encountered with forward saddle point [FSP].

Previous researchers have made some efforts to reduce the occurrence of secondary flow. Steenaert et al. [4] stated that addition fairing leading edge, would change the secondary flow structures. That effect of the position FSP that is near to the leading edge so the separation line 3D gets closer to the body. This phenomenon causes the horseshoe vortex size is getting smaller so it would give effect to reduction of blockage in the downstream area. This character agrees with Tobak and Peake [5] where the horseshoe vortex size is strongly influenced by the position of FSP. The addition of leading edge fairing has a few weakness such as the flow going to the upper side got a heavy load by increasing the angle of attack (AoA). Therefore, the addition of leading edge fairing on the strong AoA is very vulnerable to produce flow separation.

The information about passive flow control could induce the flow to be more turbulent (turbulence generated) inspire this research to reduce secondary flow. The boundary layer theory states that the increasing of turbulent fluid flow could strengthen the momentum flow in the near endwall (friction surface). This phenomenon is supported by Schlighting's theory [6]. The more turbulent flow always generates the smaller wall shear stress so the velocity profile becomes more fuller. The flow with bigger momentum predicted to be stronger to face friction effect and adverse pressure. Therefore, this study purposes reduce secondary flow by using the turbulent generator so this device is a simple way to improve the turbulent flow.

The another result by Serry et al. [7] stated that forward facing step turbulent generator (FFST) causes the fluid flow to be more turbulent, it is caused by the occurrence of two recirculation (bubble separation) zones. Where at this area transformation from laminar flow to turbulent flow becomes shorter. This phenomenon strengthens the discourse about the flow after crossing FFST become higher turbulent. Therefore, this research would reduce secondary flow through the addition FFST.

2. Methodology

This study was done through experiment at wind tunnel with visualization oil flow method from wall skin friction structure. This technique was first described by Maltby [8] from the practitioners, then popularized by Tobak and Peake [5]. They have classified the secondary flow based on skin friction 2D views, as nodes, focus and saddle. According to Tobak and Peake, 3D view is divided into attach flow and separation flow. If the flow direction closer to friction area, it called as *attached flow* and the opposite direction is called as the *separation flow*. The result of this experiment is difficult to presenting as a secondary flow phenomenon because it is very complicated. Analysis of secondary flow structure require numerical simulation as supporting data, it would prove the complexity of the secondary flow. Numerical methods held on three steps i.e., pre-processing, solver and post-processing. Pre-processing parameter is adapted to Mirmanto et al. [9]. This method is related to validation about the mesh quality.

Solver process used steady state analysis, free stream flow with $Re_c\ 10^5$ based on chord length and turbulence intensity 5% for axial direction (u'). Discretization model used second order and convergence criterion 10^{-5}. Wing profile used British 9C7/32.5C50, viscous model used Reynolds stress method. These parameters were adapted to the wind tunnel experiment conditions.

Domain numerical simulations are presented in Figure 1. The boundary condition for inlet used velocity inlet, outlet used outflow, body used wall and top surface used symmetry. It agrees with Mirmanto et al. [9]. The distance of FFST to the inlet (Lu) is 8/15C, FFST thickness (d) 4% C, the position of the body from FFST is $\mathrm{L} = 2/3\mathrm{C}$. Body profile is a British model of 9C7/32.5C50. This model means identity of base profile is C7, maximum thickness of 9% with the chamber angle is 32.5 degrees on 50% of the chord length and chord length used 120 mm. Blockage ratio in this model is 8% so the model is declared that is free from influence of the beside wall. This calculation is obtained from the maximum width of the angle of attack 16 degrees $(\mathrm{W_{max}} = \mathrm{C.sin\,16})$ then that value compared to the width of a wind tunnel (2.5C).

The initial evaluation is presented by comparing the shape factor after crossing FFST at each distance 4 cm, 8 cm, 12 cm and 16 cm. This step is to determine the optimal positions between FFST and body. The measurement of flow characteristic is done to compare the shape factor ratio between with and without FFST at the endwall so the FFST placed on the optimum distance. Analysis continued to evaluate comparison of the secondary flow structures, than the observation of secondary flow presented based on the Tobak and Peake theory [5].

3. Analysis and Result

Forward facing step turbulent generator (FFST) as a passive control flow aims to enhance the turbulence intensity flow. The measurement of the turbulent flow could be done based on the shape factor value. The shape factor presented the comparison of displacement thickness to momentum thickness. If the value of the shape factor small, it means that the momentum and turbulence flows would be greater.

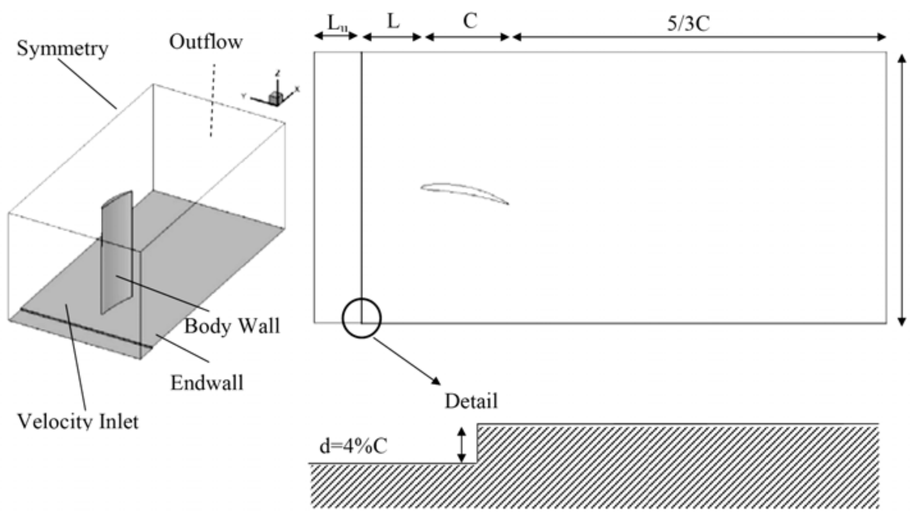


Figure 1. Domain numeric simulation and experiment.

Table 1 shows the biggest value of shape factor occurred at distance of 40 mm from FFST. This condition is predicted still near to the recirculation zone. While the boundary layer is still in the early process of development, this flow is indicated to own the characteristic of laminar flow. From Table 1 it could be seen that the highest difference of shape factor placement is occurred at 80 mm with value 5.45%. This position used to place the FFST, in non-dimensional parameter it was 2/3 from chord length.

Table 1. Shape factor boundary layer

Endwall	Shape factor			
	Position *X* (mm)			
	40	80	120	160
Without FFST	1.65	1.59	1.51	1.44
With FFST	1.80	1.50	1.43	1.40
Δ (Shape factor)	–8.95%	5.45%	5.22%	2.80%

Analysis of the boundary layer was followed up by observing the velocity profiles and fluctuation velocity component. Figure 2 shows the *u*-velocity profile with difference scale $u = f(y)$ and $u+ = f(y+)$. Velocity profile becomes smaller due to the addition of FFST, it shows the decreasing momentum in the buffer layer so the momentum increases in turbulent layer. This phenomenon is caused by changes of velocity direction from *u* to *v* after crossing FFST. This effect produces the stronger inter-particle collisions, so the fluctuation of velocity increased sharply in any direction (u', v', w'). If the occurrence fluid particle collision in the orthogonal direction, it would cause inter-particle collision more intense so vibration of particle fluid to become stronger. In the flow without FFST, the particle collision occurs only in tangential direction, so the vibration of particle fluid is relatively weaker. The result experiment by De Graaff and Eaton [11] on flat plate endwall compares the result of this numeric simulation, where the both results are shown similarity. This condition is shown in Figure 2.

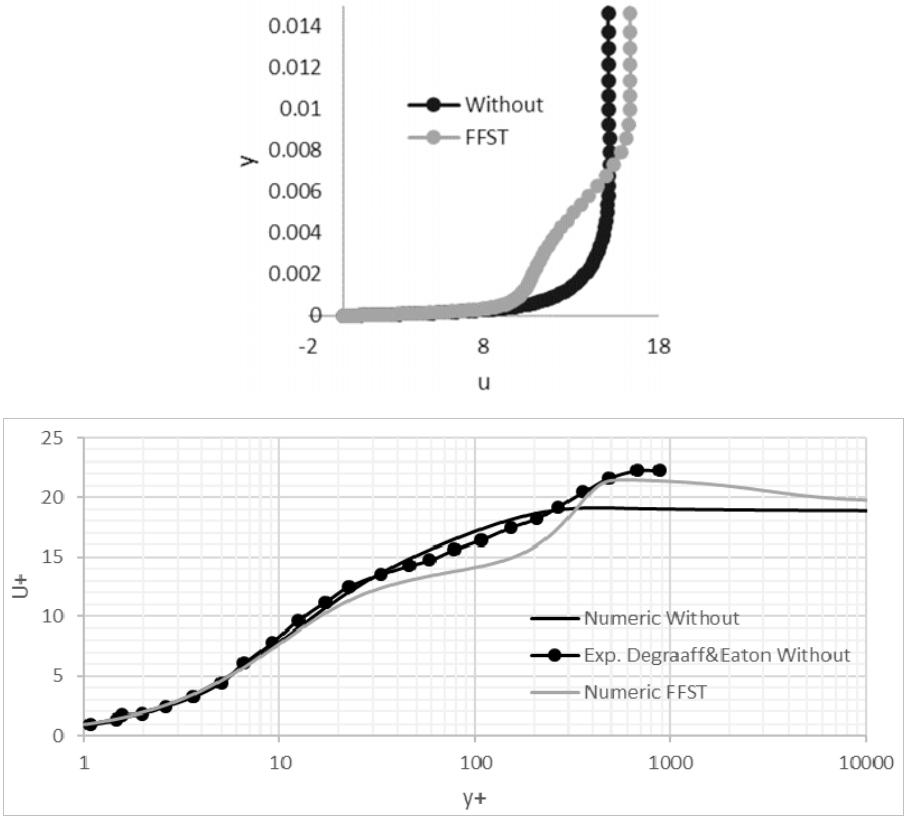


Figure 2. Velocity profile between with and without and FFST at X = 80 mm.

Figure 3 shows the increasing of velocity fluctuation with and without addition of FFST, where Reynolds stress $u'u'+$ with FFST has become larger. This phenomenon has two maximum values, i.e., in the area of the buffer layer and the turbulent layer. The increasing of Reynolds stress $u'u'+$ particularly in the area of turbulent layer, where it is not occurred if without FFST. The increase of Reynolds stress $u'u'+$ without FFST only occurred in buffer layer, so this condition causes the narrow area. On the other hand, the increase of Reynolds stress $v'v'+$ occurs in the area of buffer and turbulent layer, this effect causes inter-particle collision more intense. But Reynolds stress $w'w'+$ has same profile without FFST so profile only depends on *z*-axis disturbance. According to the theory of turbulent flow, the increase of Reynolds stress would reduce the wall shear stress. This phenomenon strengthens the prediction of flow momentum after crossing FFST would be more fuller at near endwall. The flows with fuller momentum would be stronger to facing the friction effect and adverse pressure.

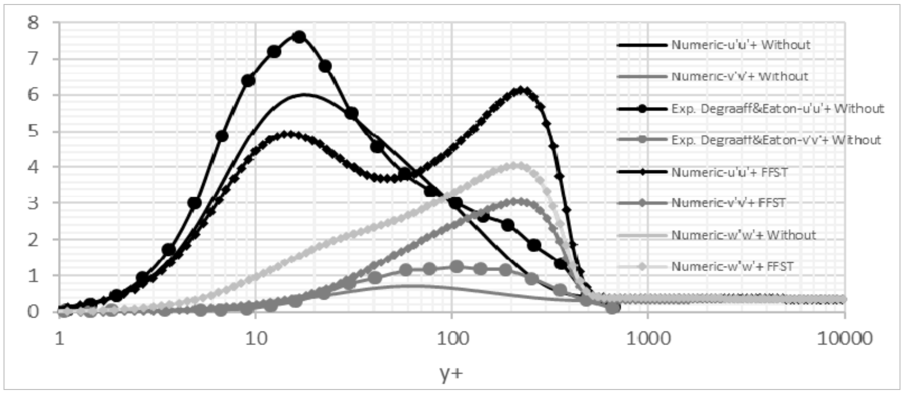


Figure 3. Fluctuation velocity profile.

In previous research, the secondary flow structure always started from the formation of the forward saddle point (FSP). The FSP position is the important parameter to form the horseshoe vortex, so this position would determine the horseshoe vortex size. Formation of FSP causes two attachment lines. Another attachment line from leading edge always comes from the end stagnation point (ESP). The ESP is the limit of inlet flows which is able to touch the leading edge. This point always indicated by the maximum pressure where the pressure coefficient is one. This result is shown in Figure 4. At the secondary flow structures, ESP is a source of attached flow which fills in the horseshoe vortex formation. The previous theory has never discussed about ESP as a determine factor to form FSP, but only focused on the FSP. This research proves that ESP is a determining factor to form the horseshoe vortex.

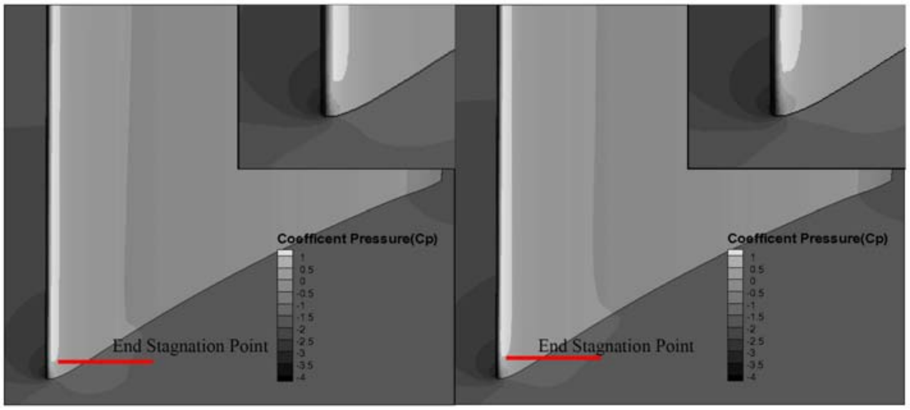


Figure 4. Pressure contour distributions.

On the using of FFST, the effect of velocity increasing and turbulent intensity in turbulent layer causes the decreasing of velocity in the buffer layer. This phenomenon causes the moving of ESP. If the ESP kept away from the endwall, it would be closer to the inviscid flow area. This position has indicated that ESP has greater energy, so the attach flows from ESP more stronger. The energy in the attached flow consists of momentum and turbulence kinetic energy as presenting in Figure 6, where the area of negative pressure is getting wider due to the addition FFST. This reaction would increase the momentum in the downstream area. This phenomenon is caused by conversion of turbulence kinetic energy to momentum energy.

Figure 6 shows secondary flow structure with 12 degrees angle of attack. The results of numerical simulations always show the similarity with the experimental results. This is caused by the flow in the formation of the horseshoe vortex which have the low momentum, so that the skin friction surface could not give the evidence clearly. Therefore the exploring of secondary flow is needed the result data from numeric simulation.

If the strong attach flows from ESP met to the attached flows from inlet, it means that FSP moves away from the leading edge. This phenomenon causes the formation of separation line 3D would get away and opened from the contours of the body whereas the previous theory always predicted occurrence the bigger of secondary flow, so it produces the larger blockage area. The addition FFST causes the structure of secondary flow become taking leave, where the occurrence of blockage in downstream becomes smaller. The blockage always contain many vortex, where the vortex produced by attachment line from ESP. The previous theory has assumed that blockage caused by the separation line 3D as Merati theory [2] for low turbulent, but for high turbulent flow this research is capable to use.

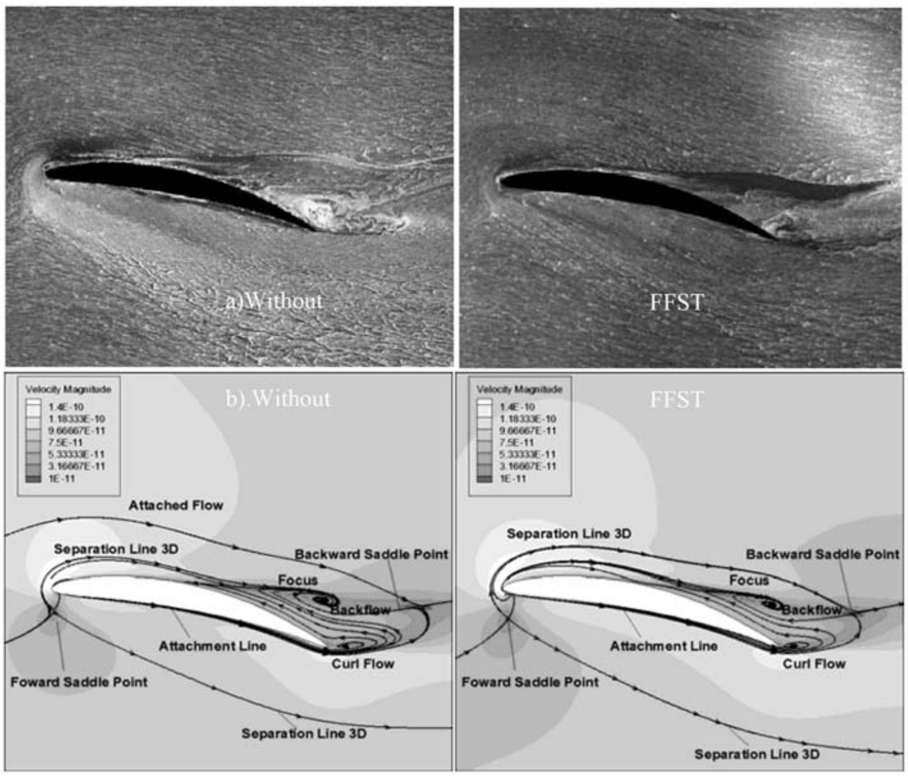


Figure 5. Secondary flow topology: (a) experiments, (b) simulation numerics.

In Figure 5, the attachment line in lower side moves around the body, goes to downstream and then across to upper side. The cross flow is caused by difference pressure between lower and upper side. This flow usually called as *curl flow* and it will more intense with increasing the angle of attack. In addition, FFST the strength attachment line in downstream is not easily influenced by the different pressure of lower and upper sides so the occurrence of cross flow becomes weaker. This strong attachment line is more tend to move toward the downstream, instead of strengthen curl flow.

The addition of FFST could strengthen the momentum on downstream area, especially on the lower side, so this flow tends to move away from contour body. Beside the flow near the endwall from midspan, especially on the lower side, moves to downstream then strengthen occurrence cross flow. The cross flow toward lower side and empties into the curl flow. Moreover, the result of separation 2D from midspan would strengthen the curl flow.

On the upper side, separation line 3D is not able to move to downstream, so this flow towards into the horseshoe vortex. The disability of the separation line 3D has a great opportunity to meet the backflow. If it happened, the flow would be trapped and produce the focus on the upper side. However, the addition of FFST causes insistence against attached flow in horseshoe vortex so it becomes stronger. Separation line 3D in lower side got easier to interact with the flow outside the horseshoe vortex formation, this flow could be reattachment. Hence the tendency curl flow met more easily with reattachment of separation line 3D. The consolidation directly between curl flow and attached flow out of the horseshoe vortex has lower possibility. The meet point of both these flows called as *backward saddle point* (*BSP*). The position of BSP is closer with the body, this effect causes the backflow become weaker so the occurrence of focus would smaller. All of incidence flow separation in the formation of the horseshoe vortex always goes to the corner wake. This phenomenon as measuring determines the occurrence of blockage. In addition, FFST could weaken the occurrence of curl flow, focus and corner wake, so it directly reduces the blockage occurrence.

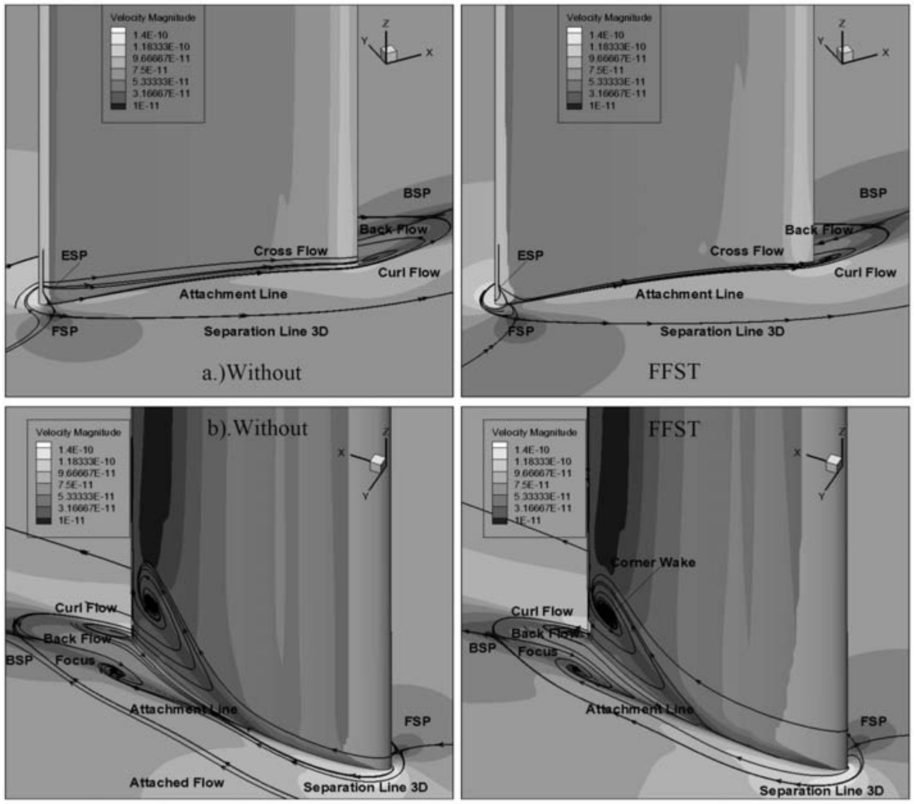


Figure 6. Secondary flow topologies: (a) upper side, (b) lower side.

Blockage is a barrier of the flow toward downstream, it also causes the energy loss. This event could present the contour of axial energy loss and in non-dimensional parameters could present in axial total pressure loss coefficient. Figure 7 shows the axial total pressure loss coefficient contour with FFST. This figure indicates that the minimum area would be wider particularly in the corner area. This condition also indicates that the axial energy becomes stronger and the blockage becomes smaller. The difference of contour is very visible in the area of the upper side where blockage occurs. This condition explains that addition of FFST in qualitatively could reduce.

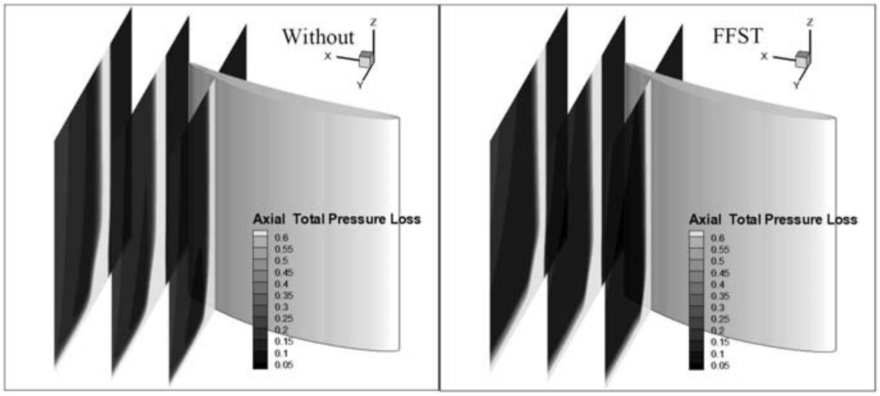


Figure 7. Contour of axial total pressure loss coefficient.

The results of evaluation of the axial total pressure loss coefficient shown in Figure 8. This figure shows FFST additions could reduce blockage in each angle of attack (AoA), but the increasing of AoA causes the reduction become smaller. However, the using of FFST at higher AoA is less effective, especially at AoA 16°. Besides the addition of FFST it does not affect the increase of load in nose, so that the flow becomes stronger to face the occurrence of flow separation. This research obtains data that using FFST would more effective with AoA up to 12°. The maximum energy loss reduction achieve 21.9% with 4° AoA and followed by 15.5% with 0° AoA, 14.6 with 8° AoA, 12% with 12° AoA and the last 2.1% with 16° AoA.

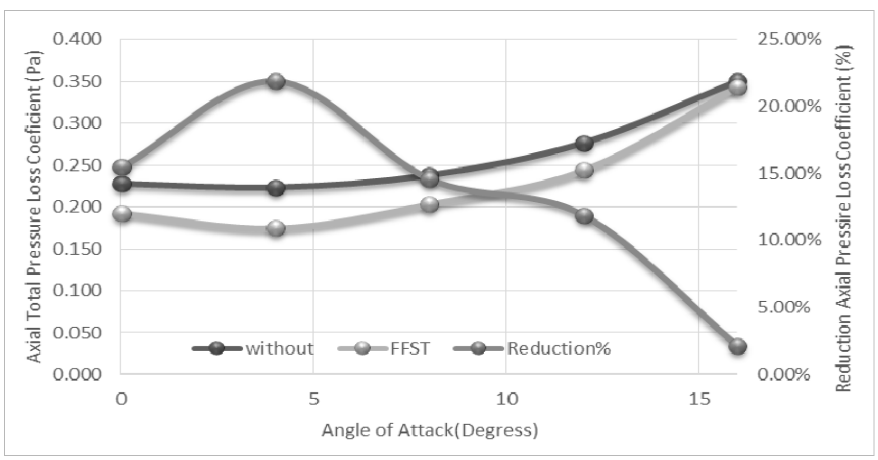


Figure 8. Graphic axial total pressure loss coefficient.

This research obtained some data that addition of FFST will change some characteristics such boundary layer profiles, secondary topology and energy resource in downstream. The addition FFST gives impact in:

a. Boundary layer characteristic, where:

- ✓ Increasing *u*-velocity profile in the turbulent layer, although the deficit in the buffer layer.
- ✓ Extending the area of Reynolds stress $u'u'$ have two-point maximum peak.
- ✓ Increasing Reynolds stress in all direction on turbulent layer area, so in the case of wall shear stress this indicates the reduction.
- ✓ Shape factor becomes smaller.

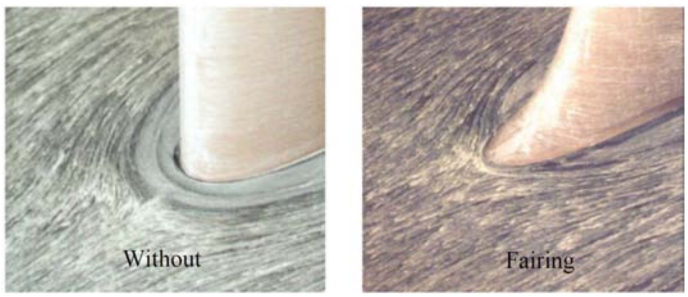
b. Secondary flow characteristic, where:

- ✓ End stagnation point is getting farther away from the endwall.
- ✓ Forward saddle point is getting farther away from the leading edge.
- ✓ Separation line of 3D is more open and get away from the body contour.
- ✓ Attachment line in the horseshoe vortex is getting closer and nearer to the body contour, so the occurrence of curl flow is getting weaker.
- ✓ Separation line of 3D could be reattachment.

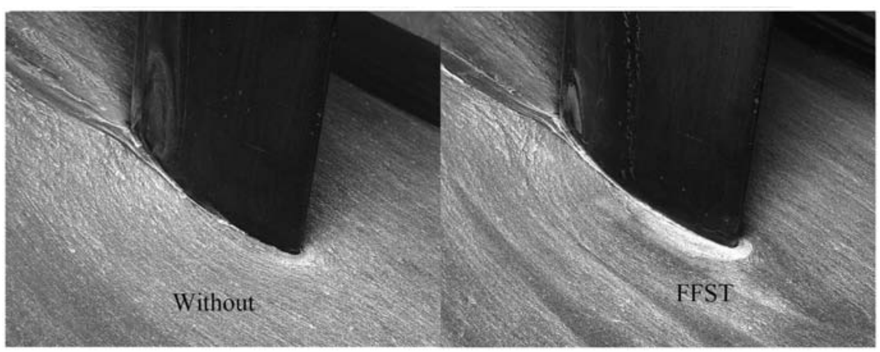
4. Conclusions and Discussion

This research confirms again that corner wake influenced by the attached flow in the horseshoe vortex. If the attachment line in the horseshoe vortex is stronger, this flow more induces toward downstream so the occurrence of curl flow becomes more weak. Where curl flow, BSP and focus always cause the occurrence of corner wake or blockage. Therefore the secondary flow theory stated that ESP was a source to form the attached flow in horseshoe vortex, so it was a determinant factor in the horseshoe-vortex size and blockage.

The previous study by Steenaert et al. [4] is presented in Figure 9. This research states that FSP closer to leading edge would generate separation line 3D which is closer to the contour the body. This phenomenon always indicates the smaller horseshoe-vortex. Addition FFST would cause opposite phenomenon on FSP as Steenaert et al. [4] result. If the separation line 3D is more open and keep away from body, it would produce the weaker horseshoe vortex. Consequently, the previous secondary flow theory is not appropriate in this case. This research resulted a new theory about the treatment of secondary flow, which is caused by higher turbulence intensity.



(a)



(b)

Figure 9. Comparing the result oil flow visualization with (a) fairing, (b) FFST.

In this study, the addition of FFST could reduce blockage till 21.9% with the angle of attack 4 degrees. If AoA increase causes the occurrence of massive separation, this numerical simulation results could not be compared with the experimental results so analysis of steady state could not be used on the massive separation. To solve this problem, unsteady state model Reynolds average Navier-Stoke (URANS) or large eddies simulation (LES) was recommended due to eddies in the flow.

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