N93-17289

1992

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

CFD ANALYSIS ON CONTROL OF SECONDARY LOSSES IN STME LOX TURBINES WITH ENDWALL FENCES

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Introduction

The rotor blade in the newly designed LOx turbine for the future Space Transportation Main Engine (STME) has a severe flow turning angle, nearly 160 degrees. The estimated secondary loss in the rotor alone accounts for nearly 50% of the total loss over the entire stage. Turbine Team of CFD Consortium at MSFC has been devoting significant effort to exploring viable means to reduce such a loss. One of the potential methods is to use fences attached on the turbine endwall (hub). According to limited information available in the open literature [1], the presence of an endwall fence can alter the overall secondary flow structure in the blade passage, so the loss due to secondary flow can be alleviated. It is recognized, however, improperly arranged fences may have detrimental effects on the turbine performance, as a fence always impose addtional blockage to the flow and increase the profile loss.

As a prelude to examining the effects of endwall fence with actual STME turbine configuration, the present study focuses on similar issues with a different, but more generic, geometry - a rectangular duct with a 160-degree bend. The duct cross-section has a 2-to-1 aspect (height-to-width) ratio and the radii of curvature for the inner and outer wall are 0.25 and 1.25 times the duct width, respectively. These geometric parameters simulate the mean values of those in the STME LOx turbine, thus the duct geometry preserves basic turning features of the actual blade passage. While a series of parametric studies with different fence geometries and flow conditions will be undertaken in the near future, the present emphasis lies in examining the effects of various fence-length extending along the streamwise direction. The flowfiled is numerically simulated using the FDNS code developed earlier by Wang and Chen [2]. The FDNS code is a pressure based, finite-difference, Navier-Stokes equations solver.

Secondary Flows and Losses

Secondary flow is a phenomenon in which a flow motion normal to the primary flow direction prevails. In turbomachinery, aerodynamic loss due to excessive energy carried by such a flow motion is termed "secondary loss." Over the past fifty years, an extensive effort, in both theoretical and experimental aspects, has been devoted to understanding the secondary flows and losses in axial turbines. Until the recent availability of three-dimensional, Navier-Stokes equations solvers, most of the earlier developments were based on inviscid flow theories. A classical model developed by Hawthorne [3] suggests that the secondary flow in a blade passage is largely dominated by a pair of counter-rotating vortices. Such a flow pattern is typical for duct flow with a mild bend [4] . In addition, due mainly to vorticity stretching throughout the passage, vortex filaments also exists near the blade trailing edge.

Until the late 1970's [5], laboratory experiments with cascade flow visualization and/or measurements started to reveal the importance of the evolution of inlet boundary layer. The boundary layer entering the cascade separates in the blade leading edge forming a horseshoe vortex and split into two legs wrapping around both sides of the blade. The pressure side leg of the vortex, as driven by the pressure gradient in the blade passage, migrates toward the suction side of the neighboring blade and becomes the passage vortex. This phenomenon represents one of the most dominating features in turbine secondary flow. The suction side leg of the horseshoe vortex, rotating in an opposite sense relative to the pressure side leg, grows thicker (radially outward) along the contour of the suction surface. Near the downstream portion of the surface, the suction side leg eventually meets the passage vortex forming a somewhat larger and stronger vortex. All these horseshoe vortex interactions combined account for one of the greatest sources for the secondary loss in a turbine cascade. Attaching a fence on the passage endwall may alter the overall flow patterns as previously described, so the loss associated with the secondary flow in the blade passage can be reduced.

Results and Discussion

Figure 1 shows velocity vector plots near the endwall region for three different fence (length) extensions; i.e. full, 3/4 and 1/2 of the turning arc along the center line of the duct width. For comparison, the case without fence is also included in the figure. Except for the length extension, the fence geometry and flow Reynolds number were kept the same for all the cases studied. The fence has a rectangular cross-section which occupies nearly 15% in both width and height of the channel flow area. Flow Reynolds number based on the channel width equals to 10 million. The computation uses a 75x21x32 grid and takes approximately 4000 steps for a converged solution. As shown in Figure 3, except near the vicinity of the fence, the flow pattern appears to preserve the major features of flow over a semi-circular turn. Even with such a severe turning, flow separation is non-existent throughout virtually the entire turning region (grid I from 23 to 53). A very minor separation which results in a relatively low pressure spot near the tip of the inner wall. In the post turn region, flow separates from the inner wall and forms a strong recirculation attaching to the surface. Imposing an endwall fence seems to have an effect to elongate the recirculation zone. However, this phenomenon is somewhat insensitive to the fence length.

Figure 2 displays the secondary flow near the mid-plane of the turn (I=38). For the case without fence, the flowfield displays a pattern consisting of two counter-rotating vortices similar to the classical model of secondary flow in a blade passage. Due to imbalance of centrifugal force and pressure gradient, the flow near the central portion of the duct moves from the inner wall toward the outer wall. The pressure gradient then forces the flow moving throughout the vortex path. Because the flow bulk inherits strong inertia for the present case, the secondary flow motion is relatively insignificant as compared to a conventional Dean-type pattern in a mild-bend duct. With the fence presence, it is clear that the secondary flow has been altered, particularly in the region close to the endwall. One important observation is that the fence diverts the low-momentum flow in the boundary layer upward and mixed with the high-momentum fluid in the mainstream. This mixing mechanism is desirable if loss reduction is of concern. Another observation is that an additional recirculating bubble appears behind the fence.

An examination on the present results reveals that the fence extension has rather insignificant influence on the overall transport phenomena in the duct. The velocity and pressure characteristics slightly away from the endwall is virtually unaffected by the presence of the fence. This is somewhat expected, as most of the total pressure loss occurs in the post-turn region, not inside the turn. Hence the present fence may not be situated on the most effective location for restructuring the secondary flow. This finding could imply that the fence length may not be a sensitive parameter for the actual LOx turbine passage. However, it is recognized that the factor of horseshoe vortex separation ahead of a turbine blade, which is absent in the present modeling, may drastically affect this observation. Analysis with actual blade configuration is considered to be a reasonable follow-on study in the future.

Acknowledgement

The author would like to thank his NASA colleague, Ms. Lisa Griffin, for her enthusiastic support throughout the course of this research. He is also grateful for Professor Michael Freeman and Dr. Frank Six for managing a very successful summer faculty research program.

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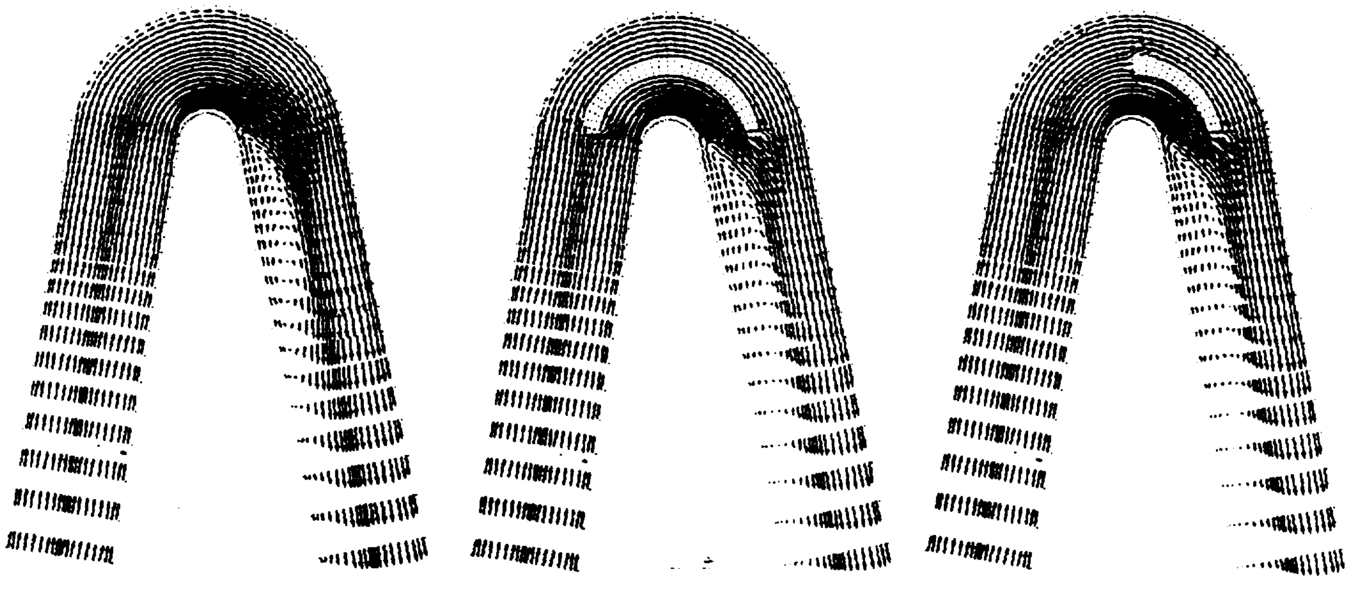
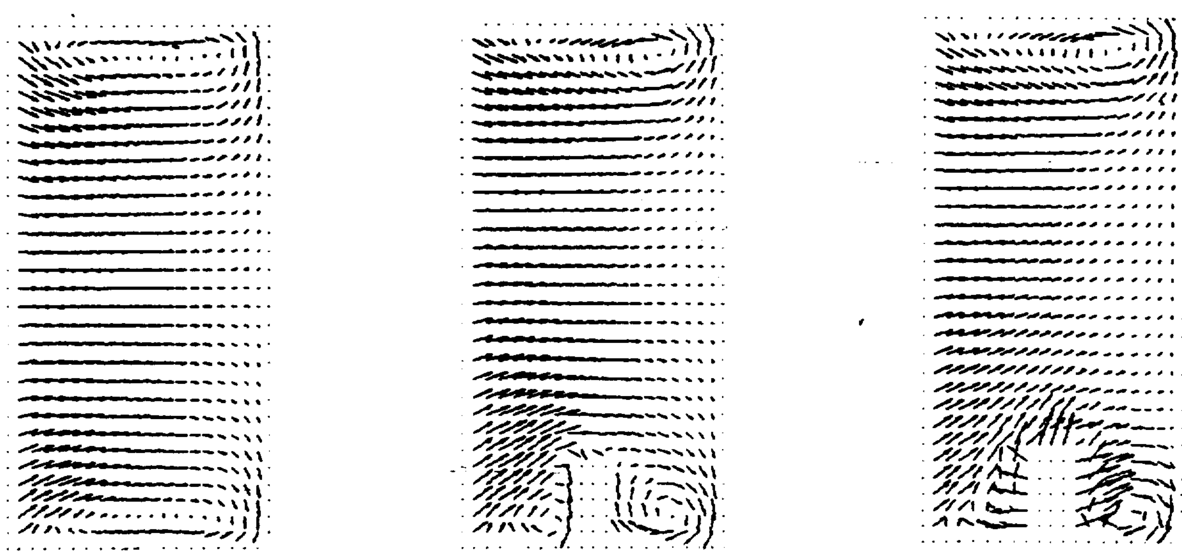


(a) no fence (b) full extension (c) 1/2 extension

Figure 1 Velocity vector near endwall



(a) no fence (b) full extension (c) 1/2 extension

Figure 2 Secondary flow pattern in the mid-plane of bend