Experimental And Numerical Investigations On Variable Area LP Turbine Nozzle Vane Flow-field For With And Without Part Clearances

Abstract

Gas turbine engines frequently operate under off-design conditions, where poor component matching can degrade overall engine performance. The Variable Area Nozzle Turbine (VANT) allows control of the mass flow rate through the hot section by varying the nozzle vane throat area, thereby improving off-design performance. VANT plays a key role in Variable Cycle Engines (VCEs) to meet the operational requirements of next-generation supersonic transport and multi-role combat aircraft, as well as advanced gas turbine engines with a wider operating range for shaft power applications. To vary the throat area in VANT, the rotation of the nozzle vanes about a pivot axis requires part clearances near both endwalls. The pressure gradient between the vane pressure surface and suction surface drives leakage flow through these clearances, forming leakage vortices and increasing aerodynamic losses. Although several studies have investigated VANT flow fields using simplified linear cascade configurations, the flow behaviour in a realistic low-pressure turbine (LPT) vane passage featuring a high-angle casing endwall and spanwise variation in inlet flow angle remains insufficiently understood. Therefore, the present work experimentally and numerically investigates the VANT flow field and the influence of part clearance over a range of vane setting angles.

To experimentally and numerically investigate the flow field through the VANT passage, which represents a realistic turbine configuration, the 2nd-stage LPT vane geometry from the Energy Efficient Engine (EEE) proposed by Pratt & Whitney was selected. A three-dimensional vane geometry was constructed using five spanwise profiles, whose pressure distributions were first validated against reported data. The geometry was subsequently scaled and modified, using spherical endwalls, to maintain a constant part clearance of 2 mm between the vane and endwalls while varying the vane setting angles based on computational analysis. The centre of the spherical endwall curvature was strategically selected along the engine axis to maintain minimal axial spacing variation as the vane setting angle changed and to leverage the pivot position to obstruct leakage flow effectively. A detailed numerical study was performed to examine the influence of pivot geometry on leakage flow behaviour. The results showed that increasing the pivot diameter effectively reduces leakage flow and associated aerodynamic losses. Based on these results and structural considerations, a circular pivot with a 20 mm diameter was selected for the experimental investigations.

An annular sector cascade (ASC) configuration consisting of nine vanes over a 40° sector was designed to experimentally investigate the VANT flow field while accounting for the radial pressure gradient. The ASC tunnel, comprising a wide-angle diffuser, a settling chamber with a honeycomb structure and screens, and an annular sector-shaped contraction duct, was designed. An intermediate turbine duct (ITD) with curved sidewalls and five inlet guide vanes (IGVs) was incorporated between the contraction duct and the test section to provide the required spanwise variation in inlet flow angle while maintaining geometric continuity. Experimental measurements using a five-hole pressure probe and surface oil-flow visualization confirmed that the IGVs successfully directed the flow through the ITD, precisely meeting the requirements at the test-section inlet.

Two sets of vanes were fabricated to investigate the flow field for cases without part clearance (yardstick case) and with part clearance and pivot (actual case). Experiments were conducted at five vane setting angles ranging from −10° to +10° with an interval of 5°, and at cascade exit flow Mach numbers of 0.3 and 0.45. The vane-turning mechanism and probe traverse mechanism were designed to precisely position the vanes in unison at the required vane setting angle and multi-hole pressure probe in the radial-circumferential plane. The upstream and downstream flow fields were measured using multi-hole pressure probes, while static pressure taps were employed to capture endwall pressure distributions. The experimentally measured upstream flow field was used as the inlet boundary condition for numerical simulations. The numerical investigations were validated using experimental results and subsequently used to study the detailed flow field within the nozzle vane passage.

The numerical and experimental investigations revealed the formation of complex secondary flow structures within the VANT passage. In the case without part clearance, the flow field is dominated by the horseshoe vortex (HSV), passage vortex (PV), and corner vortices near the endwalls. The PV increases the total pressure loss, which is evaluated using the total pressure loss coefficient. The effect of the secondary flow structure formation on the Mach number and flow angles is also analyzed in detail near both endwalls. As the vane setting angle changes from −10° to +10°, the cross-passage pressure gradient strengthens the PV, especially near the hub endwall. Hence, the overall averaged total pressure loss coefficient increases by approximately 47–50% at the +10° vane setting angle compared to the design condition. The viscous loss breakdown analysis was conducted using viscous entropy to reveal the contributions of various regions, including the boundary layers, vortices, wake, secondary flow shear and streamwise shear, to the overall viscous loss. A region-wise viscous loss breakdown showed that the increased losses were primarily associated with secondary flow shear.

In the presence of part clearance and pivot, leakage flow significantly modifies the secondary flow structures near both endwalls. Leakage flow upstream of the pivot strengthens the passage vortex, while leakage downstream of the pivot forms distinct leakage vortices near both endwalls. These leakage-induced vortices increase flow mixing and substantially increase aerodynamic losses. As a result, the overall averaged total pressure loss coefficient increases by approximately 64.7% to 175.5% compared to the case without clearance. Furthermore, the leakage vortex has a stronger influence on secondary flow shear losses at vane-closing positions, whereas the strengthened passage vortex dominates the loss generation at vane-opening positions.

The results of this study provide detailed insight into the interaction between leakage flow and secondary flow structures in a VANT passage with realistic endwall geometry and spanwise inlet flow variation. These findings contribute to a better understanding of clearance-induced losses in VANT configurations and guide the aerodynamic design and optimization of gas turbine engines with variable-geometry components to enhance operating ranges.