# RECENT PROGRESS IN NUMERICAL SIMULATION OF HIGHLY THREE-DIMENSIONAL TURBULENT FLOWS AND ENDWALL HEAT TRANSFER IN TURBINE BLADE CASCADES

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Accurate prediction of secondary flows and associated heat transfer phenomena in a cascade of turbine blades or vanes remains to be a challenging task, despite the great effort made in this area for several past decades. In a comprehensive review of secondary flow literature, covering up to 2000, Langston [2001] has stated also achievements and shortcomings of secondary flow CFD predictions at that moment. The present contribution main objective is reveal the progress achieved for the last decade.

On the way of getting reliable computational models of secondary flow, data obtained for large scale test configurations play a primary role. Test computations of last years [Kalitzin and Iaccarino 1999, Hermanson et al. 2003, Ivanov et al. 2003, Goriatchev et al. 2004, Sveningsson and Davidson 2004, Holley et al. 2005, Levchenya et al. 2006, Levchenya and Smirnov 2007, Levchenya et al. 2009b] were focused mostly on reproducing flow field and heat transfer experimental data obtained in the Langston subsonic blade cascade [Langston et al. 1977, Graziani et al. 1980, Holley and Langston 2006], in the NASA GRC transonic blade cascade [Giel et al. 1996, 1998], and in the Virginia Tech vane cascade [Kang et al. 1999]. Figure 1 illustrates geometry of the blade passages and typical computational grids used for CFD analysis.

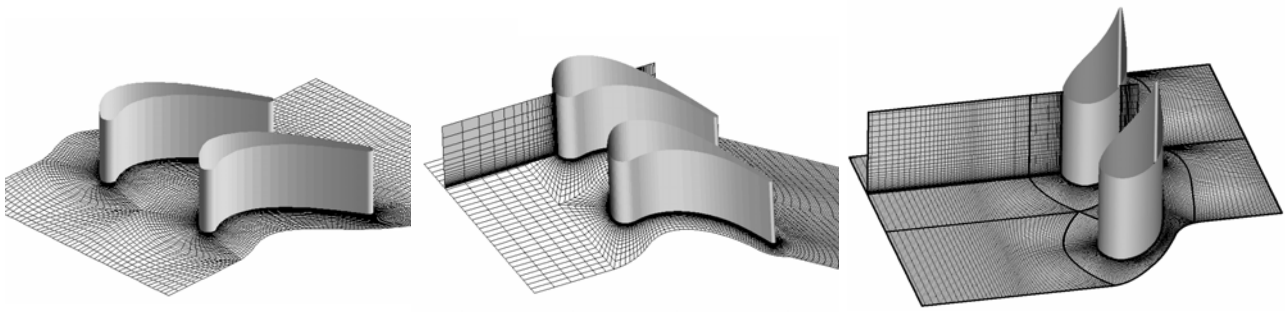

Figure 1. Geometry and typical computational grids used for numerical simulation of 3D flow and heat transfer in test linear cascades: (left) Langston subsonic blade cascade, (mid) NASA GRC transonic blade cascade, and (right) Virginia Tech vane cascade

In the region of the endwall, especially near the blade/vane leading edge (LE), the flow field is complex due to formation of a horseshoe vortex system that typically consists of a primary horse shoe vortex, a counter-rotating secondary vortex, and a tertiary vortex. Figure 2 illustrates such a system after post-processing of Reynolds-Averaged Navier-Stokes (RANS) computational data obtained by Levchenya and Smirnov [2007] with the SST k-ω turbulence model [Menter 1994] for the NACA GRC blade cascade flow.

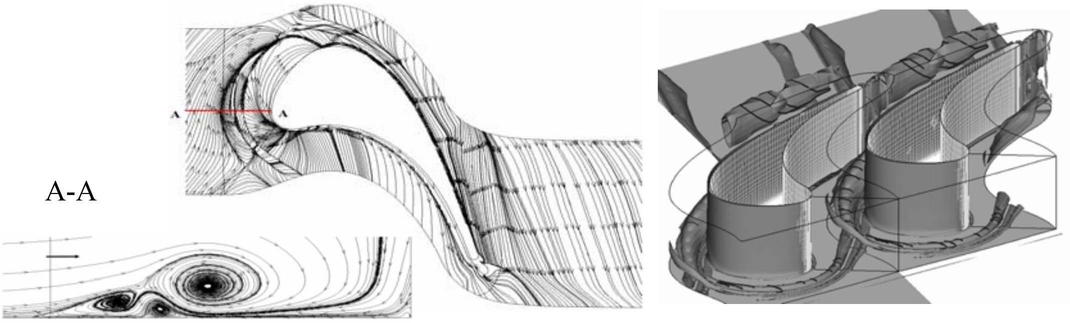


Figure 2. Secondary flow structure in the NASA GRC transonic blade cascade after RANS simulation by Levchenya & Smirnov [2007]

The underlying physics of horseshoe-vortex flows past wall mounted obstacles is studied extensively for various generic junction configurations including wall mounted symmetric airfoils and circular cylinders [Devenport and Sympson 1990, Agui and Andrepoulos 1992, Sympson 1990, Praisner and Smith 2006, Hada et al. 2008]. Devenport and Sympson [1990] have established that, under turbulent flow conditions, the horseshoe vortex dynamics upstream of the wing LE is dominated by coherent, low-frequency unsteadiness. Recently, for the symmetric body shown in Figure 3, Praisner and Smith [2006a, 2006b] performed simultaneous measurement of instantaneous flow field and endwall heat transfer by using Particle Image Velocimetry (PIV) and thermo-chromic liquid crystals in a water tunnel. Their data show that the time-mean endwall heat transfer is characterized by two bands of high heat transfer. To study the effect of the LE diameter on the horseshoe vortex dynamics and the endwall heat transfer in air flow past a symmetric body, Hada et al. [2008] used the PIV technique and the naphthalene sublimation method.

In order to resolve coherent, low-frequency unsteadiness of the horseshoe vortex system, Paik et al. [2007] employed the Detached Eddy Simulation (DES) approach for the conditions of the Devenport & Sympson experiments. Hada et al. [2008] combined their measurements with DES as well. Both the works have demonstrated the potential of DES for prediction of correct dynamics of the horseshoe vortex system. However, much effort is to be made to achieve a fully satisfactory agreement with the measurement data. Regarding the test configurations for turbine blade/vane cascades, application of DES or other hybrid RANS/LES approaches is still waiting for its turn.

In the framework of the RANS approach, resolution of the horseshoe vortex system depends both on the numerics and the turbulence model used. High-Reynolds-number turbulence models are not suitable for accurate secondary flow prediction. For the low-Reynolds-number models, the computational experience accumulated has resulted in the conclusion that the k-ω model [Wilcox, 1993] and various versions of the k-ε model do not provide a possibility of getting a multi-vortex structure, even in the case of grid-independent solution. The Menter SST model and the second-moment closure models are able to reproduce the complex horseshoe vortex system [Apsley and Leschziner 2001, Levchenya and Smirnov 2007, Levchenya et al. 2009a]. Results of simulations performed with the Durbin $v^2$-f model [Kalitzin and Iaccarino 1999, Hermanson et al. 2003, Sveningsson and Davidson 2004] do not allow the reader to make a definite conclusion for the matter.

With a fine grid and a proper RANS turbulence model one is able to get a double-peak curve representing the Stanton number variations, as illustrated in Figure 3. However, the local minima in the St distribution are deeper as compared with the measurements. It seems that just the low-frequency unsteadiness mentioned is responsible for the St curve “smoothing”.

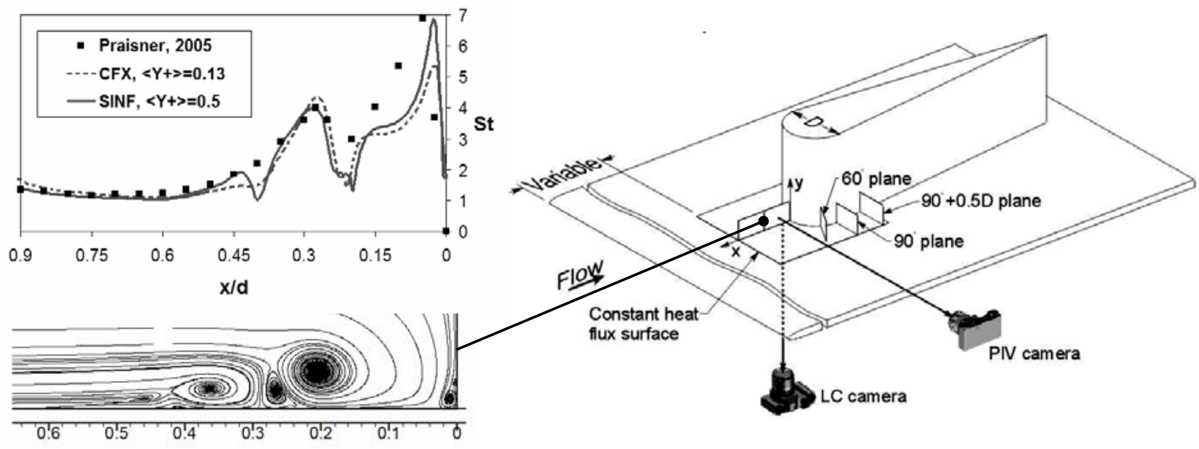


Figure 3. Experimental configuration of Praisner & Smith [2006] and results of RANS simulation of the horse shoe vortex system and endwall heat transfer near the airfoil LE [Levchenya et al. 2009]

Additional limitations of the steady-state RANS modelling are due to low-frequency unsteadiness that can develop in the exit part of a blade/vane cascade. This unsteadiness might be the main reason of typical disagreement between the experimental and computational results for the pitchwise variation of the local Stanton number in cascade exit regions, as well for the pressure losses gradients there.

Some issues concerning state-of-the-art CFD-based analysis of non-axisymmetric endwall contouring effects on pressure losses and endwall heat transfer are discussed in the full paper as well.

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