TIME-RESOLVED PIV MEASUREMENTS IN A ROTATING CHANNEL

Part II: measurements in a rotating rib-roughened channel

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Abstract

Part II of this lecture concerns the turbulent flow inside a rotating rectangular channel with one rib-roughened wall, reproducing an internal cooling passage for turbine blades. Exploiting the capabilities of the rotating facility presented in Part I, ensemble-averaged and time-resolved fields are obtained along the symmetry plane of the channel by means of two-dimensional Particle Image Velocimetry. The effects of the Coriolis forces on the stability of the shear layers are shown to affect crucially the mean velocity, the turbulence intensity and the unsteady dynamics of the separated and reattaching flow.

1. Introduction

1.1 Internal cooling channel in rotation: state of the art and objective

Internal cooling design in rotor airfoils presents an additional degree of complexity with respect to the non-rotating turbine parts: Coriolis forces and rotational buoyancy forces, inherent to the rotating frame, alter the coolant flow field, thus affecting the heat transfer. Understanding the flow physics in rotating internal cooling channels is crucial to make full use of the coolant air.

A substantial number of experimental and numerical investigations have been performed in order to predict and optimize the aero-thermal performance of internal cooling schemes when rotational effects are present. From the pioneering work of Wagner et al. (1991) and Taslim et al. (1991) to the efforts of the research groups of Iacovides (Iacovides et al., 2001), Liou (Liou et al., 2003) and Han (Wright et al., 2004), experimental research has succeeded in mapping out many of the qualitative trends relating heat transfer levels with Coriolis and buoyancy forces. However the underlying mechanisms which determine those trends are not fully explored. The prime reason is the obvious difficulty of performing flow measurements in rotation: few experimenters have measured the velocity field inside rotating cooling passages, and never with a level of detail comparable to stationary configurations. In fact, research in non-rotating cooling channels has largely demonstrated that only the velocity fields, correlated with heat transfer measurements, provide the necessary insight to tackle the complex phenomena at play in the intricate internal cooling geometries. This is all the more true for the rotating components, in which the rotational forces determine exceptionally complicated flow pattern. Most of the experimental efforts in rotating channel flows have used point-wise velocimetry techniques, such as hot wire anemometry (Watmuff et al., 1985 and Nakabayashi and Kitoh, 2005, who investigated canonical boundary layer flows), or Laser Doppler Velocimetry (Liou et al., 2003 and Iacovides et al., 2001, who studied cooling channel geometries with ribs and U-bends). This single-point approach cannot identify instantaneous flow structures and velocity gradients. Few studies in literature present full field data in rotating channels using particle image velocimetry (PIV), but they all share a strong limitation: the imaging system is not attached to the rotating test section. This is the case of Bons and Kerrebrock (1999), who studied a rotating square duct, and Servouze et al. (2003), who investigated a U-bend channel with ribs. In those experimental layouts the camera is fixed in space and triggered at each passage of the rotating test section; the relative velocity of the internal flow is obtained by subtracting the peripheral speed from the measured absolute velocity. This results in low temporal and spatial resolution and in large uncertainties, especially at high rotation rates. The highest quality results obtained to date in facilities of this kind are probably those from Elfert et al. (2010), which are however limited to low rotation rates.

On the computational side, the important features of the turbulent flow revealed by measurements in rotating channels are not properly reproduced by standard two-equation turbulence models (Speziale et al., 1998). Reynolds stress models were shown to compare favorably with eddy viscosity models (see among others Chen et al., 2000 and Younis, 2010). Still, due to the lack of experimental data, the validation of those models often needs to rely on direct numerical simulations (DNS), as the data of Kristoffersen and Andersson (1993) and Wu and Kasagi (2004). However, because of the inherent computational cost, most DNS simulations available are concerned with canonical flow geometries, whereas the few addressing realistic cooling channels configurations are strongly limited in Reynolds number (as in Laskowski and Durbin, 2007). In this perspective, large eddy simulation (LES) is gaining attention (see for example Abdel-Wahab & Tafti, 2004); however, on one side its cost is still prohibitive at industrial level, and on the other the need for validation is always present. From this scenario it emerges a lack of reliable and detailed experimental databases for rotating internal cooling channel flows.

The present contribution addresses the effect of Coriolis forces in an orthogonally rotating channel of rectangular cross section, with one wall provided of square ribs perpendicular to the flow direction. The geometrical features and the non-dimensional flow parameters are engine-representative. Both ensemble-averaged and time-resolved velocity fields are measured by means of PIV along the symmetry plane parallel to the flow and perpendicular to the obstacles. The measurements are performed in the rotating facility RC-1, which is described in detail in Part I of this lecture. The great advantage with respect to any previous PIV study in the domain of internal cooling is that both the laser and the camera are fixed on the disk, allowing for the same level of accuracy, spatial and temporal resolution as in a non-rotating rig. The first, ensemble-averaged results were presented recently by Coletti et al. (2010), whereas the time-resolved measurements are the object of a contribution submitted to the 9th European Turbomachinery Conference (Coletti and Arts, 2011).