Three dimensional flow at the junction between a turbine blade and end-wall *

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Abstract. A visualization of the flow on the suction side and end-wall of a passage between two neighboring turbine blades is compared with mass (heat) transfer measurements on the same surfaces. Besides the horseshoe and passage vortices, there are several smaller vortices formed near the junction of blade and end-wall whose origins are discussed. The vortices detach from the end-wall and move up the blade's span. These vortices, sometimes in counter rotating pairs, are responsible for substantial local variations of heat transfer.

Drei-dimensionale Strömung an der Naht zwischen Turbinenschaufel und Endwand


Nomenclature

\( V_{sc1} \) suction side corner vortex 1
\( V_{sc1s} \) portion of \( V_{sc1} \), which climbs up the blade suction surface
\( V_{sc2} \) suction side corner vortex 2
\( V_{sc3} \) suction side corner vortex 3
\( V_{sh} \) suction side leg of the horseshoe vortex
\( V_{人格} \) suction side leg of the leading edge corner vortex
\( \nu \) kinematic viscosity

1 Introduction

In the past decade numerous experimental and computational studies have improved our knowledge of the flow and heat transfer in the passage bounded by turbine blades and their end-walls: a recent review by Graham [1] describes progress made during this period and challenges still to be met. One key challenge is to improve our ability to predict the complex flow and heat transfer in the neighborhood of the junction of blade and end-wall.

Experimental studies of the flow through a turbine passage are reviewed by Langston [2] and Sieverding [3]. Other results are presented by Joslyn and Dring [4], Gregory-Smith and Cleak [5], Hodson and Dominy [6, 7], Jitk [8], Yamamoto [9, 10], Hazarika and Boldman [11], and Sonoda [12]. Examination of these studies indicates that there is general agreement on the pattern of flow (horseshoe and passage vortices, their origin and evolution) inside the passage. Near the bounding surfaces, just ahead of the leading edge and in the vicinity of the suction side end-wall corner, however, there seems to be a noticeable disagreement on the number, if any, of vortices that exist. The disagreement is in part due to different passage geometries, inlet flow conditions, measurement techniques, and interpretation of data. Similar disagreement exists with regard to the number of vortices formed ahead of a cylinder protruding from a surface, Angui and Andreopoulos [13], Pierce and Tree [14], Dargahi [15], Baker [16]. In the latter case, it has been argued that the number of vortices depend on Reynolds number and observation method or measurement technique (e.g., time-average vs. instantaneous).
Heat (or mass) transfer measurements can be used to infer characteristics of the near surface flow. This approach has often been used along with surface flow visualization; Takeishi et al. [17], Hippensteele and Russell [18], Sato et al. [19], Hippensteele et al. [20], Hippensteele et al. [21], Gaugler and Russell [22], and Graziani et al. [23]. An accurate and finely localized heat (or mass) transfer measurement can reveal minute structures of flow that may not be detected through the use of other techniques (Goldstein and Kern [24], and Goldstein, Chyu, and Hain [25], and Chert and Goldstein [26]).

Local mass transfer measurements on the end-wall and the blade suction surface near the end-wall are reported by Goldstein and Spores [27], Chert and Goldstein [26], and Chen [28], respectively. To complement these studies a surface flow visualization has been carried out. In this paper results of the visualization and mass transfer measurements are compared to further clarify the surface flow pattern in the blade passage employed.

2 Apparatus and measurement technique

The flow visualization is performed in a low-speed wind tunnel with a planar cascade of six scaled-up CF6-50 turbine blades (see Fig. 1). This is essentially the same apparatus described in references [26] and [27]. The blades have a chord length of 169.1 mm, a span to chord ratio of 3.55, an inlet flow angle of 44.3°, and an outlet flow angle of 62.7°.

An oil and lampblack technique is used to show the surface flow. A mixture of fine black cadmium and graphite particles suspended in light oil is spread thinly over a sheet of glossy shelf paper which has been attached to the area to be studied. The shear flow near the wall pushes the particles through the oil, leaving a series of streaks which give an indication of the local shear stress.

A color visualization technique, which is very similar to the oil and lampblack technique, is also employed. Oil-base paint is diluted with oil and then spread over the various regions to be studied. With color visualization, the paths of fluid filaments, which originate in different regions of the end-wall, are better identified.

3 Results and discussion

Photographs of the flow visualization traces on the end-wall and on the blade are presented in Figs. 2 to 7. These results are obtained with an approach velocity of 11 to 12 m/s ($Re_1 \approx 1.22 \times 10^5$) and an end-wall boundary layer thickness of approximately 15 mm (displacement thickness of approximately 2.15 mm) measured 18 cm upstream of the blade. Figure 2a is an overall view of the traces (black and white lines) left by the flow over the end-wall. It includes portions of the end-wall upstream of the passage, through the passage, and downstream of it. Three shades are distinct on the photos; gray areas (without many traces or apparent lines), areas with traces, and black areas. They are, respectively, areas exposed to relatively large, moderate, and small shear stress (or relative low velocity near the surface). Observations from several visualization trials indicate that if longer exposure to the flow is allowed the gray areas become lighter (whiter), the traced areas lose their traces (become gray), and some of the black areas may lose some of their particles and become traced while others remain unaffected. A black area which becomes traced is an area into which upstream particles have flowed and accumulated. To determine if a black region is due to accumulation of upstream particles, visualizations are made with oil and lampblack applied to a limited region; some results are presented in Figs. 3–5.

Figure 3 shows that there is no lampblack flow out of a spot marked SP1 also, no paint flows into the black area ahead of the leading edge, revealing that the black area ahead of the leading edge, seen in Figs. 2a and 4, is a consequence of a slower moving fluid (a separation bubble). Similar is the area immediately downstream of the trailing edge (cf. Figs. 2a and 5) where, due to the wake, the lampblack is undisturbed. The same, however, cannot be said about a stretch of lampblack near the exit of the passage along the suction side (Fig. 2a). This region clearly contains accumulated lampblack, carried downstream from upstream locations (cf. Figs. 2a and 5). Another point to be noted in Fig. 3...