little spanwise motion attributable to this in the C106 four-stage compressor. The fluid migration toward the casing over most of the stator blade passage of the single-stage compressor was caused by the blockage arising from a separation in the stator suction surface–hub wall corner.

Despite the large skew of the hub wall boundary layer through the single-stage compressor stator, no significant ethylene contour distortion onto or along the pressure surface was observed in the hub corner. In the corner formed by the casing wall and suction surface of the single stage there was elongation of ethylene contours radially inward along the blade surface, but without any sign of the core being moved radially inward by the flow.

2 The substantial mixing away from the end-walls in the tangential direction, particularly across the rotor, is mainly due to flow dispersion or chopping of wakes from upstream by the rotating blades.

3 The dispersion by the rotating blade row of wakes from a stationary upstream row can cause a significant increase in the mixing coefficient in the mainstream across the subsequent stator row by generating periodic patches of random unsteadiness.

4 The relative fluid motion inside the rotor blade wakes is mainly responsible for the larger tangential mixing across the stator in the mainstream region. Low-momentum fluid is transported toward the pressure surface of the stator blade by the relative motion in the rotor wakes.

5 For the Deverson single-stage compressor the mixing coefficient around midspan in the stator was low without IGVs upstream of the rotor; the mixing level was increased significantly with IGVs upstream and was then close to the value in a multistage machine. For the C106 four-stage compressor (with inlet guide vanes), the spanwise mixing coefficients were found to be of similar magnitude for the different stages; the mixing coefficient in the mainstream was about the same, while in the end-wall regions it was slightly higher in the first stage. The effect of wakes on mixing is not additive and it is concluded that this is because the blade wakes decay rapidly through succeeding blade rows.

6 Tip clearance flows play an important role in the mixing process by thickening the endwall boundary layer and by creating high levels of turbulent diffusion in the endwall region. The radial distribution of spanwise mixing coefficients can be approximately uniform or can vary significantly: Large casing tip clearance and hub corner separation have been found to lead to locally increased mixing levels near the endwall.

7 Tests with a simple flow in a duct confirmed that anisotropic turbulence can produce tracer gas contours in corners distorted in ways similar to that sometimes previously found in compressors. Anisotropic turbulence contributes to the greater diffusion parallel to solid walls than normal to them.

8 Mixing in the tangential direction, particularly along the end-walls, is usually larger than the radial mixing because of the combined effects of secondary flow convection, periodic transportation by the rotor blade wakes, and anisotropic inhomogeneous turbulent diffusion.

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DISCUSSION

A. Goto

Since I had an opportunity to work on the same compressor as that used by Li and Cumpsty, I would like to add a few points to this paper.

Additional measurements were carried out at 0.7, 2, and 3 percent rotor tip clearances and the dominant effect of the small-scale turbulence, generated within the rotor, on mixing across the downstream stator was confirmed. The maximum value of the mixing coefficient in the casing region was found to increase linearly with the rotor tip clearance, starting from the value at midspan, because of turbulent-type small-scale unsteadiness due to the diffusion of the tip leakage vortex. Figure 9 compares the ethylene tracer-gas spreading in the hub region between three different rotor tip clearances. In every case, a radial contour distortion is observed in the hub-pressure surface corner region. Although the cause of the difference between the present results and Li and Cumpsty’s result (compare Fig. 9(c) with contour 1 in Fig. 2) is as yet unexplained, the distortion is identical with that found in duct flow measurements (Fig. 8), by which Li and Cumpsty pointed out the possibility of anisotropic turbulence as the mechanism of contour distortion.

What I have commented here will be the subject of a paper to be submitted to the 1991 International Gas Turbine and Aeroengine Congress and Exposition.

D. C. Wisler

Professor Cumpsty and his students continue to make im-

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important contributions to the understanding of mixing in axial-flow compressors. Of particular interest in this paper are the effects of the IGVs and rotor tip clearance on mixing. I would like to discuss these effects first, noting similarities with our data. An assessment of the relevance of the duct flow results is given at the end.

I believe that there is now considerable agreement about the mechanisms causing mixing in axial compressors. That both convective and diffusive effects can and do operate in the mixing process is no longer disputed. This became apparent during the discussion at the end of the Mixing session in Brussels.

The effects of the IGVs on mixing are very interesting and I agree with the analysis of Li and Cumpsty. In fact Wisler et al. (1987) presented ethylene trace-gas data across the rotor that can be directly compared with those of Li and Cumpsty. The Wisler et al. (1987) results in their Fig. 19(a) also included here as Fig. 10(a), give spreading across the fourth rotor when ethylene was injected into the wake of the upstream imbedded stator at 50 percent immersion. The Li and Cumpsty (1991) Part II data in their Fig. 4(c) show similar spreading across the first rotor when ethylene was injected into the wakes of rods that simulate IGVs, also at 50 percent immersion. The agreement in the shapes of these fourth and first rotor contours in both the circumferential and radial directions is striking.

Both Wisler et al. and Li and Cumpsty attribute this spreading at 50 percent immersion to turbulent diffusion and wake dispersion. Increasing the turbulence level increases the spreading as shown by Li and Cumpsty (1991) in Figs. 4(b, c) and Wisler et al. (1987) in Figs. 10(a, b). These results are important in developing wake dispersion models, such as that of Walker.

Do the authors have similar data across the rotor but taken in the tip clearance region at the casing? This would complement their tip clearance results in Fig. 5 and would allow further comparison with Wisler et al.'s Fig. 25, shown here as Fig. 11, where not only diffusion but circumferential and radial convection are seen as well.

The new results of Li and Cumpsty in Fig. 5, showing the effects of tip clearance on spreading levels, are dramatic. It does seem to me that there is much less boundary layer skew in these results than in those of Wisler et al. (1987). Perhaps this difference in the compressors is partly responsible for the lack of distinctive distortion in the Fig. 5 contours near the pressure surface.

The duct flow results in Fig. 8 of Li and Cumpsty, Part II, require further consideration. The idea here is that a simple, rectangular duct, having no secondary flow, is used to demonstrate how anisotropic and inhomogeneous turbulent diffusion distort ethylene contours. These distorted contours from the duct are then compared to those from the compressor of Wisler et al. (1987), and similarities in shapes are noted. Based on these similarities, one is then to conclude that anisotropic turbulence is the dominant mechanism responsible for the mixing in the endwall and corner regions of a compressor.

In response to this, I believe that the shapes of the contours in the duct are accurate, classical, and predictable data. That anisotropic turbulence is responsible for distorting these duct contours and that this mechanism, in some measure, also operates very near surfaces in compressors is both correct and practical.

However, there are very significant differences between the flow in the corner of a long, straight, rectangular duct and that in the end-wall region of an imbedded stage of a highly loaded HP compressor, particularly with respect to boundary layer skew. I think that these differences must be taken into account when diagnosing causes of contour distortion (mixing). After all, both convection and diffusion can distort contours.

Mere general similarity of the shapes of ethylene contours between the duct and the compressor does not mean similarity of causes. Both diffusion and convection have been shown by Leylek and Wisler (1991) to operate in the endwall region in question in compressors. It seems only logical to conclude that both of these mechanisms operate to cause the mixing.

References


Authors' Closure

Response to Discussion by Dr. A. Goto

We greatly appreciate the additional information about the mixing phenomenon obtained by Dr. Goto in the single-stage compressor. Dr. Goto points out quite correctly that his measurements on the same machine show much more radial distortion of the tracer gas contours. One possible reason for the difference between the contours in Fig. 9(c) obtained by Dr. Goto and contour 1 in Fig. 2 of our paper is that the flow coefficients may have been slightly different in the two cases. Furthermore the rotor had been stripped and rebuilt many times and there may have been some slight difference in stagger. The difference between the shape of the contours is, nevertheless, significant and worth pointing out.

It is also worth noting that the radial distortion of the contours found by Dr. Goto is more pronounced at the two smaller tip clearances, shown in his discussion as Figs. 9(d, b). Our