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Design and performance of thin, circular arc, wind-tunnel turning vanes

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1.0 INTRODUCTION

Although test rig data exists for $\frac{1}{4}$ circle turning vanes, the actual performance of these vanes once installed in a wind tunnel, and the extent to which test rig results are replicated, is rarely known. This paper compares pressure loss coefficient and velocity profile data from a vane test module with measurements taken in the low speed wind tunnel described in Ref. 1. The pressure loss coefficient, K_L is defined as the ratio between the static pressure loss in a corner and the inlet dynamic pressure:

$$K_L = \frac{p_1 - p_2}{\frac{1}{2}\rho U_1^2}$$

Where, p is the static pressure, ρ is the air density and U is the mean velocity, and subscripts 1 and 2 indicate upstream and downstream.

Previous investigations in test rigs have shown that thin $\frac{1}{4}$ circle turning vanes with a space to chord ratio (s/c) of between 0.20-0.25, produced $0.12 < K_L < 0.20^{(2)(3)(4)(5)}$. However, these sources focused on determining K_L rather than quantifying the flow quality downstream of the vanes. Although K_L is important in terms of achieving a high tunnel energy ratio, it is perhaps secondary to downstream flow quality since the stream exiting the corners of a typical wind tunnel enter into components whose performance may be affected by flow quality.

2.0 VANE TEST MODULE

A constant area vane test module was constructed to enable K_L and velocity profile data to be obtained for vanes of the same chord as that used in the corners of the wind tunnel. The span of the test vanes was limited to 450mm, since the test module had to mate to the end of the working section of an existing blower wind tunnel. The wind tunnel had a turbulence intensity of 0.1% in the working section, which was similar to the value of 0.15% for the wind tunnel of Ref. 1. Tests were performed at the chord Reynolds number (R_{ec}) seen in the second corner of the wind tunnel when running at its design speed.

As shown in Fig. 1, the vanes were designed with an angle-of-attack of 4° ⁽⁴⁾, since K_L is a minimum for a vane cascade at around this angle⁽⁶⁾. Since K_L reduces with increasing R_{ec} , it was decided to employ vanes of large chord (c). Aside from the aerodynamic benefit, vanes of large chord are more rigid and also reduces the number of vanes, and hence cost, required for a given s/c . The test vanes were constructed from 1.5mm thick rolled aluminium with an inside radius, r , 245mm. To encourage the flow to leave the vanes axially, a trailing-edge extension (TE) of 165mm was employed. This geometry resulted in a chord, c , of 468.5mm, which gave an R_{ec} of 5.74×10^5 during tests.

The vane test module is shown in Fig. 2. With three vanes installed an s/c of 0.237 was achieved, which was as close as it was possible to get to the s/c of 0.25 suggested by most sources for

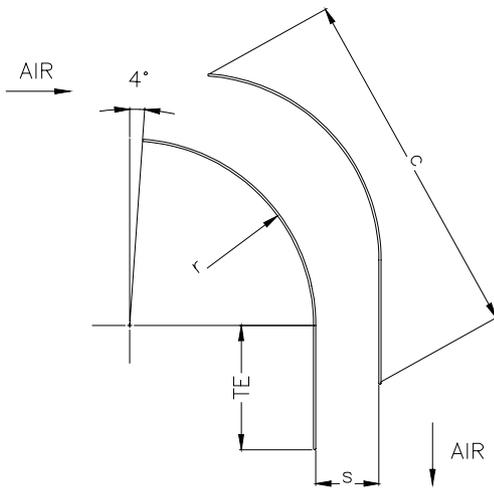


Figure 1. Turning vane used in test module and wind tunnel.

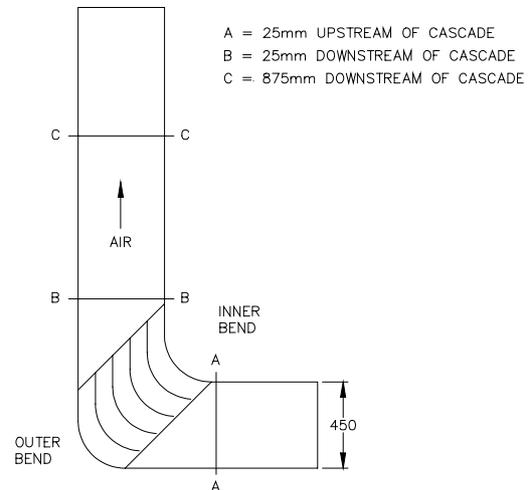


Figure 2. Vane test module with four vanes installed.

minimum K_L . However, since one investigator had proposed that greater stability of the near wall stream may be obtained by employing an s/c of 0.20⁽⁴⁾, a fourth vane was added to the test module (producing an s/c of 0.190) to enable additional tests to evaluate this suggestion.

The pressure loss coefficient, K_L , was determined by measuring the static pressure loss across the cascade and dividing this by the dynamic pressure in the working section of the blower wind tunnel to which the test module was mated. Static pressure loss across the cascade was measured by means of the averaged reading from a ring of static tappings located at positions A and B on Fig. 3. A and B were respectively located 25mm upstream and 25mm downstream of the inner bend of the cascade. An additional ring of tappings was provided at C . Each ring comprised four tappings located at the midpoint on each side of the module.

Velocity profiles were measured perpendicular to the test module walls at locations A , B and C using a pitot probe referenced to the averaged reading from the relevant ring of wall static tappings. The flow was ejected to atmosphere 600mm downstream of location C . The head of the pitot was placed in the same plane as the tappings, and was traversed across the mid span of the vanes in 10mm increments. The pitot probe was constructed from tubing with an outside diameter of 3.3mm and an inside diameter of 2.5mm.

For both pressure loss and velocity profile measurements, differential pressure transducers with an accuracy of 0.25% of reading was used. Data was sampled at 1kHz for 10 seconds and averaged over ten repeats to promote confidence in the mean. A two-minute settling time was allowed between readings since the tubing used was necessarily long.

2.1.1 Test module results

The velocity profiles presented in Figs 3 and 4, are non-dimensionalised by dividing the local axial velocity, u , measured by the traversed pitot, with the freestream velocity, U , measured by a pitot static in the working section of the blower wind tunnel.

Figure 3 shows that 25mm upstream of the cascade, the flow exhibits a flat velocity profile with inner and outer wall boundary-layers that are free from reversed flow. Continuity of flow through the test module, leads to u/U being slightly greater than 1.0 outside of the boundary layers. Downstream of the cascade, the observed velocity minima are in line with the trailing edges of the vanes. The vane wakes for both s/c 's tested, show a greater deficit on the suction side of the vane, that is due to a thicker boundary-layer. The

additional work performed by the three vane cascade compared to the four vane is evidenced by the larger wakes and lower velocity minima produced by the former. K_L data for the two s/c 's investigated, are shown in Table 1, and it is clear that there is little difference between the two configurations.

Table 1
 K_L values at Re_c of 5.74×10^5

| l/c | K_L |
|-------|-------|
| 0.237 | 0.132 |
| 0.190 | 0.128 |

The value of K_L measured at an s/c of 0.237 may be compared to previous test rig data⁽⁴⁾, which produced a K_L of 0.120 for $1/4$ circle vanes at an s/c of 0.25 and an Re_c of 2×10^5 .

Non-dimensionalised velocity profiles measured 25mm upstream, and 875mm downstream of the cascade are presented in Fig. 4. Downstream of the cascade, the three-vane configuration shows a significant momentum deficit at the inner bend compared to the four vane set-up. This is surprising given how closely matched the inner wall profiles of the three and four vanes were, 25mm downstream of the cascade, but supports the improved near wall stability suggested in Ref. 4. Due to this better inner bend flow quality an s/c of 0.190 was chosen for use in the wind tunnel⁽¹⁾.

3.0 WIND-TUNNEL RESULTS

Vanes used in the wind tunnel were identical to those employed in the vane test module except that the thickness was increased to 3mm to enhance rigidity. It also enabled more roundness to be applied to the leading edge to make the vanes less sensitive to inlet flow angularity. The internal dimensions at inlet to the second wind tunnel corner were 2,180mm high (i.e.: vane span) and 2,630mm wide, resulting in 28 vanes in the cascade.

Figure 5 presents velocity profiles measured perpendicular to the tunnel walls at mid span, on the inner and outer bends, 220mm upstream and 80mm downstream of the corner, which was as close as it was possible to get to the corner's inlet and exit. The local widths, Y , at the traverse planes shown in Fig. 5, differ from the corner dimensions because of the diffusers located upstream and downstream of the corner. Positive and negative values of Y relate to the inner and outer bends respectively. Velocity profiles were determined using a pitot probe referenced to the averaged reading from a

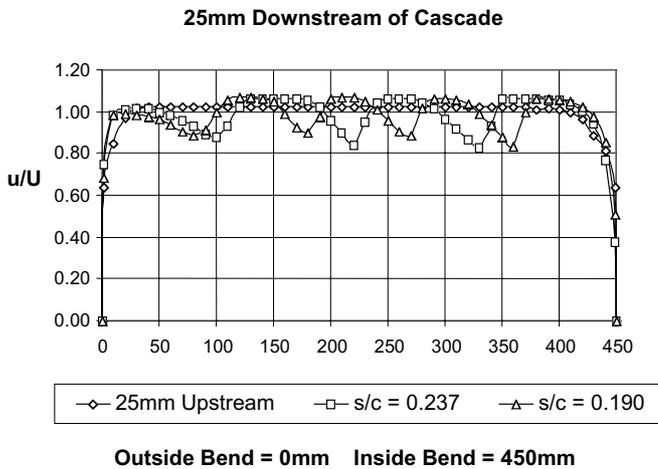


Figure 3. Velocity profiles at mid span, measured 25mm upstream, and 25mm downstream of the cascade.

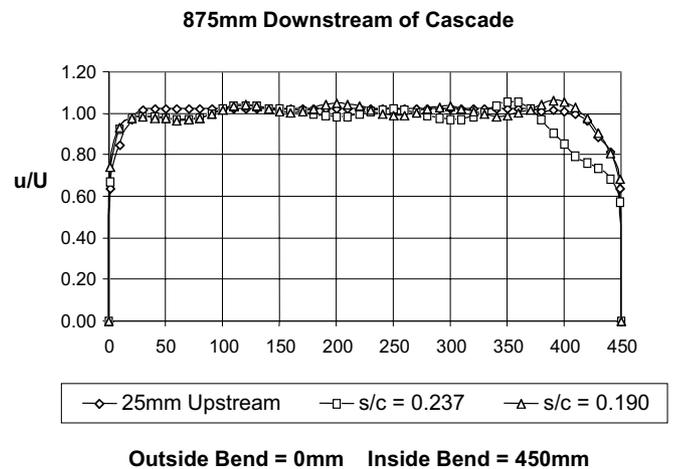


Figure 4. Velocity profiles at mid span, measured 25mm upstream, and 875mm downstream of the cascade.

ring of four wall static tapings. One tapping was located at the mid point of each wall of the wind tunnel in the same plane as the head of the pitot. The probe was traversed across the vanes in 10mm increments. The construction of the probe, data acquisition and reduction technique employed were the same as for the vane test module. Remnants of the wakes from the first corner can still be seen in the upstream flow for the inner bend. The different Y-location of these wakes is due to the flow having passed through a diffuser. Downstream it can be seen that the wakes from the outer bend have mixed out whilst those from the inner bend have not. This is a consequence of the flow having had to travel further along the outer wall than the inner. Variations can be seen in the wake profiles downstream of the inner bend. This may partly be due to greater mixing towards the outer bend and perhaps also due to local inlet

non-uniformity resulting in variations in the amount of work done by each vane.

To determine K_L , the static pressure loss was measured by means of the averaged reading from the rings of static tapings located upstream and downstream. This resulted in a K_L of 0.160 at an Re_c of 5.74×10^5 . The difference from the test vane module value is not surprising given that significant differences exist in the upstream velocity profiles, particularly in the wall region. Whilst the differences between the wind tunnel and test module values for K_L appear to be large, it should be noted that in absolute terms the difference in pressure loss was seven Pascals.

The possible influence of upstream velocity profile is illustrated by results for the first corner, which was located behind the working section. With an empty working section, the velocity profile was

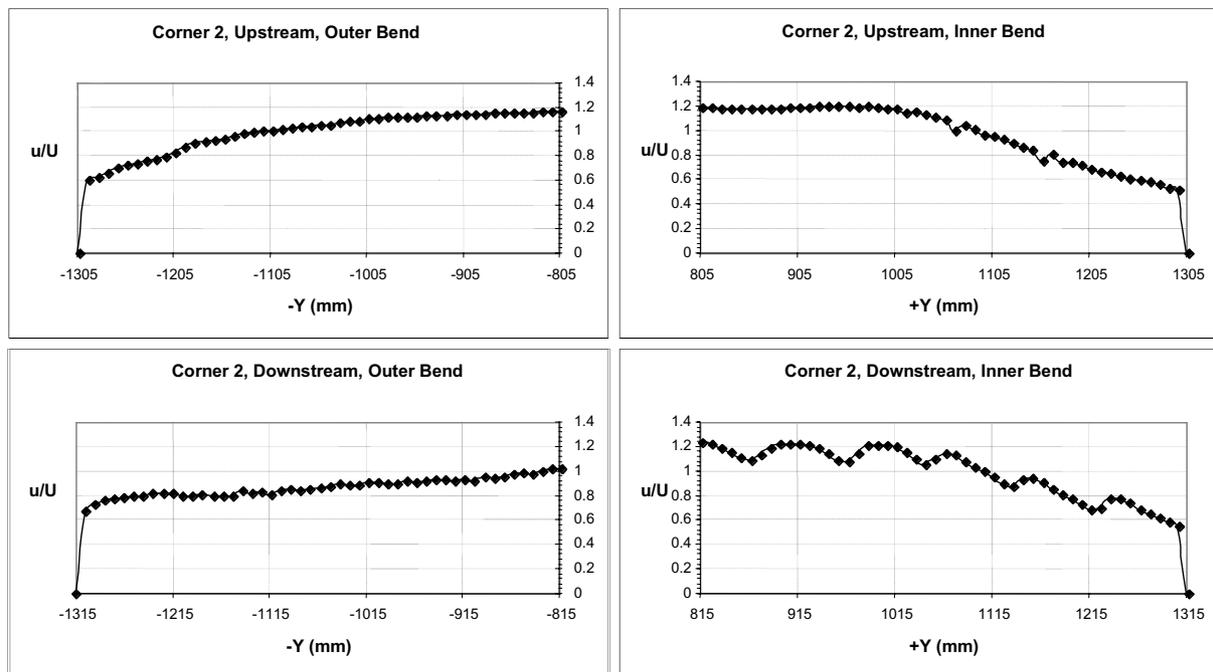


Figure 5. Velocity profiles upstream and downstream of the second corner.

more uniform than seen for the second corner, and with significantly thinner wall boundary-layers. When run at an Re_c of 5.74×10^5 , the value of K_L , was approximately 0.109. The results for the two corners suggest that test rig data can be used to predict pressure losses through vanes, although it may be prudent to factor the K_L values for each successive corner.

4.0 CONCLUSIONS

- Test module results have shown that $\frac{1}{4}$ circle vanes set at space to chord ratios of 0.190 and 0.237 produced comparable boundary layer profiles 25mm downstream of the cascade, but that the $s/c = 0.237$ cascade produced a momentum deficit in the inner bend boundary-layer further downstream.
- Whilst the vane test module was unable to simulate the boundary layer seen on the wind tunnel walls, K_L data derived from the test module is of the correct order to that measured in the wind tunnel.

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