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The use of coloured smoke to visualize secondary flows in a turbine-blade cascade

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A coloured-smoke-visualization technique has been developed for the investigation of complex three-dimensional fluid flows. In particular, a coloured-smoke wire technique is used for the study of secondary flows in straight turbine cascades. Based on a large number of photographs and direct flow observation, the evolution of horseshoe and passage vortices through a high-turning turbine-blade passage is described.

1. Introduction

Smoke visualization has contributed considerably to the better understanding of the qualitative behaviour of complex flow structures. First used around the end of the 19th century (Mach 1896), the technique rapidly found wide application. Two distinct methods have been developed for flow visualization in wind tunnels: the smoke is either introduced from outside through rakes mounted in the contraction upstream of the test section or it is generated within the test section by electrically heating a thin wire coated with oil. A typical example of the latter method is described by Babill & Mueller (1981).

Until now, smoke visualization has been done exclusively with white smoke (the term 'smoke' is generally used to refer to what is, in fact, vaporized oil), which is perfectly suitable for two-dimensional flow fields. However, it is extremely difficult to trace the path of specific flow filaments in a complex three-dimensional flow field. This is clearly demonstrated in figure 1 for the case of the endwall flow in a high-turning turbine cascade. The photograph shows how an initial plane stream surface within the endwall boundary layer upstream of the cascade becomes extremely distorted when passing through the blade passage. The motion of the streamlines is dominated by the leading-edge horseshoe vortex and the so-called passage vortex. The latter designates that vortical motion which occurs when an endwall boundary layer is submitted to a transverse pressure gradient (e.g. flows in curved ducts). It appeared that significant progress in the visualization of such complex three-dimensional flow patterns could be expected only if coloured smoke filaments were used.

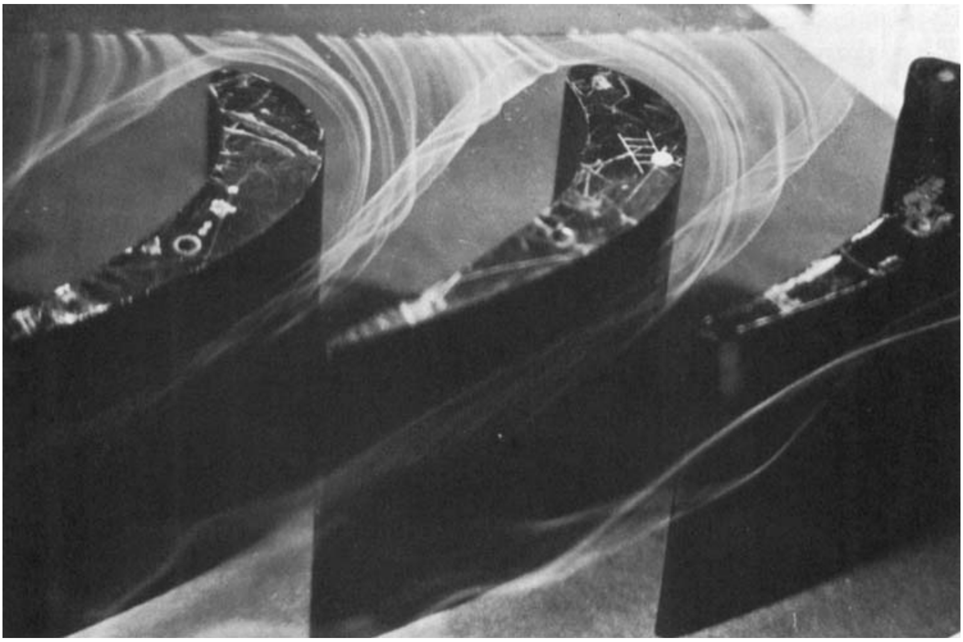

FIGURE 1. Flow visualization with standard smoke-wire technique – smoke wire inside endwall boundary layer.

2. Coloured-smoke-wire technique

Coloured smoke can indeed be produced quite easily by evaporating commercially available dyes such as the Waxoline dyes from ICI (Imperial Chemical Industries) or the Sudan dyes from BASF (Badische Anilin- und Sodafabriken). The ICI Waxoline dyes are used in the textile industry while the Sudan dyes are used in the mineral-oil industry. The dyes exist both as powder and liquid dyes. Only powder dyes were used to implement the smoke-wire technique. The wire is coated with a paste of dye powder and oil, no more of the latter being used than is necessary to coat the wire. Coating is facilitated by preheating the wire very slightly. Most of the tests were done with tungsten wire of 0.25 mm diameter. The wire had to be prestressed in order to avoid sagging during tests.

The duration of the smoke emission from the wire obviously depends on the amount of coating material. The wire diameter after coating was typically of the order of 0.5 mm in our tests. This resulted in smoke emissions of up to 15 s, which allowed a direct observation of the smoke filaments from various angles during a single test. The maximum allowable coated wire diameter depends of course on each particular case, noting that oil-coated wires of 0.1 mm (standard dimension for usual smoke wire techniques) have a maximum smoke emission time of about 2 s (Babill & Mueller 1981).

Both the Sudan and Waxoline dyes are available in a wide range of colours. The powders can also be mixed to produce additional colours. The problem is to select the colours so that there is sufficient contrast between the various flow filaments on one side and between the flow filaments and the background on the other side. Another problem is due to the fact that the various dyes do not evaporate at the same temperature.

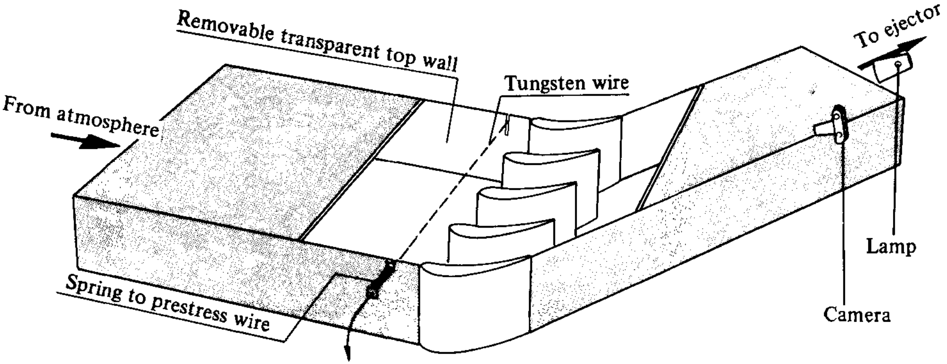

FIGURE 2. Schematic of test set-up.

The photographs were taken with a single-lens-reflex Nikon camera. The test section was illuminated with a 2000 W lamp. Exposure time and aperture were typically of the order of $\frac{1}{30}$–$\frac{1}{60}$ s and $f/8$–$f/16$.

3. Experimental set-up

The cascade tunnel is set up horizontally on a table in order to facilitate observation of the flow and allow easy access to the smoke wire and the blades (figure 2). Two different sets of blades were used: (*a*) a nozzle vane with 65° turning ($\beta_1 = 0°$, $\beta_2 = 65°$); (*b*) a rotor blade with 95° turning ($\beta_1 = 30°$, $\beta_2 = 65°$). Each cascade consists of five blades of 100 mm height and 120 mm chord. Top and side walls of the tunnel are made of Perspex. The air is sucked from the atmosphere through the cascade by means of an ejector mounted at the downstream end of the cascade tunnel. A honeycomb in the upstream duct of the cascade serves to reduce the inlet turbulence level. The flow velocity is kept very low (velocity downstream of cascade ≈ 2 m/s). The thickness of the endwall boundary layer is approximately 12 mm.

The smoke wire is placed parallel to the endwall 40 mm from the leading-edge plane. The distance with respect to the endwall can be varied. In most cases the wire was coated with yellow dye in the stagnation region and elsewhere a blue coating was applied. Little was gained by using more than two colours, except when using more than one wire.

4. A qualitative description of the secondary-vortex system

Figure 3 (plate 1) shows a few examples of coloured-smoke-wire visualizations: (*a*) nozzle vane with smoke wire at the edge of the endwall boundary layer at 12 mm from the top wall; (*b*) nozzle vane with smoke wire within the endwall boundary layer at 6 mm from top wall; (*c*) rotor blade with smoke emission from wire within endwall boundary layer at 6 mm from top wall (a second wire without smoke emission at 12 mm wall distance is visible).

From the evidence of a large number of photographs, and even more importantly from the direct observation of the smoke filaments during the tests, we have attempted in figure 4 to show the evolution of two different stream surfaces through the passage formed by two rotor blades, A and B. Stream surface S_1 is situated 6 mm from the top wall within the endwall boundary layer. Stream surface S_2 is situated just outside the endwall boundary layer. Upstream of the cascade, the stagnation

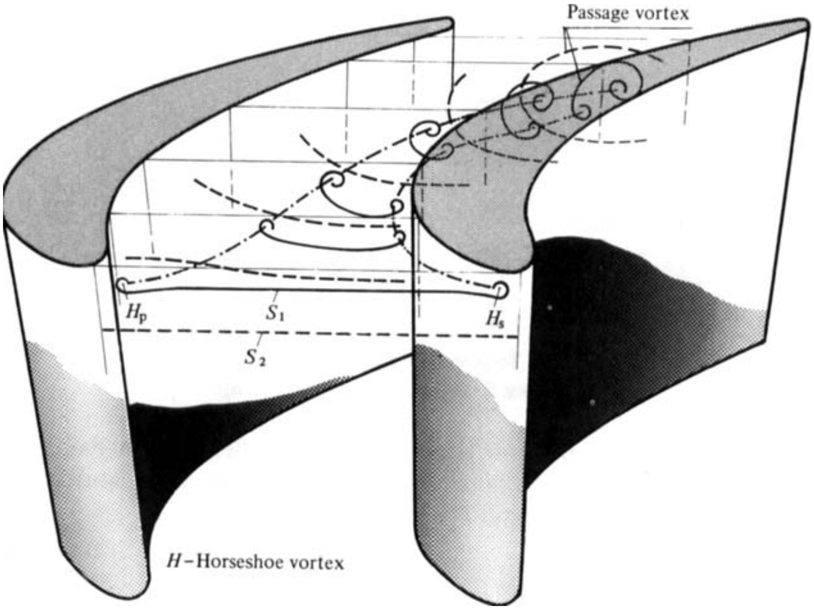

FIGURE 4. Evolution of horseshoe and passage vortices through rotor-blade cascade.

streamlines of blades A and B mark the boundaries of the stream surfaces S_1 and S_2 in the lateral (pitchwise) direction. The shapes of the stream surface are presented in planes parallel to the cascade front.

As the blade leading edges are approached, the lateral ends of the stream surface S_1 start to roll up into two counter-rotating vortices. The left vortex is the pressure-side leg of the horseshoe vortex H_p of blade A and the right vortex is the suction-side leg of the horseshoe vortex H_s of blade B. Behind the leading-edge plane the whole stream surface starts to rotate. The right-hand side of the stream surface with vortex H_s is shifted slightly downwards, while the left-hand side with vortex H_p is moved upwards. The rotation of the stream surface continues with increasing downstream distance. At about 50 % of the axial chord length the position of the vortices H_s and H_p has turned by about 90°. All parts of the stream surface, including the vortices H_s and H_p, take part in this vortical motion, which is known as the passage vortex. The locus of the centre of the horseshoe vortices H_s and H_p is indicated by dash–dotted lines in figure 4. The sense of rotation of the passage vortex is the same as that of the pressure-side horseshoe vortex H_p. The question as to the exact location of the centre of the passage vortex and the positioning of the vortices H_s and H_p with respect to it, is difficult to answer. However, the flow visualization in figure 3(*c*) does give some interesting information about the evolution of the horseshoe vortices with respect to each other. Looking at the lines of the vortex cores – follow the yellow stream tubes in figure 3(*c*) – it appears that the H_p vortex tube follows basically a smooth curve through the passage without any noticeable rotational motion, while the H_s vortex tube wraps itself around the H_p vortex tube. The position of the H_s vortex with respect to the H_p vortex depends on the rotational speed of the passage vortex, which in turn depends on the cascade geometry and the overall flow conditions. This feature is clearly demonstrated when comparing the flow visualizations in figure (3(*b*) (nozzle vane with 65° turning) and figure 3(*c*) (rotor blade with 95° turning).

Stream surface S_2 (figure 4), which lies entirely outside of the endwall boundary layer, also takes part in the formation of the passage vortex. However, the vortical motion of surface S_2 is much slower than that of S_1.

It should be noted that the evolution of stream surface S_1 in figure 4 is not necessarily representative of all stream surfaces starting upstream of the cascade within the endwall boundary layer. In particular, the evolution of the stream surfaces very close to the endwall and near the outer edge of the endwall boundary layer can differ significantly from that of S_1.

5. Conclusions

It has been demonstrated that coloured-smoke streaklines can be generated by heating a tungsten wire coated with a paste of Waxoline or Sudan dye powders and a minimum amount of oil. This coloured-smoke-wire technique served to study vortex patterns in low-speed high-turning turbine passages. The use of different colours made it possible to distinguish very clearly between the suction-side and pressure-side branches of the leading-edge horseshoe vortex and the passage vortex throughout the cascade (figure 3). The flow visualizations show that horseshoe and passage vortex do not exist independently of each other, but are part of the same vortex structure (figure 4).

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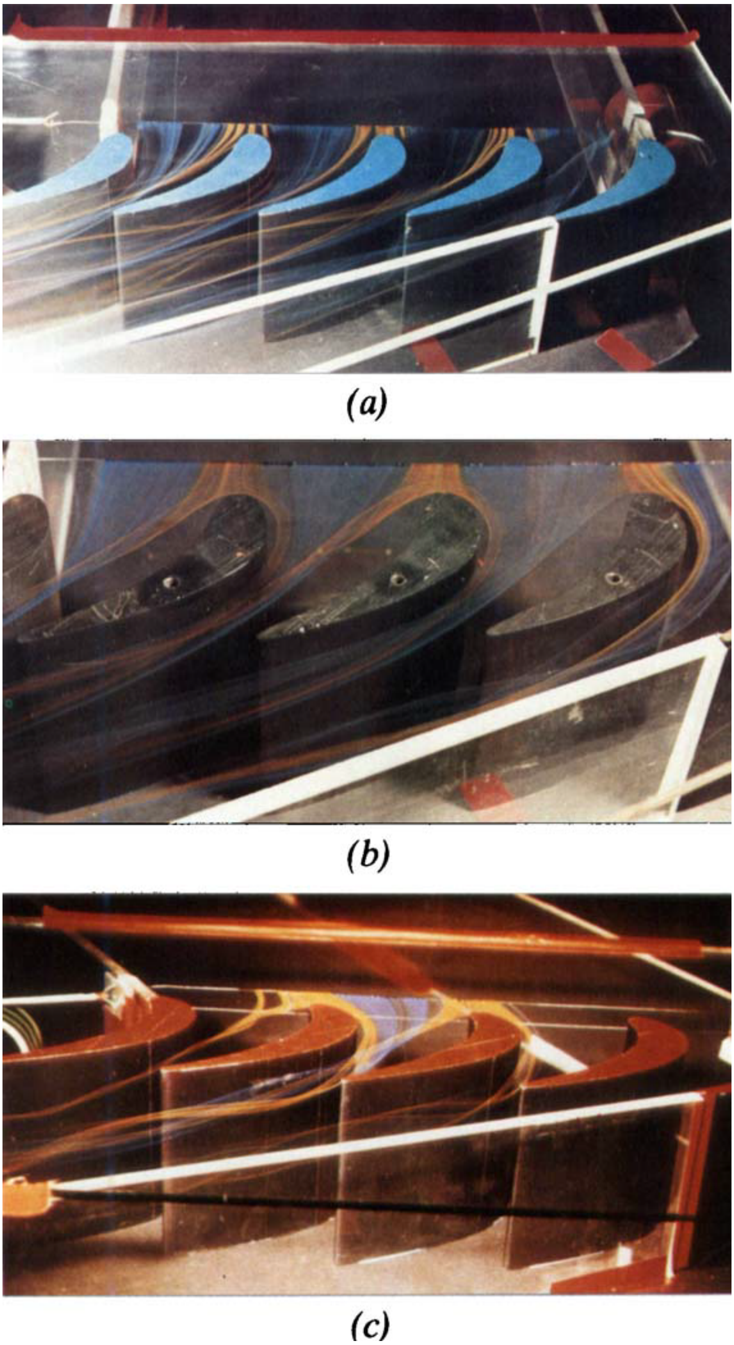

FIGURE 3. Coloured-smoke visualization: *(a)* nozzle vane – smoke wire outside endwall boundary layer; *(b)* nozzle vane – smoke wire inside endwall boundary layer; *(c)* rotor blade – smoke wire inside endwall boundary layer.