Boundary-Layer Separation and Transition Visualized by Liquid Crystal Coating

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1. Introduction

Flow visualization techniques are of increasing importance to support point by point measurements of flow properties on surfaces. Especially the boundary layer behaviour, like transition and separation, tend to be influenced by threedimensional effects even in a 2D or Q3D arrangement of a linear cascade.

Liquid crystal coatings have been used in the past to detect transition by making use of the different heat transfer rates of laminar and turbulent boundary layers (Holmes and Obara, 1987) and (Mee et al., 1991). In the present work, however, compressor blade sections were thermally insulated by a plastic film or made completely out of carbon fiber composite and then covered by liquid crystals. By accurate adjustment of the upstream total temperature within the colour band of the liquid cristals, a near adiabatic wall temperature could be visualized. Whereas with the heat transfer method only transition and, of course, cooled or heated blade surfaces can be visualized, the present method does provide additional information about the flow properties along the blade surfaces.

2. Liquid Crystal Coating

We used the LICRITHERM general purpose coating (TCS) of BDH Limited. The standard type TCS 1006 has a colour range from 29 deg Celsius to 35 deg Celsius with a temperature response curve as shown in Figure 1. The curve shows that the highest sensitivity exists at the low temperature side with red to yellow and green colours. The transparent coating has to be sprayed on black surfaces, which was in our case established by a black paint. A comprehensive description of thermochromic liquid crystals is available from BDH Limited (Sage and Archer, 1989).

3.Application

When we started the tests with a transonic blade section and near sonic inlet velocity we saw so many different temperature fields, which we could not explain, that we quickly switched to a subsonic blade section. But even there at the desing inlet Mach number of 0.62 we had difficulties to understand what we saw. Figure 2 shows the design and measured surface Mach number distribution of this blade section which we had tested extensively in the past (Steinert et al.,1991).

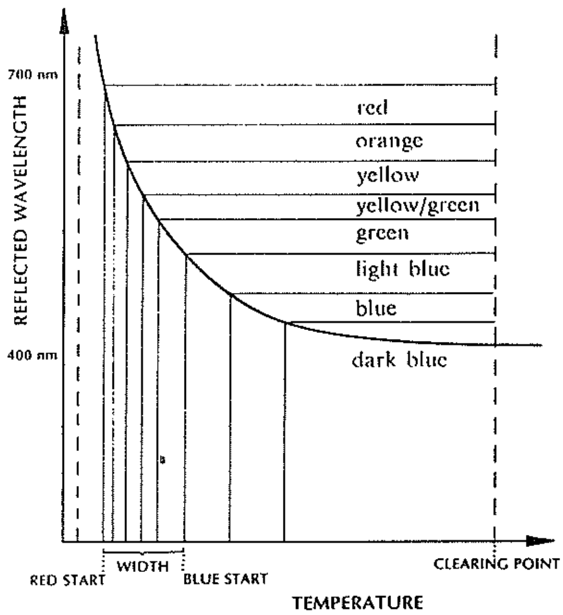

Figure 1. Typical pitch vs temperature response curve of a thermochromic liquid crystal mixture

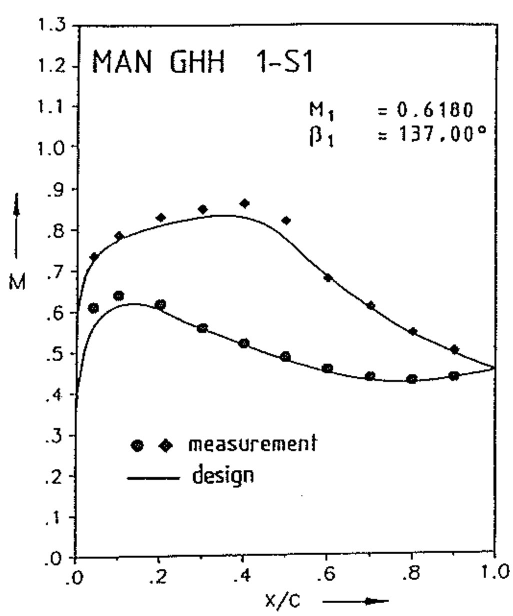

Figure 2. Design calculation and measured surface Mach numbers

Along .the suction surface the flow is accelerated until 40 percent of chord and then decelerated. We expected therefore, laminar boundary layer conditions in the front part and turbulent ones in the rear part, probably with a laminar separation bubble in between.

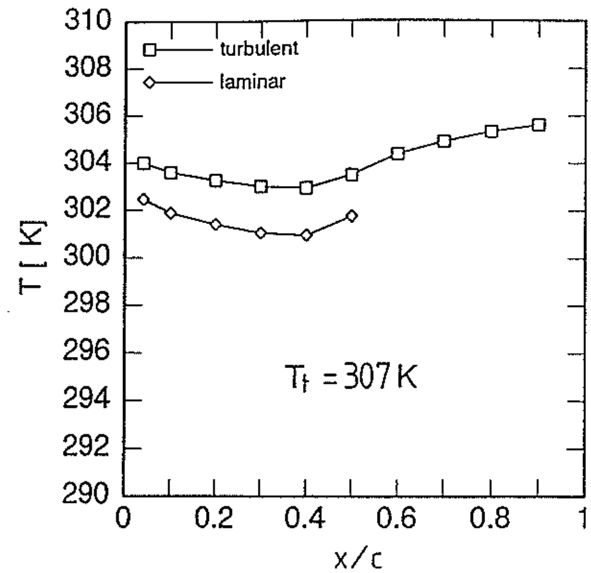

Figure 3. Calculated adiabatic wall temperature

The corresponding adiabatic wall temperature levels calculated from the measured velocities are shown in Figure 3. Between laminar and turbulent boundary layers about 2 degrees of wall temperature exists which should be detectable by the liquid crystals used in the tests. The experimental results verified this as shown in Figure 5. Near black, that means cold areas, are visible in the laminar front part of the blades and green, which means warm areas are visible in the turbulent rear part. Additionally clear yellow turbulent wedges, starting at the leading edges can be observed. However, between these wedges, a yellow band, that means higher temperatures, can be observed between 40 and 50 percent of chord. Additional tests, by releasing ink out of the pressure taps, showed that the yellow band corresponds to a laminar separation bubble. A local separation bubble is therefore characterized by a wall- temperature higher than in the laminar boundary layer region. The following cold region is probably caused by longitudinal "Görtler vortices". This asssumption is mainly based upon the streaky temperature stucture in this region which was especially clear at negative incidence as shown in Figure 6. In this case the total temperature has been raised by about one degree compared to Figure 5. Only due to this cold "transitional vortex region" it is possible to see by this method besides the beginning also the end of the separation bubble.

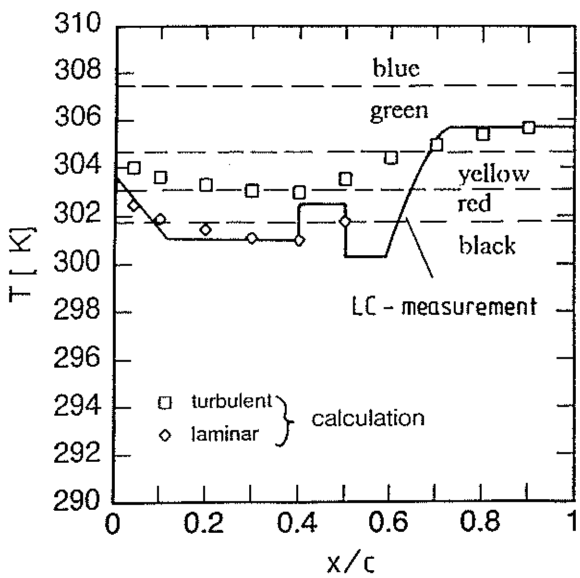

Figure 4. Calculated and measured adiabatic wall temperature

In Figure 4, the approximate development of the surface temperature, as derived from the liquid crystal picture, is compared to the calculated adiabatic wall temperatures at design conditions. These curves confirm that really the adiabatic wall temperature is shown by the liquid crystals. It can also be derived that within a laminar separation bubble a recovery factor may be defined which is near or equal to that one of a turbulent boundary layer. In the reattachment area behind a separation bubble, however, a recovery factor lower than that one of the laminar boundary layer has to be used to predict the adiabatic wall temperature there.

Natural transition as shown in Figure 7 around ten percent of chord gives also a streaky stable structure probably caused by vortices as this has been described in the literature. The same figure shows also a sudden temperature drop around 55 percent of chord visualized by a colour change from green to yellow. This is caused by complete separation which can therefore also be detected by this method. The recovery factor in the totally separated areas seems to be of the order of that one of the laminar boundary layer or even lower.

In Figure 8, which was taken at choked condition, the complete separation is even more distinct around 50 percent of chord. This figure shows the additional phenomenon of a closed laminar separation bubble followed directly by complete separation. Similar flow configurations have been observed already on other blades at transonic velocities.

The response of the liquid crystal coating on unsteady flow phenomena can be observed by a video system. Figure 9 and Figure 10 show the suction surface of the same test point at positive incidence and an inlet Mach number of 0.77. The pictures were derived from a video tape with a time difference of 1/25 second. They show an oscillating shock between 18 and 25 percent of chord with shock boundary layer interaction, and with local separation.

4. Conclusions

The conclusions, which can be drawn from our experiments are :

The visualisation of the adiabatic wall temperature on blade surfaces presents the possibility of detecting:

- natural laminar- turbulent transition
- closed separation bubbles
- total separation
- "footprints" of vortices
- low frequency fluctuations of transition or separation.

5. References

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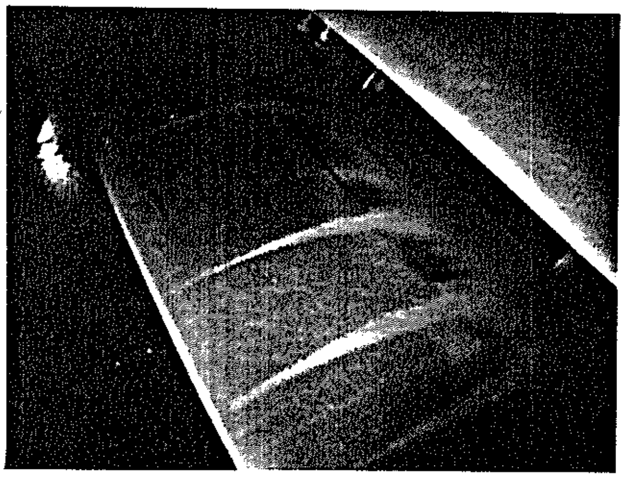

Figure 5. Liquid crystal picture of suction surface at an inlet Mach number of 0.62 and design incidence

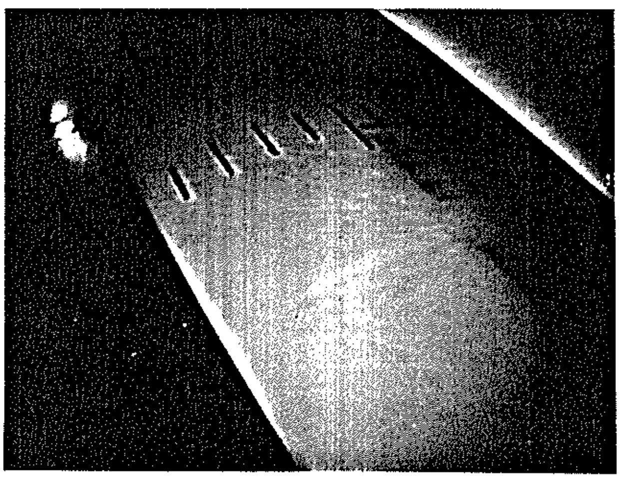

Figure 6. Liquid crystal picture of suction surface at an inlet Mach number of 0.62 and negative incidence

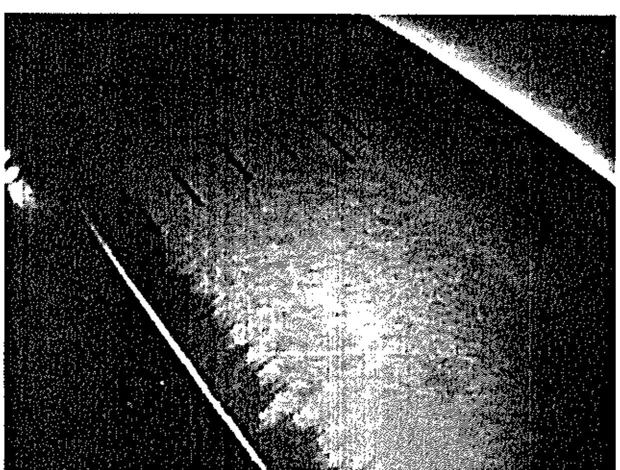

Figure 7. Liquid crystal picture of suction surface at an inlet Mach number of 0.62 and positive incidence

Figure 8. Liquid crystal picture of suction surface at an inlet Mach number of 0.64 and negative incidence

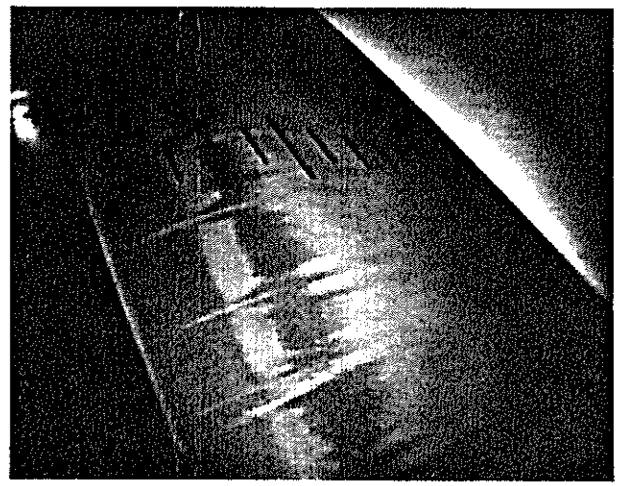

Figure 9. Liquid crystal picture of suction surface at an inlet Mach number of 0.77 and positive incidence

Figure 10. Liquid crystal picture of suction surface at an inlet Mach number of 0.77 and positive incidence