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The Effect of a Particle travelling through a Laminar Boundary Layer on Transition

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Abstract This study investigates how a particle travelling through an initially laminar boundary layer can lead to its breakdown to turbulence. With increasing kerosene costs and an awareness of limited available oil reserves, laminar flow technologies are again being considered to realize the necessary efficiency increases of aircraft, and more detailed information on the operational issues is required. The adverse impact of flying through cirrus clouds has been simplified to the effect of a single particle on a laminar boundary layer over a zero-pressure gradient flat plate. First results indicate that the critical values could be substantially smaller than initially assumed.

1 Background

Laminar flow technologies, which could substantially contribute to efficiency increases required for air transportation in order to cope with forecasted growth and simultaneously limit the environmental impact due to air traffic, have been found to be non-functional while flying through cirrus cloud. The first recognition of this phenomenon was made by Northrop during its X-21 flight test program, which investigated a full chord suction type Laminar Flow Control (LFC) system in the early 1960s. Laminar flow was entirely lost when entering thick cirrus clouds and even slightly degraded when light haze (leaving visibilities of up to 80 km) surrounded the aircraft.

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The effect was attributed to the ability of the ice crystals contained in cirrus to produce turbulence within their wakes while travelling through the artificially maintained laminar boundary layer. Subsequent theoretical analysis in conjunction with the available flight test data resulted in the so-called "Hall criteria" [3], which is presented in Figure 1 and suggests that there exist both a minimum ice crystal diameter and a minimum crystal flux above which laminar flow is progressively degraded with increasing ice particle number concentration. Further dependencies proposed were air density and viscosity (thus temperature or altitude), flight speed, leading edge geometry and the shape of the ice particle being investigated [2].

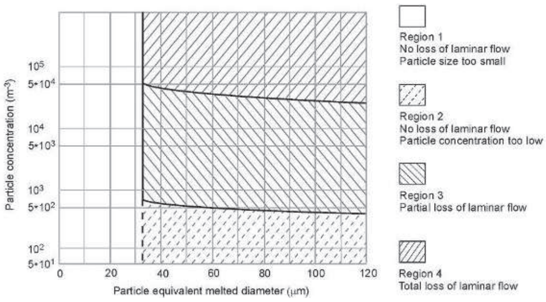

Fig. 1 The "Hall Criteria", valid for an altitude of 40,000ft, a Mach number of 0.75 and a cylindrical (ice) particle approximation with a length-to-diameter ratio of 2.5, redrawn from [2]

When correlating the effect to results from other experimental studies found in the literature [4-7], additional parameters must be taken into account, especially if different flow media and particle materials are engaged. The density ratio between the particulate and the continuous phase, for instance, is believed to play a role; however, this still might not complete the picture.

Correspondingly, Ladd & Hendricks [4] assumed that the particles would temporarily stick to the surface acting as a roughness element. Petrie et al. [7] suspected the observed post-impingement spanwise fluctuations as representing a parameter which could have initiated transition. Furthermore, the effect of the no-slip condition on the particle itself, which most likely causes a temporary deformation of the velocity profile of the laminar boundary layer investigated, found to the authors' knowledge only very little consideration until today. Despite the values ranging from 450 to 800, the order of magnitude of the critical Reynolds number for a spherical particle to trigger a turbulent event seems to be generally agreed.

2 Experimental Work

Schmidt & Young [8] have shown that the effect can be re-created in a laboratory wind tunnel environment. Both the double pitot measurement approach as well as surface mounted hot films were capable of detecting premature transition caused by a particle cloud dispersed into the free stream; whereas, the latter was seen to produce more accurate answers. Furthermore, these preliminary experiments indicated that substantially smaller particles than previously assumed could cause turbulent events to be triggered.

In order to gain a deeper insight into the problem, the flow field alterations caused by a single, freely-suspended, spherical particle entering a laminar boundary layer over a flat plate in low speed zero-pressure gradient conditions are under investigation. As it was suspected that the vertical component of a freely falling particle could exceed critical conditions before entering the boundary layer, a pendulum approach has been applied to the particle to elude this problem. Both hot wire traverses and surface mounted hot film measurements have been taken downstream of the region impacted by the particle.

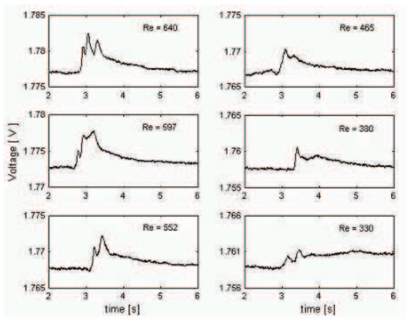

Fig. 2 Hot film data, showing turbulent structures in the signal taken downstream of the particle impact at various Reynolds numbers

The hot film data obtained support the earlier speculation that the Reynolds number for a particle to contaminate laminar flow could be considerably lower in comparison to information published previously, as turbulent structures are apparent for Reynolds numbers as low as 330 (see Figure 2). No effect could be determined from the hot wire traverses outside the laminar boundary layer, showing that the pendulum approach succeeded to suppress critical conditions within the free stream. Furthermore, when assembling the measurement curves of a traverse into a single figure, similar trends were evident compared to results published by Cantwell et al. [1] for an artificially generated turbulent spot.

3 Numerical Work

In order to analyse in more detail the differences of the critical values obtained during this work when compared to previously published information, a numerical study has been done in which the conditions of the experimental work of Petrie et al. [7] have been re-created.

It was found that the streamwise velocity component of the near-neutrally buoyant spherical particles used adapted almost instantaneously to changes in the flow field within the boundary layer when entering it. Thus, the major contribution to a critical particle Reynolds number originated from the particle's transverse velocity component, which in most cases had achieved its terminal value and was in the order of the free stream speed. As such these particles were supercritical before reaching the boundary layer and developed their wake in a nearly vertical direction. This might explain why the corresponding vortices could not be observed in the flow visualisation of the original study [7]. Interestingly, in this numerical analysis, the lowest particle Reynolds number of all considered cases, for which the generation of a turbulent spot had been reported originally, was in the order of 300.

4 Concluding Remarks

The information on how ice crystals occurring in cirrus cloud can lead to the temporary loss of laminar flow technology's benefits is not sufficiently complete to enable the full potential of such systems to be realized in terms of optimized fuel planning.

First experimental results give an indication that the Reynolds number, above which a spherical particle impinging on a surface subjected by an air flow could trigger a turbulent event within a laminar boundary layer over that surface, is considerably smaller than previously thought. Whether this is due to the shear flow prevailing within the boundary layer or if other previously detected mechanisms play an additional role is not clear at the moment and requires further investigation.

Consideration of the flow field actually "seen" by the particle has led to the design of a new test facility, where the particles are held at a fixed position and the surface to be investigated is moved instead. This procedure, it is hoped, will provide for useful information and circumvent the issues encountered when trying to re-create realistic conditions in a laboratory experiment.

References

1. Cantwell, B., Donald, C., Dimotakis, P. Structure and entrainment in the plane of symmetry of a turbulent spot. J. Fluid Mech., Vol. **87**, Part 4, 641–672 (1978)
2. Davis, R. E., Maddalon, D.V., Wagner, R.D.: Performance of Laminar Flow Leading Edge Test Articles in Cloud Encounter. NASA CP-1987-2487, Langley Research Center (1987)
3. Hall, G.R.: On the Mechanics of Transition Produced by Particles Passing Through an Initially Laminar Boundary Layer and Estimated Effect on the Performance of X-21 Aircraft. Northrop Corp., Contract-No.: N79-70656, (1964)
4. Ladd, D.M., Hendricks, E.W.: The effect of background particulates on the delayed transition of a heated 9:1 ellipsoid. Exp. in Fluids, Vol. **3**, 113–119 (1985)
5. Lauchle, G.C., Gurney, G.B.: Laminar Boundary Layer Transition on a Heated Underwater Body. J. Fluid Mech., Vol. **144**, 79–101 (1984)
6. Lauchle, G.C., Petrie, H.L., Stinebring, D.R.: Laminar Flow Performance of a Heated body in particle-laden water. Exp. in Fluids, Vol. **19**, 305–312 (1995)
7. Petrie, H.L., Morris, P.J., Bajwa, A.R., Vincent, D.C.: Transition induced by Fixed and Freely Convecting Particles in Laminar Boundary Layers., The Pennsylvania State University, Appl. Res. Lab., PA, USA (1993)
8. Schmidt, C. ,Young, T.M., The impact of freely suspended particles on laminar boundary layers. 47th AIAA Aerospace Sciences Meeting (ASM), 5-8 Jan, Orlando, Florida, USA (2009)