The influence of cirrus cloud on drag reduction technologies based on laminar flow

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Abstract

Due the increasing gap between the growth of air traffic on one side and the requirement to lower its environmental impacts on the other, laminar flow technologies attract renewed interest as they offer a potential of greater than 10% fuel savings for long-range jet transport aircraft. Further reductions could be achieved if the impact of environmental factors, such as the performance degradition that occurs on laminar flow technologies when encountering cirrus haze or cloud, were better understood, as this could allow for more optimized fuel planning. This will on one hand require accurate en-route cloudiness prediction tools. On the other hand, the exact determination of the critical parameters will be crucial if the original assumption should hold true that the phenomenon is a turbulent contamination problem. Furthermore, it must be determined, whether additional mechanisms are active in the process. For these purposes, experimental work has been undertaken investigating the effect of particles moving through a laminar boundary layer in air. The results indicated a critical Reynolds number that is substantially lower than previously published values.

Nomenclature

DNS	Direct Numerical Simulation
GASP	Global Atmospheric Sampling Program
HLFC	Hybrid Laminar Flow Control
LEFT	Leading Edge Flight Test program
LFC	Laminar Flow Control
NASA	National Aeronautics and Space Administration
NLF	Natural Laminar Flow
RANS	Reynolds Averaged Navier Stokes
SAS	Simulated Airline Service
UDF	User Defined Function
D, d	diameter
K	shear parameter
L	length
Ma	Mach number
Re	Reynolds number
u	local velocity in streamwise direction
U_∞	local boundary layer edge velocity in streamwise direction
y	coordinate in transverse direction
δ	boundary layer thickness
$_x$	subscript corresponding to the streamwise length from the leading edge
$_p$	subscript corresponding to a particle diameter

1. Introduction

Worldwide air traffic is predicted to double within the next 15 years [1]. However, even current environmental impact levels from jet transport operation raise concerns in terms of fuel consumption, CO_2 emissions and persistent contrail formations.

In order to meet with forecasted needs and contemporaneously with the ambiguous goals set by the European 2020 Vision, a considerable increase in aircraft efficiencies will be required. Whilst new materials, structural optimisation and further developments in the propulsion system will provide for some improvements, drag reduction due to boundary layer control could contribute a more than 10 % reduction in fuel consumption [2-3].

Following more than a century of research in this field, three techniques have emerged to be practically applicable: the passive principle of Natural Laminar Flow (NLF), active suction type Laminar Flow Control (LFC) and the combination thereof, i.e. Hybrid Laminar Flow Control (HLFC). Arnal & Archambaud [4] consider them “matured”, as the prospects and limitations of the single techniques are well understood and the different concepts have been successfully proven in several flight experiments [5-9].

However, the incomplete understanding of the deteriorating effects that arise due to ice crystal impacts which occur during flights through cirrus cloud, and the lack of corresponding data, do still not allow for a pre-mission fuel planning that is sufficiently accurate to enable full advantage to be taken for such laminar flow systems.

2. Objectives

(1) This work reviews the available experimental results regarding the influence of cirrus cloud on drag reduction technologies based on laminar flow.
(2) The experimental work focuses on investigating the impact of particles travelling through a laminar boundar layer on a flat plate. Some attention has also been paid to possible differences between particles impacting on surface and ones that do not.
(3) The study seeks to contribute to an improved understanding of the basic mechanisms of how the presence of small particles in a free stream leads to the breakdown of laminar flow.

3. Background

2.1 Flight tests and their analyses

Researchers at Northrop were the first to recognize the effect of cirrus during their USAF X-21 flight tests investigating full chord suction type LFC in the early 1960s. Laminar flow was entirely lost whenever thick clouds were penetrated and the systems performance was even deteriorated while flying through light haze (corresponding to the pilot's visibility of approximately 80 km).

Subsequent theoretical analyses in connection with the available flight test data resulted in the so-called "Hall-criteria" suggesting both a minimum particle size and a minimum flux below which a laminar boundary layer would not be affected in both cases (Regions 1 and 2 in figure 1). Above those limits, however, the laminar flow is progressively degraded with increasing particle number concentration (Region 3) until the entire boundary layer is turbulent (Region 4). The effect has been entirely attributed to the ice crystals' capability to produce turbulence within their wakes while travelling through the laminar boundary layer [10].

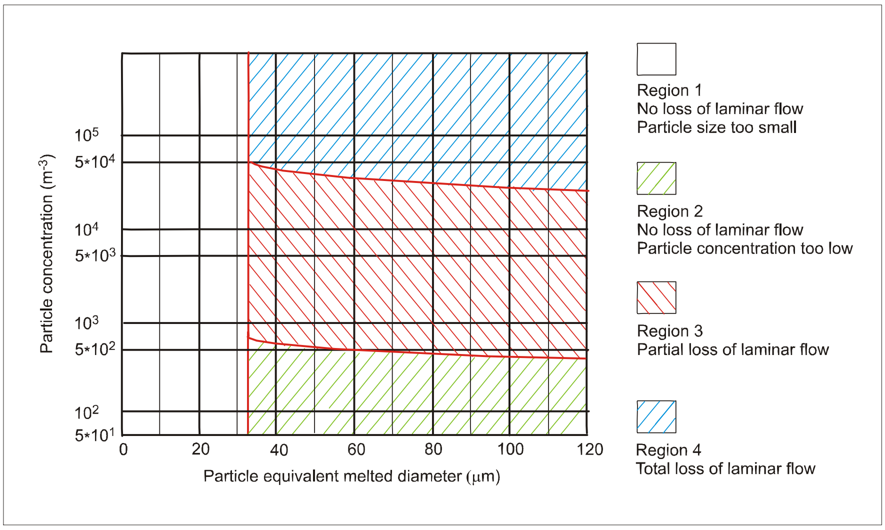

Figure 1 The "Hall Criteria" (redrawn from Davis et al. [11])

It should be noted, however, that the criteria shown in figure 1 is limited to the flight envelope of the X-21 tests, namely a cruise speed of Ma = 0.75 at an altitude of 40,000 ft, as well as an elliptical estimate of the corresponding wing's leading edge geometry, and cylindrical approximations with a length-to-diameter ratio, L/D, of 2.5 for the particles, which was chosen by Hall [10] as being the best representative on an average of naturally occurring ice crystals. A further limitation was seen by Pfenninger [12] in the sweep angle, as an alteration of this would also change the particles' residence time within the boundary layer and the spanwise deflection of affected boundary layer velocity profiles.

In an attempt to validate Halls [10] criteria, NASA obtained principle agreement during its Leading Edge Flight Test (LEFT) program in the 1980s. However, the available measurement equipment did not allow for conclusive measurements of particles smaller than 60 µm at the chosen flight speed. Thus, the existence of "Region 1" of figure 1 could neither be questioned nor confirmed. Furthermore, situations corresponding to "Region 2" have been published to result in an up to 15% loss of laminar flow as opposed to the zero effect proposed initially [11].

Reviewing the available literature and taking reference on laboratory work on single disturbance elements, Schmidt & Young [13] believed that "Region 2" in figure 1 does not exist at all, but is a result of the response time of the measurement equipment used during the X-21 flight tests.

2.2 The impact on fuel planning

Within one phase of the NASA LEFT program, the LFC equipped Jetstar was flown along normally operated airline routes within the United States, whereby neither adjustments, nor out of schedule maintenance procedures especially on the LFC systems were undertaken. This Simulated Airline Service (SAS) routine, besides giving confidence into the operational practicability of the tested system, resulted in an overall average of 6% of cruise time per flight, when LFC was incapable to serve its purpose due to the encounter of cirrus haze or clouds [9].

Such a figure was seen to be in general agreement with information obtained earlier during NASA's Global Atmospheric Sampling Program (GASP), a project that had been setup to explore the overall impact of air traffic on our atmosphere on a global scale. Besides many other weather phenomena, the cloud encounters of four in normal-service Boeing 747 aircraft had been recorded between 1975 and 1979, resulting in over 88,000 samples (a full analyses of which can be found in Jasperson et al. [14]).

The average value of about 6% cloud encounter has subsequently been reported in numerous reviews of the general subject of laminar flow (e.g. Joslin [5]). However, while such a mean has been adequate for stating that the overall impact is effectually low enough to not question the usefulness of laminar flow technologies in general, it is not sufficient to serve as a basis for an optimised fuel planning of correspondingly equipped aircraft.

It must not be overlooked that Jasperson et al. [14] concluded with seasonal and regional changes and thus with strong variability in the likelihood to encounter clouds from route to route. Furthermore, during both programmes flights were reported where en-route cloudiness was as severe as 50%. Whereas, those events were only single occurrences and the majority of flights were shown to encounter clouds for less than the average, the most conservative assumption has to be taken into account, when making the fuel planning for a specific mission. This in turn would mean nearly all missions operated with laminar flow technology will carry fuel that will not be used, the amount of which can be considerable in some cases. This extra fuel represents an excess of weight, which translates directly into an excess of fuel burn throughout the mission.

Thus, only more detailed information about the impact of cirrus cloud on laminar flow and the incidence of cirrus cloud on flight routes before departure will allow to fully capitalise on the potential of laminar flow technology. Young et al. [15] propose that, once sufficient information were available, a cloud parameter could be included within the fuel planning of future aircraft equipped with laminar flow technology in a similar manner as the wind parameter is used today, which also identifies the future need for reliable en-route cloudiness prediction tools.

2.3 Related previously published laboratory work

More definite statements on the effect of ice crystals on laminar boundary layers can only be drawn, when the crucial information of the minimum size limit above which a turbulent event is generated by an impacting particle can be clearly defined for all situations. This critical size can be derived from the flow field parameters once the critical Reynolds number is known, where turbulent structures can first be observed in the particles wake.

Roshko [16] provides a detailed study of the wake development downstream of cylinders in a uniform flow. Three different regimes could be distinguished: the stable range for Reynolds numbers (Re) of 40 to 150, a transitional range for Re between 150 and 300, and the irregular range for $Re > 300$. Considering, that ice crystals are generally described as irregular in shape, it is likely that they act as three dimensional disturbance elements, thus bypassing the transitional regime and placing the critical value at 150.

Sakamoto & Haniu [17, 18] extensively studied the flow past a sphere in both a uniform flow and a uniform shear flow. In the former case, they report turbulence in the wake to appear at Re > 650 in the form of transition occurring in large-scale hairpin-shaped vortices. For the latter, they found that the critical Reynolds number for such vortices to be shed decreases linearly with increasing shear parameter (K), defined as the transverse velocity gradient of the shear flow non-dimensionalised by the approach velocity at the center of the sphere and the Reynolds number of the sphere based on the same velocity and its diameter. Additionally, they observed that the shedding occurred at a fixed location on the high velocity side of the sphere. It is worth noting in this regard that Kiya et al. [19] recognized an opposite trend, while exploring the wake of a cylinder in a uniform shear flow.

Hall [20] investigated the effects of the wakes of fixed, but elevated, particles in an undeveloped laminar pipe flow, which still showed some stabilizing favourable pressure gradient due to the persistent boundary layer growth. Depending on the elevation, critical Reynolds numbers of 450 to 650 were determined, based on the particle diameter and the free stream velocity at the top of the sphere.

Similar results had been obtained by Mochizuki [21] during earlier wind tunnel experiments on spheres attached to a flat plate, whereby a dependency on the local ratio of the particle diameter to the boundary layer thickness could be found. For very small ratios a critical Reynolds number of 600 can be extrapolated from the published information.

Observations of particulates contained in the free stream being responsible for performance degradation of laminar flow control have also been made during efforts of reducing the drag of marine bodies by thermal heating of their surface. Lauchle & Gurney [22] found that filtering the water for particles larger than 5 µm considerably improved the performance of their heated ellipsoid. While investigating the effect of free stream particulate on the maximum achievable transition length Reynolds number, they could not determine a minimum critical particle size, but found that all sizes considered had a detrimental effect.

This observation led Lauchle et al. [23, 24] to investigate whether or not the pure presence of the particles would result in premature transition. Surprisingly, when the particles were injected from within the boundary layer, no influence on the laminar flow could be found for any size. This strongly supports the view that a minimum slip velocity between the flow medium and the particle must exist for the particle being effective in triggering a turbulent event.

Ladd & Hendricks [25] studied the effect of four different particle size samples, namely 12.5 µm, 38.9 µm, 85.5 µm and 132.2 µm, on a somewhat smaller heated ellipsoid. They could not detect an effect from the two smaller sized samples, when compared to the filtered water case, whereas the two larger samples showed a strong influence. Unexpectedly, the effect was reduced for the largest size, which, however, they could successfully attribute to the lower number concentration prevailing in the 132.2 µm sample compared to the one containing the 85.5 µm particles.

Petrie et al. [26] investigated the subject in a two-fold way by carrying out experiments on both fixed and freely suspended spherical particles on a laminar boundary layer over a flat plate. For the fixed case the observations made by previous researchers could be generally substantiated. However, the mechanisms leading to transition at particle Reynolds numbers of about 700 due to the freely suspended case was described as being substantially different. The dye visualisation technique failed to show the expected vortices in the particles wake, but instead illustrated spanwise fluctuations ahead of the rapidly developing turbulent spot, which led Petri et al. [26] to propose, that "…convecting particle wakes have little, if any, effect on turbulent spot generation". This is in clear contradiction to Hall's [10] initial assumption.

4. Experimental Work

4.1 Preliminary Work

Schmidt & Young [27] have shown that the effect can be re-created in a laboratory environment. Figure 2 shows a sketch of the principle that was adopted.

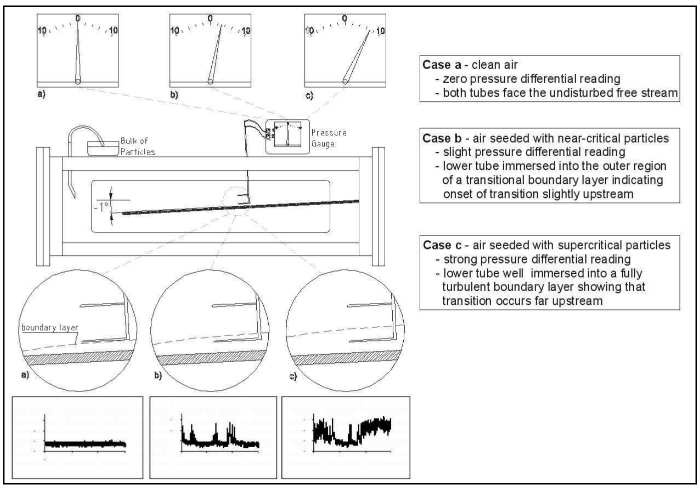

Figure 2 Experimental setup and results for different particle samples (reproduced from Schmidt & Young [13])

Differential total pressure readings from a raised double Pitot tube, that was placed with its lower tube above the edge of a laminar boundary layer, facing a flow of (a) clean air, (b) air seeded with particles of near critical diameters, and (c) air seeded with particles of supercritical size. Furthermore, it could be proven that besides the initially applied raised double Pitot approach hot film anemometry can also be used to demonstrate this effect. Corresponding measurement results obtained during the experiments are also shown at the bottom of figure 2.

4.2 The experimental setup

In order to gain a deeper insight into the problem, a joint project between the Universities of Limerick (Ireland) and Glasgow (Scotland) has been launched investigating 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.

The objective of the investigation was to determine the particle's critical parameters that are necessary to generate a turbulent spot and to answer the question whether turbulence produced in the particles wake is the only effect disrupting the laminar boundary layer or if disturbances introduced by the impingement itself, as proposed by Petrie et al. [26], play an additional role.

The facility comprises a non-return wind tunnel with a 4 m long test section having a squared cross sectional area of 91.44 cm (3 ft) length. The maximum achievable velocity is 2.4 m/s, the turbulence intensity has been determined to be 0.5%. The flat plate consists of several sections of carefully adjusted plywood boards (along the vertical centerplane), with the upper sides sprayed with a thin layer of black lacquer. To the most upstream of these sections an elliptically shaped leading edge has been attached.

In order to force the stagnation line onto the upper side, two grids have been installed at the test section outlet, one covering the whole cross sectional area above the plate and the other one leaving an opening above the plates surface covering the remaining area upwards. The appropriate height of the second grid has been chosen with the help of visual observation of smoke flowing around the leading edge in order to obtain an optimum configuration that provides for both a minimum pressure loss due to the grids and a minimum leading edge separation of the flow.

As in previous investigations, the concern is that when a particle is simply dropped into the test section its vertical velocity component could achieve a critical value already before it enters the laminar boundary layer over the plate. The expererimental work, herein described, attempted to circumvent this issue by controlling the particle's path using a pendulum. Thus, a spherical particle of 6 mm in diameter was fixed by a thread of adjustable length to the ceiling of the test. It could be launched from a vertically adjustable position some distance upstream and could be captured after travelling once through the plate's boundary layer.

Both hot film and hot wire measurements were taken at a distance of 300 mm downstream of the pendulum's maximum deflection location. Furthermore, this setup allowed for the measurements of two different effects of the particle on the plate's laminar boundary layer, namely one with and one without impingement to the surface. For the former the thread of the pendulum was long enough to ensure the particle would touch the plate's surface while swinging through its boundary layer. In the latter case, the thread was shortened to a length that did not allow for an impact of the particle to occur. The gap between the particle and the surface of the plate at the pendulum's maximum deflection was set manually to the condition where a source of light could be seen through it, and it was estimated to be in the order of 0.1 mm. The current experimental setup is illustrated in figure 3.

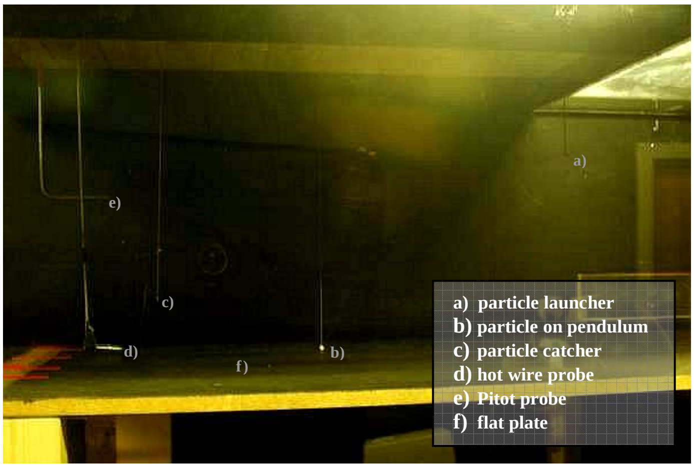

Figure 3 The experimental setup at the University of Glasgow

4.3 Methodolgy and Results

Hot wire boundary layer traverses resulted in mean velocity profiles that were in close agreement to Blasius' solution. At the anticipated measurement location of 2.1 m downstream of the leading edge and the chosen free stream velocity of 1.5 m/s, the laminar boundary layer thickness was approximately 23 mm. Having assured that no interference would occur from the upstream installed wires, which were required for launching and capturing the particle, the hot wire probe was placed at several transverse locations and the particle released to swing through the laminar boundary layer in each case. Measurements were taken at a sample rate of 2 kHz over a period of 20 s.

In order to discover whether or not the actual impingement of a particle would have an additional effect, the experiment was carried out for two different configurations: one with the particle flying through the boundary layer while making no contact to the plate and one with the particle impacting on the plate's surface. The corresponding results are presented in figure 5, and in figure 6, respectively.

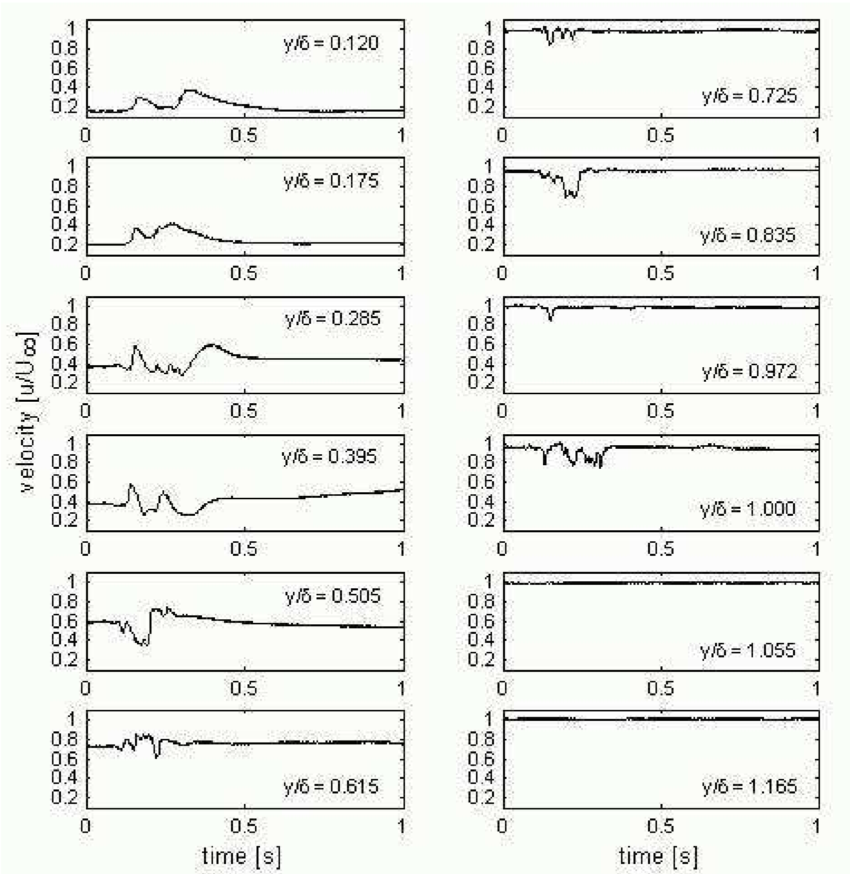

Figure 5 Hot wire data during the impact of a particle with surface impingement

As is apparent from both figures, the effect of the particle is clearly visible. The data with particle impingement (figure 5) show a trend of a time-wise reducing effect from the surface to half the boundary layer thickness, where it increases again towards the boundary layer edge, when ignoring the value for $y/\delta = 0.972$. For the results without impingement, this trend seems to be reversed. However, the accumulated so far data is insufficient to allow for a definite conclusion to be made in this regard. It is apparent, however, that there is a general shift of the disturbance signal from a positive deflection close to the surface to a negative one towards the boundary layer edge. This is unlike earlier results from Guilleme [28], where the particles have been dropped from a tube protruding from the wind tunnel ceiling and the velocity profile has shown acceleration throughout the boundary layer.

Surprisingly, in both cases investigated within this work, no effect could be determined at probe locations that lay outside the thickness of the laminar boundary layer, which was determined earlier. This, on one hand, indicates that the relative particle velocity was successfully kept below critical for locations outside the boundary layer. On the other hand, a temporary thickening of the boundary layer was initially expected due to the generation of a turbulent event; however this is not evident in the measurements taken.

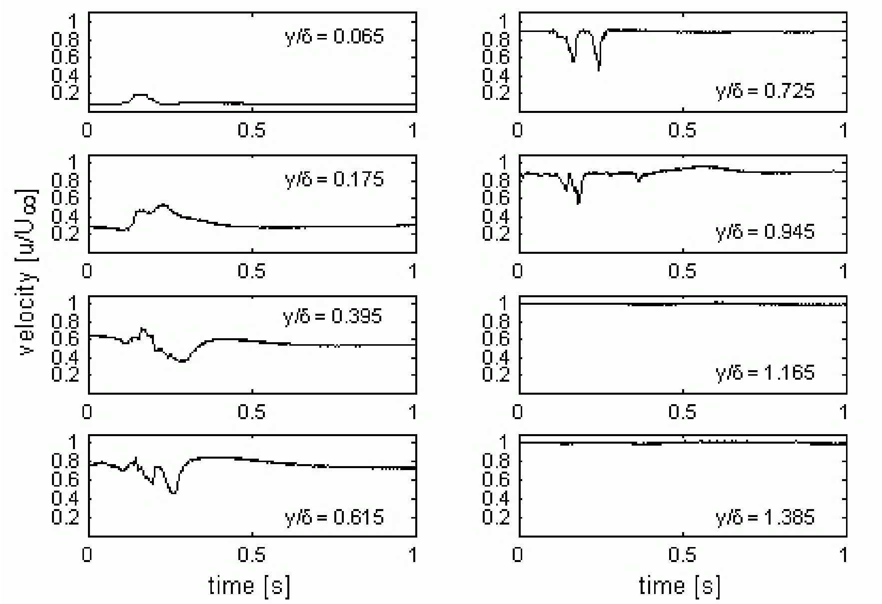

Figure 6 Hot wire data during the impact of a particle without surface impingement

Further measurements have been taken using a surface mounted hot film. Starting with a supercritical value for the particle Reynolds number being greater 600 resulted in an obvious deterioration in the hot film signal. Reducing the wind tunnel speed, the disturbance persists down to Reynolds numbers of 330, where the effect seems to die out (see figure 7). A similar observation has been made in an earlier experiment of Schmidt & Young [13], who reported Reynolds numbers as low as 300 to be critical for both particle samples which they seeded into the free stream. The effect had been attributed to irregularities in the shape of their particles, being described as flake-like and crystalline, however, the results obtained during this study dealing with a perfectly round spherical particle propose, that this is not the case.

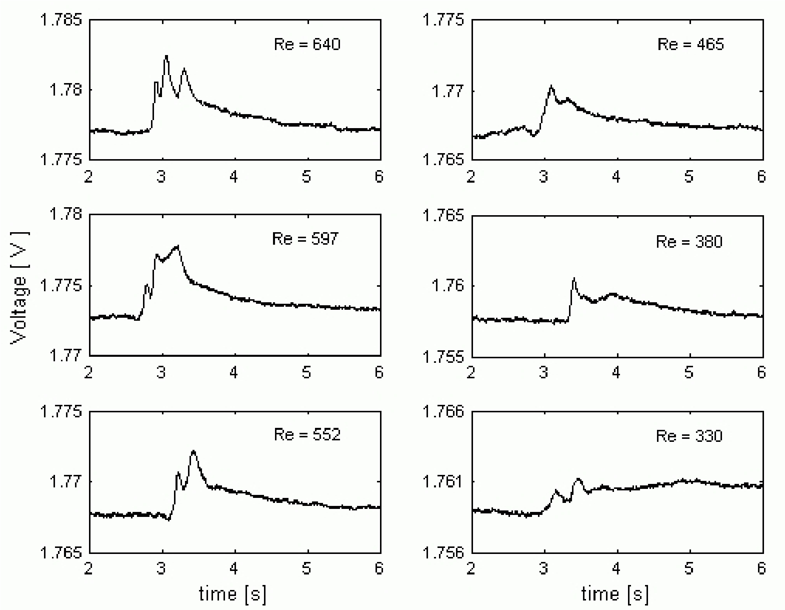

Figure 7 Hot film data during the impact of a particle with surface impingement

As the original signal was effected from some amount of noise, the information provided in figure 7 has been lowpass-filtered at 500 Hz.

5. Discussion

While analysing the effect of particles on a laminar boundary layer, the question arises on what location the critical parameters should be based on, since a boundary layer comprises a nonuniform flow field. While Sakamoto & Haniu [18] based their critical Reynolds number on the velocity persisting at the center of the sphere, fixed particle investigations (e.g. Hall [21], Mochizuki [22]) chose the velocity at the top of the particle in accordance with experiments on roughness elements. A particle, however, moving with the free stream will 'see', when entering the boundary layer, its highest relative velocity at its bottom side close to the plate's surface, where the flow medium will adhere to the surface. Thus, assuming the particle's mass and the geometrical extend of the laminar boundary layer will avoid the particle to adapt to the rapidly occurring changes in the flow field, determination of the critical Reynolds number from the local boundary layer edge velocity is believed to be a good approximation.

Only slight differences could be found, when comparing the measurement results, which were subjected from particles with surface impingement to data where no contact to plate has been made by the particles. Interesting remains in this regard the observation of Petrie et al., who did not observe any vortices in the wake of their freely suspended particle using dye visualisation technique. Since these experiments, however, were done using nearly neutrally buoyant particles, it is possible that the particle was considerably decelerated by the retarded free stream within the boundary layer. The open question remaining is, why the turbulent spot is still being produced at a Reynolds number of 700, which is in close agreement to the theoretical value. Nevertheless, a reduced particle velocity would mean that the actual Reynolds numbers were lower and thus critical at lower values.

Our hot film measurements point into the same direction, as the occurrence of a turbulent structure at particle Reynolds numbers as low as 330 could be observed. This again could be related to a relatively strong shear parameter occurring in the velocity profile close to the surface, which has in many previous studies found no attention.

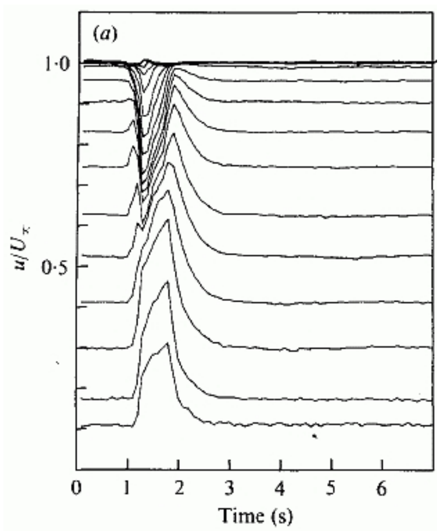

Figure 8 Ensemble-mean velocity data of a passing turbulent spot (re-produced from [29])

The hot wire boundary layer traverses, which were taken at critical conditions based on the assumptions made above, clearly reproduced structures of a turbulent spot. This can be concluded with confidence when reviewing measurements taken by Cantwell et al. [29] (see figure 8), who investigated in detail the development of artificially generated turbulent spots. Comparison of the information in figures 5 and 6 to that in figure 8 makes apparent that from the single curves of the former similar illustrations could be assembled as found in the latter.

The question why the passing of the spot did not show at locations outside the initially laminar boundary layer cannot be conclusively answered at the time. This is in contradiction to Wygnanski et al. [30], who proposed that a spot would growth at the same rate as a turbulent boundary layer initiated at the same location, where the spot has emerged. It could be argued that the distance between the particle's impact and the measurement location was to short to clearly show the effect, but this requires furhter investigation.

Whether or not, the spot is generated by the wake of the particle can only be determined using flow visualisation techniques. In this regard, work is currently in progress.

6. Conclusion

(1) The available information to date regarding the impact of cirrus cloud on laminar flow technology is sparse, limited to special cases and partially outdated.

(2) Hot wire traverses of a laminar boundary layer over a flat plate in an airflow under the upstream impact of a suspended spherical particle at critical conditions were found to recapture the occurrence of a turbulent spot with good agreement when compared to previously published measurements.

(3) The critical particle Reynolds number, Re_p, at which a turbulent event can be produced by a spherical particle within the flat plate's laminar boundary layer is proposed by our hot film measurements to be considerably lower than previously published values.

(4) The differences are believed to be connected with several assumptions found in earlier studies, which are not appropriate to fully capture the impact of a freely in air suspended ice particle on a laminar boundary layer. Prior investigations on fixed particles assumed the top of the particle to be the critical side; however, in this scenario it should be the lower side (i.e. closest to the surface).

(5) These results conducted in air are considered to be more relevant than corresponding results obtained in water channels. This is due to the large density ratio that exists between air and ice; consideration of which is important to capture all mechanisms occurring in the process.

(6) The effect of the shear parameter on the reduction of the critical Reynolds number of a sphere should be accounted for. If the particle is sufficiently small compared to the local boundary layer thickness, the assumption of a uniform shear in close proximity to the surface is deemed to give a good approximation for a flat plate experiment.

7. Future Work

As proposed by Schmidt & Young [13], the extreme difficulties faced while trying to establish experiments that relate as close as possible to the real conditions encountered during flight, make it desirable to get further support from numerical analyses. Whereas trajectory data of sufficient accuracy could be determined from computations of a k-epsilon turbulence model of a commercial RANS package, this information could be used as in input for User Defined Functions, reflecting the inherently unsteady conditions 'seen' by a particle, in a Direct Numerical Simulation (DNS) approach, considering only the flow field in near proximity to the particle.

On the experimental side, the authors believe that useful information could be drawn from experiments where the particles are held at a fixed position and the surface to be investigated is moved instead. This could be done in appropriately equipped facilities, but also experiments on rotating cylinders could provide further insight into the problem. Besides achieving a considerable simplification of the experimental setup, the particle would experience a flow field similar to that occurring in reality as discussed in more detail in section 5.

Acknowledgement

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References

[1] Airbus Flying by nature – Global Market Forecast 2007-2026, Airbus S:A:A, 31707 Blagnac Cedex, France, 2007.

[2] Young, T.M. and Fielding, J.P. Potential Fuel Savings due to Hybrid Laminar Flow Control under Operational Conditions, *Aeronautical Journal*, Vol. 105 (1052), 2001, pp. 581-588.

[3] Schrauf, G. & Kühn, W. Future Needs and Laminar Flow Technology, *Air & Space Europe*, No.3/4, Vol. 3, May-Aug 2001, pp. 98-100.

[4] Arnal, D. & Archambaud, J.P. Laminar-Turbulent Transition Control: NLF, LFC, HLFC, *AVT 151 Lecture Series on Advances in Laminar-Turbulent Transition Modelling,* June 9-13, 2008, von Karman Institute for Fluid Dynamics, Brussels.

[5] Joslin, R.D. Overview of Laminar Flow Control, NASA TP-1998-208705, Langley Research Center, Oct. 1998.

[6] Boeing. *High Reynolds Number Hybrid Laminar Flow Control (HLFC) Flight Experiment*, NASA CR-1999-209325 / CR-1999-209326, Boeing Commercial Airplane Group, Apr. 1999.

[7] Henke, R. Airbus A320 HLF Fin Flight Tests, "Aerodynamic Drag reduction technologies:", *Proceedings of the CEAS, DragNez European Drag Reduction Conference*, 19-21 June 2000, Potsdam, Germany, edited by Thiede, P., Notes on Numerical Fluid Mechanics, Vol.76, Springer, 2001.

[8] Bieler, Dr. H. (comp.) HYLTEC – Hybrid Laminar Flow Technology - Synthesis Report, Airbus Deutschland GmbH, Bremen from Jan 1998 - Dec 2001, Apr 2003.

[9] Maddalon, D.V. & Braslow, A.L. Simulated-Airline-Service Flight Tests of Laminar-Flow Control with Perforated-Surface Suction System, NASA TP-2966, Langley Research Center, 1990.

[10] 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.

[11] Davis, Richard E. et al. Performance of Laminar Flow Leading Edge Test Articles in Cloud Encounter, NASA CP-1987-2487, Langley Research Center, 1987.

[12] Pfenninger, W. Design Considerations of Long-Range and Endurance LFC Airplanes with Practically All Laminar Flow, NASA Joint Institute for Advancement of Flight Sciences, Aug 1982.

[13] 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.

[14] Jasperson et al. GASP Cloud Encounter Statistics: Implications for Laminar Flow Control Flight, *Journal of Aircraft*, 1984.

[15] Young T.M., Brown, P.R.A., Fielding, J.P. The Impact of Cloud Encounter on Hybrid Laminar Flow Control Aircraft Operations, *CEAS Aerospace Aerodynamics Research Conference*, Cambridge, Paper 58, 10-12 June 2002.

[16] Roshko, A. On the Development of Turbulent Wakes From Vortex Stresses, NACA TR-1191, Langley Research Center, 1954.

[17] Sakamoto, H., Haniu, H. A study of Vortex Shedding from Spheres in a Uniform Flow, *J. of Fluids Eng*., Vol. 112, 1990, pp. 386-392.

[18] Sakamoto, H., Haniu, H. The Formation Mechanism and Shedding Frequency of Vortices from a Sphere in a Uniform Shear Flow, *J. Fluid Mech*., Vol. 287, 1995, pp. 151-171.

[19] Kiya, M., Tamura, H., Arie, M. Vortex shedding from a circular cylinder in moderate-Reynolds number shear flow, *J. Fluid Mech*., Vol. 101, 1980, pp. 721-735.

[20] Hall, G.R. Interaction of the wake from bluff bodies with an initially laminar boundary layer, *AIAA Journal*, Vol. 5, No. 8, pp. 1386-1392.

[21] Mochizuki, M.V. Smoke Observation on Boundary Layer Transition Caused by a Spherical Roughness Element, *J. Phys. Soc. of Japan*, Vol. 16, No. 5, pp. 995-1007.

[22] Lauchle, G.C. & Gurney, G.B. Laminar Boundary Layer Transition on a Heated Underwater Body, *J. Fluid Mech*., Vol. 144, 1984, pp. 79-101.

[23] Lauchle, G.C., Petrie, H.L., Stinebring, D.R. Effects of Particulates on the Delayed Transition of a Heated Body, Applied Research Laboratory Technical Memorandum 86-213, 1986.

[24] 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, 1995, pp. 305-312.

[25] 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, 1985, pp. 113-119.

[26] Petrie, H.L., Morris, P.J., Bajwa, A.R., Vincent, D.C. Transition induced by Fixed and Freely Convecting Particles in Laminar Boundary Layers, 1993, The Pennsylvania State University, Appl. Res. Lab., PA, USA.

[27] Schmidt, C. & Young, T.M. The Impact of Cirrus Cloud on Laminar Flow Technology, *7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, 18-20 Sep, Belfast, Northern Ireland, 2007.

[28] Guilleme, J. Study of the laminar-turbulent transitionin the trail of a particle bouncing on a wall with a laminar boundary layer, Internship Report, Department of Mechanical and Aerospace Sciences, University of Glasgow, 2008.

[29] Cantwell, B., Donald, C., Dimotakis, P. Structure and entrainment in the plane of symmetry of a turbulent spot, , *J. Fluid Mech*., Vol. 87, 1978, part 4, pp. 641-672.

[30] Wygnanski, I., Sokolov, N., Friedman, D. On the turbulent ‚spot' in a boundary layer undergoing transition, *J. Fluid Mech*., Vol. 78, 1976, pp. 785-819.