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Role of Laminar Flow in Aeronautics

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Abstract:
We study the laminar flow and laminar flow control, Benefits of Laminar flow control, Laminar Flow control design methodology, Manufacturing Tolerances, Suction and thermal laminar flow control, Laminar flow control (LFC) in high-speed boundary layer with the help of passive porous coating, applications of laminar flow control in aircraft operations.

I. Introduction

The Study of fluid mechanics goes back at least to the days of ancient Greece, when Archimedes investigated fluid statics and buoyancy and formulated his famous law known as The Archimedes principle. Evolution of Flow in different direction began when the French mathematicians Alexis claimant in 1740 and d'Alembut in 1752 discovered equations for third flow Their equations govern the velocity components u and v at point (x,y) in steady two dimensional flow

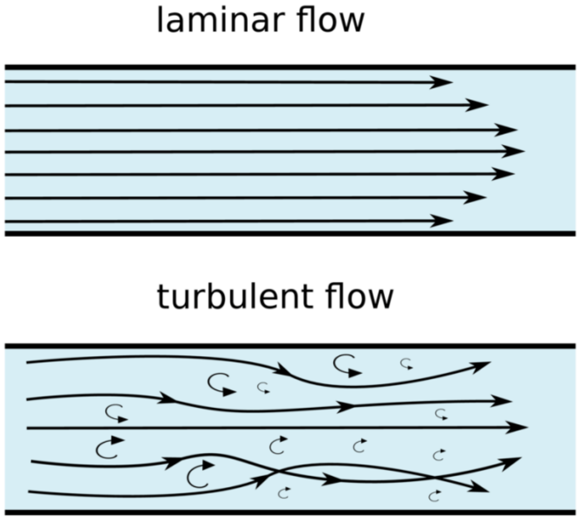
Fluid Flow plays a crucial role in a vast variety of natural phenomena and manmade systems. The life cycle of stars, the creation of atmospheres, the sounds we hear the vehicles we ride, the system we built for flight, energy generation and propulsion all depend in an important way on the mechanics and thermo dynamics of fluid flow. The purpose of this topic is to introduce us to the Aeronautics and astronautics to the fundamental principle of fluid mechanics with emphasis of Laminar flow control.

II. Laminar Flow

A type of fluid flow in which the fluid travels smoothly or in regular paths. The fluid in contact with the horizontal surface is stationary but all other layers slide over each others.

Laminar Flow occurs at lower velocities below a threshold at which the flow becomes turbulent. The velocity is determined by a dimensionless parameter characterizing the flow called the Reynolds number which also depends on the viscosity and density of the fluid and dimensions of channel. Laminar Flow or streamline flow in pipes occurs when a fluid flow in parallel layers with no disruption between the layers. At low velocities the fluid tends to flow without lateral mixing and adjacent layers slide past one another like playing cards,for example, the flow of air over an aircraft wing, the boundary layer in very thin sheet of air lying over the surface of the wing. Because air has viscosity, this layer of air tends adhere to the wing.

A common application of laminar flow is in the smooth flow of a viscous liquid through a tube or pipe. In that case the velocity of flow varies from zero at the walls to maximum along the cross sectional Centre of the vessel. The flow profile of laminar flow in a tube can be calculated by dividing the flow into thin cylindrical elements and applying the viscous force to them.



Turbulent flow is a type of fluid flow in which the fluid undergoes irregular fluctuations or mixing in contrast to laminar flow. In turbulent flow the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction

III. Laminar Flow Control

This over views the state of the art of laminar flow control (LFC), laminar flow control (LFC) research began in the year 1930s and flourished through the 1960s. During the 1970s when the OPEC embargo caused a fuel shortage and drove costs up, laminar flow control(LFC) research became important again because of the aerodynamic performance benefits it could potentially produce for Commercial aircraft. The next 20 years of research resulted in numerous significant achievements in both the wind tunnel and flight.

Laminar Flow Control is an active boundary layer flow control technique employed to maintain the laminar flow state at chord Reynolds numbers beyond those that are normally characterized as being transitional or turbulent in the absent of control.This definition is an important first step towards understanding the goals of this technology.

A significant advancement made in the development of laminar flow control (LFC) in the technology of Hybrid Laminar Flow control (HLFC), HLFC integrates natural laminar Flow (NLF) with Laminar flow Control (LFC) to reduce suction requirements and system complexity. Natural laminar flow employs favorable pressure gradient to delay the transition process is sweep limited, and usually has poor off design cruise aerodynamic performance, Laminar flow control is complex, involving suction over the whole wing chord.
The key features of Hybrid laminar flow control are :

a) Suction is required only in the leading edge region ahead of the front spar.
b) Natural laminar flow is obtained over the wing through proper tailored of the surface geometry.
c) The hybrid laminar flow has good performance in the turbulent mode.

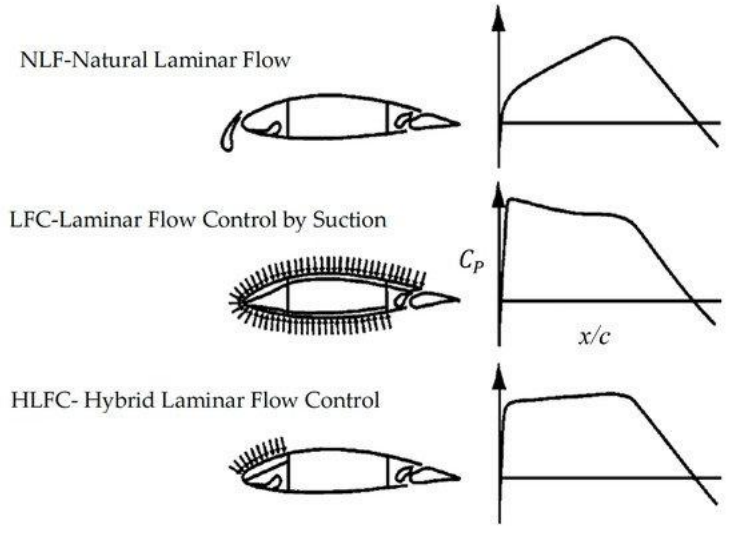
3.1. Benefits of Laminar flow control

A Study have shown that skin friction drag could amount to about 50% of the total drag for a subsonic transport aircraft. Total drag is the function of the aircraft size. Since laminar skin friction can be as much as 90% less than turbulent skin friction at the same Reynolds number. it is obvious that laminar flow would be more desirable than turbulent flow for reducing the drag of aerodynamic vehicles.

But achieving laminar flow over the entire configuration is not possible because of the sensitivity of laminar flow to external and vehicle disturbance. However drag reduction generated by laminar flow can be achieved.

Aerodynamic performance benefits brought by skin friction drag reduction can translate into reduced operating costs of an aircraft. There is a lot of impact of fuel cost on laminar flow control benefits. Essentially 5 to 8% of fuel cost can be reduced.

Besides fuel savings and reduced emissions and noise, laminar flow Control leads to reduced aircraft size because of reduction in fuel.which leads in total aircraft operating costs. The fuel saving resulting from LFC would enable an aircraft to extend its operating range.



Schematic of NLF, LFC, and HLFC concepts for wing . Diagrams show suction locations and surface pressure coefficient (Cp) versus chordwise extent (x/c).

3.2. Laminar Flow control design methodology

For a laminar flow control design the analysis begins by defining an initial wing geometry. With wind geometry defined the wing pressures and velocities can be obtained by using transonic wing theory or computational fluid dynamics. The inverse approach of prescribing a target pressure distribution and solving for the wind geometry is then used. After obtaining the external flow field for the final geometry, boundary layer and stability theory calculations are used to determine the suction flow rates and distribution for the desired transition location. With the suction flow rate determined from boundary layers stability considerations, the pressure drop through the skin must be set to obtain a reasonable subsurface Compensation Scheme and perforation spacing distribution for the desired suction distribution. Finally the suction system ducting and compressor specifications are prescribed.

Besides the design procedure, other information that must be understood for laminar flow control (LFC) design includes

a) The impact on surface tolerance,
b) Slot suction, porous & perforated suction and thermal laminar flow control
c) The methodology and limitations of transition prediction

3.4 Manufacturing Tolerances

As discussed, investigations in the 1930s recognized that small roughness and waviness at high Reynolds numbers could reduce the laminar flow extent. The stringent surface smoothness and waviness criteria (tolerances) for laminar flow posed a major challenge for research in the 1950s and 1960s. A partial explanation for the demise of subsonic laminar flow control(LFC) in the 1960s was the severe surface manufacturing tolerances required to achieve laminar flow .

However, manufacturing technologies of the 1990s have matured to the point that surface-definition tolerances are readily achievable. For laminar flow control design, Braslow et al (1990) gives formulae for manufacturing tolerances. Flight and wind-tunnel tests have provided our current understanding of the mechanisms that cause transition to move forward because of surface imperfections. The impact of a surface imperfection (such as a rivet head) on the transition location can be viewed either by looking at the transition location as a function of imperfection size for a fixed unit Reynolds number, or by keeping the size of the imperfection fixed and looking at transition location as a function of unit Reynolds number.

In either case, the imperfection stimulates engine modes in the boundary layer; the linear stability of the flow dictates whether these modes will grow or decay as they evolve in the flow. However, as the height of the imperfection or unit Reynolds number increases, a point is reached when flow separation occurs because of the surface imperfection. At this point, inviscid instability arising from the inflectional velocity profile can grow and induce transition, if the imperfection is sufficiently large, linear instability amplification is by passed and transition follows by way of a non-linear process. Finally, our current understanding of imperfections suggests that larger critical step heights can be realized using rounded steps, because a reduced region of separation and a reduced inflectional instability growth are encountered in the experiments. Based on our understanding of the flow associated with a surface imperfection, we summarize that

a. A local separation region caused by the surface imperfection can induce transition;
b.The local adverse pressure gradient caused by the surface imperfection could cause amplification of TS disturbances and decrease the laminar flow extent;
c. The beneficial stabilizing influence of compressibility on TS disturbances opposes the detrimental increase in amplitude of the pressure disturbance caused by compressibility near the surface imperfection;
d. The critical wave height decreases with increased number of waves; and
e. Forward-facing rounded steps can increase the critical step height compared with forward-facing square steps.

This section ends with a brief mention of innovative tools used to estimate the influence of a surface imperfection on laminar flow extent. Interacting boundary-layer theory (which accounts for viscous-inviscid interaction) coupled with linear stability theory can be used to establish parameters for allowable surface imperfections for maximizing laminar flow extent while minimizing constraints put on manufacturing.

IV. Suction And Thermal Laminar Flow Control

For subsonic and transonic flight Mach numbers the feasibility and potential benefits of laminar flow control by suction have been demonstrated in several wind tunnel experiments already. There have been several successful wind tunnel experiments on laminar flow control by suction.

In most of these experiments suction was applied through slits or drilled micro holes. Suction can delay laminar-turbulent transition because it changes the shape of the laminar boundary layer such that the overall growth of those disturbance which finally Triggers the breakdown of the laminar boundary layer is reduced.

Even if there is no premature transition, the increased geometrical roughness of the suction panel and the non-uniformity of the suction may introduce additional disturbances at increased initial amplitude into the laminar boundary layer on the other hand. Therefore the reduction of total disturbance growth by suction usually is at least partly compensated by an increased amplitude level in the initial disturbance spectrum. Often so called N-factor methods are used for transition prediction.

The application of such N factor methods for transition prediction requires their prior calibration suitable empirical parameters are determined.

Since N factor methods estimate the transition location from the computed total linear disturbance growth inside the laminar boundary layer, only the negative effects of suction described above are not taken into account directly and have to be modeled instead by an adequate reduction of the transition N factor values. Consequently, for realistic estimates on the actual benefits achievable by laminar flow control using suction information on the reduction of the transition N-factor.

Thus the objectives of the suction & thermal flow control are-

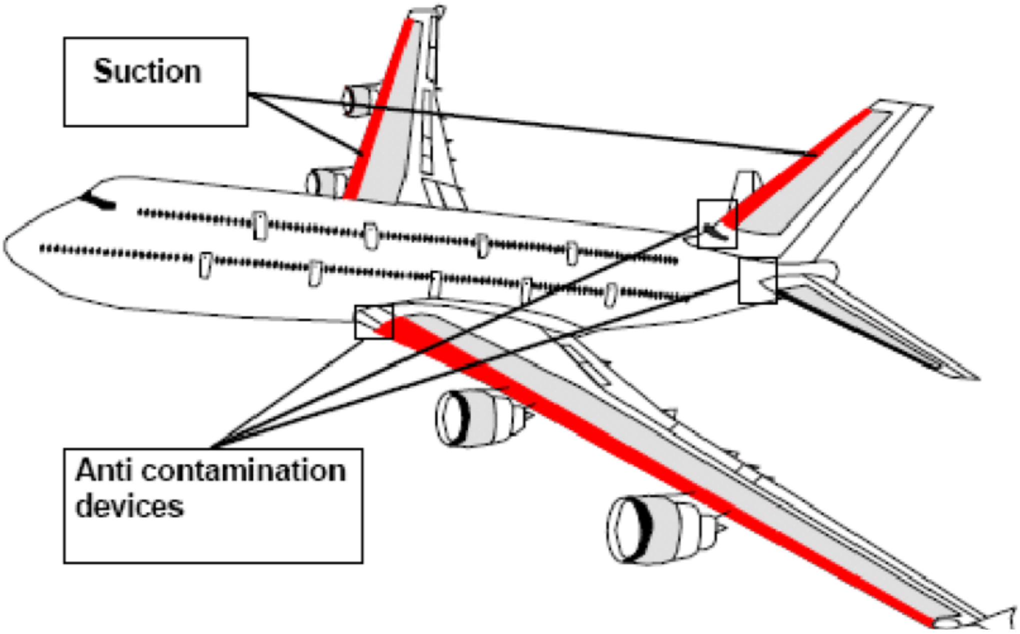
a. To demonstrate the feasibility of laminar flow control by suction performed in small wind tunnel with rather low operation cost
b. Successfully delay laminar-turbulent transition
c. Test the potential of suction panel
d. Determine the cross flow transition N-factors with and without suction.

Mac Manus and Eaton performed three dimensional Navier stokes simulations of suction through holes. The simulations showed that

a. irregularities of the hole shape had minimal effect on the induced flow
b. It was undesirable to have holes inclined to the surface
c. The flow field at the hole in let was highly three dimensional
d. The pressure drop and mass flow rate were insensitive to the hole inlet shape.
e. Significant interphone flow field effects existed for multiple rows of holes

Besides the suppression of disturbance growth by suction, cooling can be used to suppress disturbances.

Laminar flow control (LFC) concepts of the future must trade off the benefits of various boundary layer control concepts, including HLFC suction on the leading edge with either strips of perforated suction control or thermal control which furthermore radius the costs associated with manufacturing these systems.



Showing suction location

V. Transition prediction design tool methodology

The LFC design of an aircraft requires an accurate prediction of the amount of laminar flow or the accurate prediction of suction distribution for a given target transition location. This described conventional and advanced transition prediction tools. Some of which include prediction of perturbations, and the linear and non linear propagation of these perturbations which ultimately leads to transition.

The instability characteristics of the infinite swept wing laminar boundary layer without and with suction were studied both by classical linear local instability theory and by nonlocal theory based on linear parabolized stability equation (PSE).

In local theory a parallel flow assumption is made thus, ordinary differential equations have to be solved. Moreover, the curvature of the model surface is usually neglected. The PSE approach on the other hand takes into account both surface curvature and stream wise variation of the boundary layer. The resulting partial differential equations are solved by a marching procedure starting from an initial solution obtained by classical local theory. For transition prediction the e^Nmethod was used in which the N factor is defined as $N(x)=\int_{XI}^{X}\sigma$ (x) dx

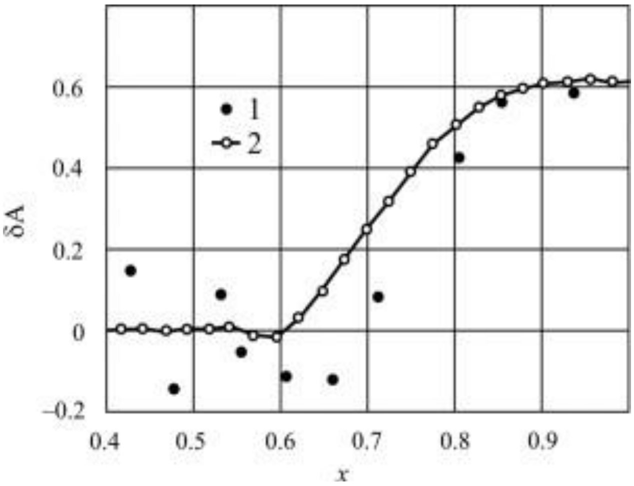
Where σ represents the disturbance growth rate obtained have either from local or non local theory. The disturbance growth rate is integrated in chord wise direction starting from the chordwise position $x_I$where the disturbance is given frequency f and a given span wise wave number β becomes unstable for the first time.

In the N factor integration strategy applied here, disturbance frequency and span wise wave number are kept constant while integrating/marching in chords direction. Both frequency f and wave number are varied systematically.

Laminar turbulent transition is assumed to occur at the chord position where a certain N-factor value, the transition N-factor, is exceeded for the first time for any (f, β) Combination. This value of transition N-factor does not only depend on N-factor integration strategy used but also needs to be calibrated for each wind tunnel separately.

VI. Laminar flow control (LFC) in high-speed boundary layer with the help of passive porous coating

In a high-speed predominantly two-dimensional boundary layer both the first (Tollmien–Schlichting waves) and the second (high-frequency acoustic) modes of disturbances can dominate. At large enough local Mach numbers (approximately Me≥4 for boundary layer on heat-insulated surface without external pressure gradient) the second mode becomes dominant. Surface cooling destabilizes the second mode in contrast to the first one. As the surface temperature of the typical high-speed flight vehicle is essentially lower than the temperature of the heat-insulated wall, instability of the first mode is suppressed naturally whereas the second mode grows faster and can lead to rather early transition to turbulence. In this case for an increase in extent of a laminar site it is necessary to stabilize disturbances of the second mode. The assumption has been stated that the passive porous coatings absorbing high-frequency acoustic disturbances (ultrasound) can effectively stabilize such instability. This hypothesis further has been confirmed both by theoretical and experimental researches executed in the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Science . At TsAGI the stability of the hypersonic boundary layer (at freestream Mach number $M\infty=5.95$) on a sharp cone with a porous coating which absorbs high-frequency disturbances was considered by I.V. Egorov et al. This research was carried out on the basis of numerical solutions of the non-stationary Navier Stokes equations. Results of calculations have been compared with experimental data and with results of the linear stability theory.



Boundary layer stabilized by porous coating

VII. Applications Of Laminar Flow Control In Aircraft Operations

Crucial to maintaining LF in flight, the accumulation of ice, insects, or other debris must be prevented or minimized. Such accumulation would cause a surface imperfection and potentially degrade the amount of LF. Whereas anti icing systems have been operational for many years on the leading edge of wings and on nacelles, only limited research results for realistic insect-prevention systems are available.

1 Insect Contamination

The impact of insects on an aircraft is a function of the population density of insects (or insects per volume) and of temperature, moisture, humidity, local terrain, vegetation, climate, wind speed, altitude, and vehicle surface shape.

Glick (1939), Coleman (1961), and Croom& Holmes (1985) showed that the highest density of insects was measured at low altitudes (near the ground), with the number of insects decreasing rapidly with increased altitude. Recent flight results of Croom& Holmes (1985) indicated that the largest insect accumulation occurred near 75◦F in 4- to 8-mph winds and rapidly decreased in cooler and hotter temperature ranges. These results are consistent with the early studies of Glick (1939) and Coleman (1961). Coleman (1961) noted that no consistent correlations for insect population density have been identified for barometric pressure, humidity, light intensity, precipitation, or the electrical state of the atmosphere. The accumulation of insect debris on the leading edge of laminar wings has been recognized as one of the most significant operational concerns associated with laminar flow. The threat of contamination is typically limited to operational phases close to the ground.

Based on estimations by Humphreys [24] 50-60% of the insects are collected during the ground run and the balance at low altitude during climb out, final approach and landing. At altitudes above 1,000 ft contamination is normally negligible. During the critical phases the aircraft speed is high enough to cause a rupture of the insect body. These remaining debris create three dimensional roughness elements in the boundary layer, which disrupt the laminar flow and may cause premature transition due to turbulent wedges behind the surface disruption.

To generate turbulent wedges, insect residue must exceed a critical height, which is a function of insect size, impact angle and impact speed . Additional factors that define the critical height are the Reynolds number and the relative position of the residue on the wing (state of the boundary layer) . Depending on these factors the share of critical insects on overall contamination is about 9-25% . The appearance of insects in the atmosphere is generally coupled with factors like season, local terrain, altitude, temperature, humidity and wind speed .Hence, the problem of insect contamination is expected to have distinct regional and seasonal character.

Elsenaar and Haasnot conducted a field study at Schiphol Airport to analyze these effects in more detail . Within a time period of one year, weekly visual inspections on eight aircraft were performed in order to quantify the number of insects on the aircraft leading edges. All aircraft were operated in normal airline service on short-to-medium haul missions within a European network. It becomes obvious that contamination is strongly varying with season. During the warm summer months a global maximum is reached, with two local maxima in May and August. In the winter period contamination appears to be no problem. Based on the study it can be assumed that contamination within the European region is limited to approximately 35 weeks per year. However, due to the geographic character of the samples, the data can only be used in a limited way to derive a universally valid contamination model and contamination rates. In practice, the contamination level and the repercussive effects on flight performance of an aircraft with no insect protection actions will also depend on the utilization profile of the aircraft (flight cycles per day) as well as the contamination rate per flight cycle.

During normal flight operations the aim should be to keep the contamination level as low as possible in order to achieve maximum fuel savings. However, an intensive utilization profile with short turn-around times may not allow for leading edge cleaning between frequent landings. Surface cleaning between each flight seems also to be an unfavorable solution by airlines , since this could cause longer turn-around times which may lead to a reduced aircraft utilization. For this reason, a creeping deterioration of flight performance must be expected from flight to flight. The techniques to either eliminate or prevent insect contamination include

a. Mechanical scrapers that scrape the surface free of insects;
b. Deflectors that either catch the insects or cause their paths to be deflected away from the surface;
c. Paper covers that cover the surface until sufficient altitude is reached and the cover is either released or extracted into the aircraft (leaving a clean surface for cruise);
d. A cover dissolved by fluid discharge and removed by a thermal process or carried away in flight by the high shear; and
e. Continuous liquid discharge.

For each anti insect device, a weight-and-system–complexity penalty arises. Of the techniques tested, paper coverings, continuous liquid discharge, and deflectors have been demonstrated in flight to prevent the loss of LF owing to insect accumulation. Gray & Davies (1947) with the King Cobra flight test, Head et al (1955) with the Vampire porous-suction flight test, Groth et al (1957) with the F-94 slot-suction flight test, and Runyan et al

(1987) with the B-757 NLF flight test have successfully used the paper-cover concept to protect the test section from insect accumulation during takeoff and climb. Peterson & Fisher (1978) and Maddalon&Braslow (1990) with the Jetstar aircraft and Croom& Holmes (1985) with the Cessna 206 showed that continuous spray could be effective in preventing insect accumulation. Maddalon&Braslow (1990) with the Jetstar and Collier (1993) with the B-757 indicated that the Krueger insect shield was effective in deflecting the insects from the LFC test region.

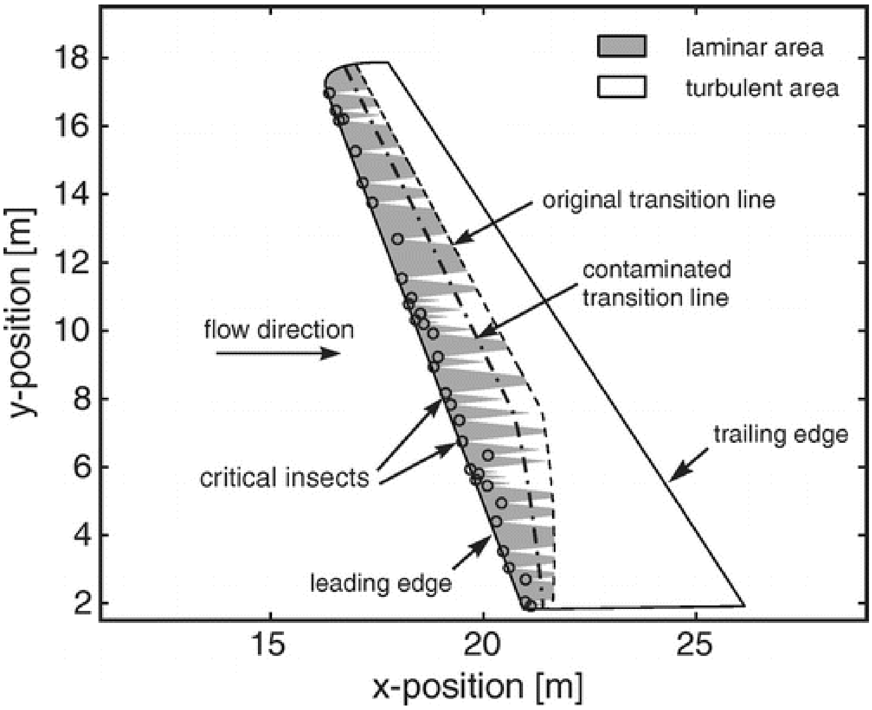


Figure 5: Impact of insect contamination on laminar flow

2. Ice Accumulation and Atmospheric Effects

The accumulation of ice on the leading edge of wings can significantly alter wing geometry and cause drag and performance degradation. Furthermore, atmospheric effects—including gusts, rain, clouds, and pollution—can potentially degrade LFC aircraft performance. Similar to a non-LFC aircraft, an LFC-type aircraft must account for potential ice accumulation and prevent such a detrimental and dangerous encounter by the use of anti-icing techniques—either by applying heat or by dispelling antifreeze agents.

The icing issue for NLF and LFC is more of a system design problem than a technical obstacle to achieving LF. Concerning atmospheric effects, loss of LF had been reported during cloud encounters for the X-21 (Hall 1964), the F-94 (Groth et al 1957), and the Jetstar (Maddalon&Braslow 1990) LFC flight tests. In an F-14 NLF flight experiment, Anderson & Meyer (1990) showed that turbulent bursts were measured during cloud encounters. During these encounters and loss of LF, the charge patch indicated the presence of ice particles.

In all of the above flight experiments, LF was soon regained after emerging from the cloud. Also, LF was maintained in moderately gusty weather; however, strong atmospheric turbulence levels led to a loss of LF. Finally, Smith &Higton (1945) reported the impact of rain, dust, flies, and surface-finish polish on the flow during King Cobra flight tests. Drag results from dust and water accumulation showed no deviation compared with smooth clean-surface drag measurements.

3. Operational Maintenance of Laminar Flow

Laminar flow research in the 1940s through the 1960s had difficulty retaining surface smoothness specifications during the day-to-day operations of NLF and LFC flight test aircraft. However, manufacturing techniques have improved for aircraft in the 1990s, and operational maintenance problems of the past are no longer a major concern. Aside from surface-quality maintenance issues, Meifarth& Heinrich (1992) presented a list of operational issues related to achieving and maintaining NLF and LFC. Some of the issues included the need for additional spare parts and maintenance as a result of the suction system, uncertainties in the potential contamination resulting from pollution residue on the structural surface, and operational planning for suction-system failure. Clearly, the literature attests to the awareness that an operational plan for an LFC aircraft must account for many of these issues, and Robert (1992) stated that LFC brings benefits even after the penalties (system and operational) are factored into the costs.

VIII. Conclusion:

1. The air travel industry is facing the environmental and economic pressures, that can reduce by . this process. it is important to achieve greater performance of future aircraft using laminar flow control.
2. From an environmental point, reducing fuel burn is the greatest long-term priority, the expectation that future fuel prices will be sustained at substantially higher levels in real terms than at any time in the past. The need to reduce fuel burn is arguably greater now than it has ever been.
3. Much progress has been accomplished toward the goal of commercial incorporation of LFC (and NLF) on wings, tails, and engine nacelles.
4. Finally, significant additional benefits (reduced part count and distributed arrays) could be bought with LFC if new innovative suction systems could be developed and tested. Such futuristic concepts can be found in the embryonic technologies of active flow control.

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