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Sublimating Chemical Technique for Boundary-Layer Flow Visualization in Flight Testing

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With the introduction of modern aircraft utilizing laminar flow, flow visualization has become an important diagnostic tool in determining aerodynamic characteristics such as surface flow direction and boundary-layer state. Oil flow and sublimating chemical techniques are discussed, and the use of sublimating chemicals is examined in detail. Oil is used to visualize boundary-layer transition location, shock-wave location, regions of separated flow, and surface flow direction. Sublimating chemicals are used to visualize both the location and mode of boundary-layer transition. The different modes of transition are characterized by different patterns in the developed sublimating chemical coating. The discussion includes interpretation of these chemical patterns and the temperature and velocity operating limitations of the chemical substances. Information for selection and application of appropriate chemicals for a desired set of flight conditions is provided.

Nomenclature

a,b,c = constants used in determining vapor pressure
g_s = rate of transfer of mass from unit area of surface, oz/s-ft^2
K = recovery factor
K_g = local mass transfer coefficient
m = molecular weight of a substance
m_∞ = molecular weight of the freestream
M = Mach number
p = static pressure, mm Hg
p_s = absolute vapor pressure, mm Hg
p = freestream static pressure, mm Hg
R = gas constant
R' = unit Reynolds number, ft^{-1}
T = freestream temperature, °C or °F
T_{aw} = adiabatic wall temperature, °C or °F
U = freestream velocity, fps
γ = specific heat ratio, $\gamma = 1.4$
ρ = density of diffusing vapor, slugs/ft^3
ρ_∞ = freestream density, slugs/ft^3
ψ = concentration, ρ/ρ_∞
ψ_∞ = concentration in the freestream
ψ_s = concentration corresponding to saturation
Λ = leading-edge sweep angle, deg

Introduction

PAST flight research has made extensive use of flow visualization for determining aerodynamic characteristics, such as boundary-layer state (laminar, transitional, turbulent, or separated), shock wave location, and surface flow direction. Measurement of these characteristics becomes important to the aerodynamicist with the introduction of modern smooth aircraft surfaces which are compatible with laminar flow requirements. Flow visualization can be used for determining the boundary-layer transition characteristics while supplementing other analytical measurements for validation of aerodynamic design behavior.

Several techniques have been developed for in-flight flow visualization, including sublimating chemicals[1,2] and oil flow.[3] Each technique has its own advantages and disadvantages. The oil flow technique can provide information for a wide variety of flow conditions, from boundary-layer transition to flow separation and shock wave location. At the same time, oils can be very messy and must be viewed during flight. The sublimating chemical method provides a detailed pattern of boundary-layer transition that can be examined on the ground following the flight test. Whereas oil flow can show regions of laminar and turbulent separation, sublimating chemicals are far more useful for determining transition modes, including crossflow and Tollmien-Schlichting types of instabilities, as well as laminar separation.

The purpose of this paper is to describe the sublimating chemical technique for flow visualization. A method for selecting appropriate chemicals based on a set of flight conditions is provided. A brief description on the use of oils for flow visualization is included. The advantages of both flow visualization techniques for testing modern aircraft are discussed.

Sublimating Chemicals

Description of Technique

The chemical sublimation method for indicating boundary-layer transition was developed at the Royal Aircraft Establishment by W. E. Gray in 1944.[1] Originally devised for low-speed wind tunnel testing, the method was extended to aircraft in flight with the introduction of more durable coating materials. The sublimation method has the advantages of simplicity, rapidity, low cost in operation, and ability to provide a very detailed graphic record of the transition from laminar to turbulent flow over the surface. For many flight applications, the chemical pattern developed at the desired test condition can be viewed on the ground following the flight. The method has been effective at subsonic speeds for temperatures down to −20°F and altitudes up to about 20,000 ft and at supersonic speeds up to Mach 2 for temperatures down to −55°C and altitudes up to 55,000 ft.[4]

The sublimation method for indicating boundary-layer transition involves coating the surface to be observed with a very thin film of a volatile chemical solid. During exposure to a freestream airflow, areas develop in which the chemical film sublimates more rapidly due to greater local shear stress within the boundary layer, as depicted in Fig. 1. Greater rates of sublimation will occur in regions of high shear stress or skin friction such as that found in turbulent flow. The regions near

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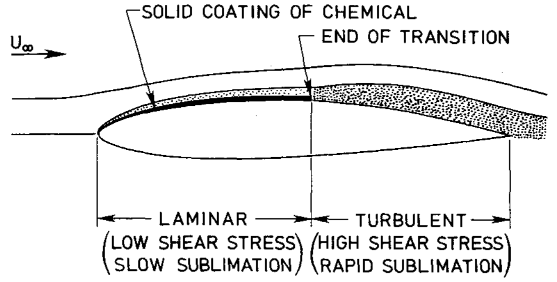


Fig. 1 How sublimating chemicals indicate boundary-layer transition.

Table 1 Practical sublimating chemicals for transition visualization

Chemical substance	Chemical formula	Molecular weight
Naphthalene	$C_{10}H_8$	128.17
Biphenyl	$C_6H_5C_6H_5$	154.21
Acenaphthene	$C_{10}H_6$-1,8-CH_2CH_2	154.21
Fluorene	$C_6H_4CH_2C_6H_4$	166.22

stagnation on the surface will also see high shear stresses and hence greater rates of sublimation. It is the stress-induced heating that produces the rates of sublimation.

There are several criteria necessary for the coatings to remain solid, opaque, and durable at temperatures for which transition indications are obtained and examined. The chemicals must have high melting points, be resistant to moisture, have no adverse effects on surface finishes, have low vapor pressures for aerodynamic use, and be soluble in a fast evaporating carrier. These considerations restrict the possible compounds to solids with melting points above 50°C, of low or medium molecular weights, and with high hydrogen content. The types of solid compounds suitable are hydrocarbons, esters, alcohols, ethers, ketones, acylamines, and azohydrocarbons.[2] Another consideration for selecting appropriate chemicals is safety from health hazards associated with the use of such compounds. Four useful compounds which meet these requirements and provide a practical range of operating characteristics (sublimation rates) are naphthalene, biphenyl, acenaphthene, and fluorene, listed in Table 1. An added feature of fluorene is its fluorescent properties, which makes it possible to obtain high quality photographic transition pattern data by using ultraviolet lighting.

The solvents used must be of low toxicity, low corrosiveness, and be highly volatile. Water and the low-volatility alcohols have insufficient vaporizing characteristics to be used as solvents. Some of the esters which are low in toxicity are corrosive to metals in long-term use. The solvents found to be most suitable are acetone and light petroleum fractions, such as 1,1,1 trichloroethane and trichlorotrifluoroethane (Freon TF). The requirement for a highly volatile solvent is a result of the process by which the sublimating chemicals are applied to the surface. A technique called "dry-spraying" is used whereby the chemical solute is dissolved in the solvent and the solution is sprayed onto the surface. It is necessary that the solvent be almost completely evaporated before the spray solution has time to wet the surface, leaving the sublimating chemical coating on the surface.

The chemical is applied to the test surface by compressed-air spraying. A solution of eight parts solvent to one part solute (by volume) has been found to be nearly optimum for uniform application. The solution is ready for spraying when the solute has completely dissolved. When using standard compressed-air spray equipment, good control in uniform thickness of the chemical coating is best achieved using a spray gun with a flat fan nozzle of minimum size orifice and needle (orifice diameter between 0.030 and 0.040 in.). Spraying is done using about 25 psi air pressure, for either siphon feed or pressure feed equipment. If pressure feed equipment is used, the reservoir pressure should be about 5 psi. The spray nozzle should be held between 10 to 20 in. from the surface being coated for proper dry-spraying. Proper spray technique will produce a powdery matt appearance of the chemical coating; when the spray goes on too wet the coating appears crystalline. After spraying, the chemical coating is brushed with a large soft bristle brush, wiped with cheesecloth, or rubbed with a rubber-gloved hand to loosen chemical particles which can adhere to the coating and cause turbulent wedges.

A standard rate of chemical solution application is one quart per 20 to 30 ft^2. At the application rate of one quart per 20 ft^2, a very heavy coating will result. Depending on temperature and airspeed, such a coating thickness has a sufficiently long reaction time to permit ample offcondition flight time for takeoff, climb, descent, and landing without affecting the chemical pattern developed at the test condition. This feature permits transition data to be observed and recorded on the ground, following the flight. Extra thick coatings can be applied by brushing the surface between repeated applications of a "standard" thickness. This technique can be useful for thick applications of rapidly sublimating chemicals to extend the allowable offcondition time for climb to high altitude test conditions, for example.

During the test flight, airspeed and altitude should be held as long as needed to obtain a transition pattern. If the fuel burn at the test condition changes airplane weight by more than about 10%, a speed schedule should be worked out to keep the airplane lift coefficient constant (for conditions where compressibility can be ignored). For high-speed tests where compressibility is a factor, an altitude schedule should be flown to maintain a constant Mach number at constant indicated airspeed. For most flight measurements of transition using the sublimating chemicals, response time is sufficiently rapid that constant speeds and altitudes can be flown and weight changes have an insignificant effect on transition location.

An intentional boundary-layer trip, such as a very small piece of tape located within 6 in. of the leading edge, is useful for indicating the rate of transition pattern development in the chemical coating. When the chemical pattern appears mature, the descent and approach should be flown as near to the indicated test speed and as close in to the landing as is safe. Since at most test conditions of interest, pattern development times are greater than 10 min, ample time is usually available for normal approaches and landings.

In order to provide quality photographic reproduction of the developed chemical pattern, it is recommended that the test surface be painted a dark, contrasting color. Flat black works extremely well as a contrast to the white chemical. When the surface color cannot be contrasting to the chemical, coloring can be added to the solution prior to spraying. Food coloring has worked well to enhance the contrast on white surfaces. Fuel dyes have also been used; however, they tend to leave a slight coloring on the test surface.

Selection of Chemicals

Selecting an appropriate chemical for a given flight condition requires an understanding of the chemical process involved. The rate of sublimation is simply the rate of transport of a foreign gas through the boundary layer. Thus, the rate of mass transfer will depend on the surface concentration of the diffusing gas. The sublimation rates can be approximated by considering the relationships between diffusion, heat transfer, and skin friction. This paper covers only the principle equations for predicting sublimation rates; a more detailed analysis appears in Ref. 5.

The rate at which mass is transferred across a unit area of the surface, g_s, is given by

$$g_s = K_g \rho_\infty U_\infty (\psi_s - \psi_\infty) \qquad (1)$$

where K_g is the local mass transfer coefficient, ρ_∞ and U_∞ are the freestream density and velocity, and ψ_s and ψ_∞ are the foreign gas concentrations at the surface and the freestream, respectively. The concentrations can be represented by the general form

$$\psi = \frac{\rho}{\rho_\infty} \tag{2}$$

where ρ is the density of the diffusing vapor. For the sublimation process occurring in air, ψ_∞ can be taken as zero; however, determination of ψ_s is less obvious. There are two stages for the sublimation of a substance into a stream of air.[5] The first stage is purely molecular and takes place in a very thin layer near the surface. It involves a continuous evaporation and recondensation of gas molecules in the surface layer of chemicals. The second stage can be represented by the diffusion through the boundary layer of those molecules which escape from the surface layer. The number of molecules that do escape can be determined by the difference between the partial pressure of the vapor at the surface and the saturation pressure. It has been shown[5] that the concentration at the surface corresponds closely to saturation. This can account for the fact that relatively smaller amounts of molecules are carried away from the surface, as compared to the larger quantity evaporating and recondensing in the surface layer. For the sublimation of substances used for boundary-layer observation, the concentration at the surface can be approximated by

$$\psi_s = \frac{m p_s}{m_\infty p_\infty} \tag{3}$$

where m, m_∞ are the molecular weights of the substance and the air, respectively, p_s is the absolute vapor pressure, and p_∞ is the freestream static pressure.

Combining Eqs. (1) and (3) and the assumption that $\psi_\infty = 0$, the rate of sublimation can be rewritten as

$$g_s = K_g \rho_\infty U_\infty \left(\frac{m}{m_\infty}\right)\left(\frac{p_s}{p_\infty}\right) \tag{4}$$

Using the ideal gas law yields to rearrange Eq. (4).

$$g_s = \frac{K_g}{R}\left(\frac{m}{m_\infty}\right)\frac{U_\infty p_s}{T_\infty} \tag{5}$$

For most liquids and solids, the variation of vapor pressure with temperature will follow the Clasius-Clapeyron law and is expressed as

$$\log_{10} p_s = -52.23\frac{a}{(T_\infty + b)} + c \tag{6}$$

where p_s is the vapor pressure in mm Hg at temperature T_∞ in °C and a, b, and c are constants for a particular substance. Approximate values of a, b, and c for the four solids selected as suitable boundary-layer transition indicators are taken from Refs. 6 and 7 and are reproduced in Table 2. It must be mentioned here that values of p_s for a particular substance are not always consistent from one source to another. Some of these differences result from the difficulty of determining very low (at $T_\infty < 0°\text{C}$) vapor pressures. Figure 2 shows the relation between vapor pressure and temperature from Eq. (6) over a range of temperatures compatible with flight operations.

Table 2 Vapor pressure constants for selected sublimating chemicals

Chemical substance	a	b	c
Naphthalene	30.759	187.22	6.846
Biphenyl	53.942	273.10	8.221
Acenaphthene	54.279	273.10	8.033
Fluorene	56.615	273.10	8.059

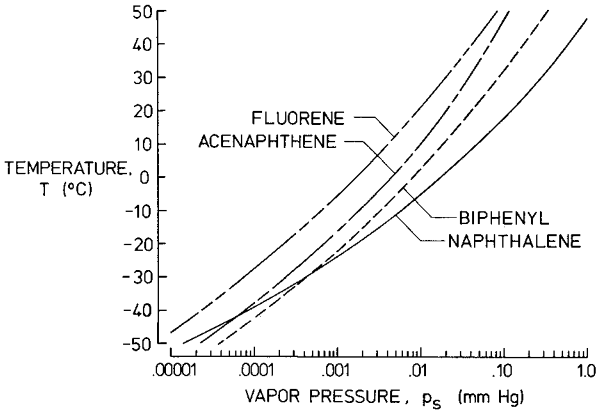
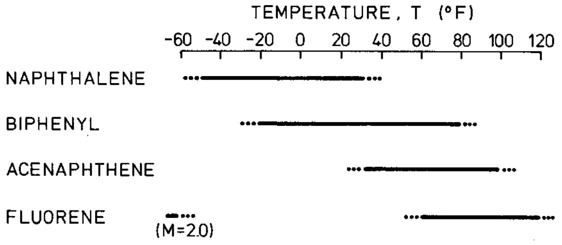
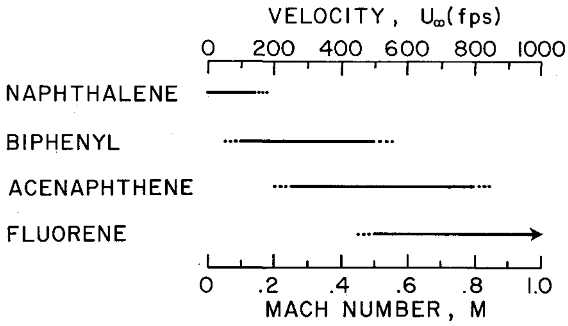


Fig. 2 Vapor pressures of sublimable solids.



• SUBLIMATION RATE IS ALSO PROPORTIONAL TO DYNAMIC PRESSURE (SKIN FRICTION)

Fig. 3 Temperature operating ranges for selecting sublimating chemicals.



• BASED ON SEA LEVEL STANDARD DAY CONDITIONS

Fig. 4 Velocity operating ranges for selecting sublimating chemicals.

For first approximations, the local mass transfer coefficient K_g is proportional to the local skin friction. In regions of high skin friction, such as near the stagnation or attachment line, or in the turbulent boundary layer, values of the local mass transfer coefficient will also be high. A complete description and analysis of this mechanism is available in Ref. 5.

Based on past flight experiments, a practical summary is provided in Figs. 3 and 4 to guide selection of suitable chemicals for given test conditions. These recommendations will allow reasonable times for chemical pattern development at the test conditions and still provide adequate time for offcondition (climb and descent) portions of a flight profile. As given in Eq. (5), the rate of sublimation is proportional to ambient temperature, freestream velocity, and local skin friction.

Figure 3 presents the operating temperature ranges of the four chemicals. Each solid bar represents typical limits; the dashed ends suggest variability resulting from coating thickness. For the fastest sublimating solid, naphthalene, the useful temperature range at subsonic speeds is from $-50° < T_\infty < 32°\text{F}$. Biphenyl and acenaphthene have subsonic temperature ranges of $-20°\text{C} < T_\infty < 80°\text{F}$ and $32° < T_\infty < 100°\text{F}$, respectively. A subsonic temperature range for fluorene would be $60° < T_\infty < 120°F$. The additional data point for fluorene at the low temperature was for a supersonic aircraft ($M = 2.0$) tested by McTigue et al.[4] One of the factors that allows the use of sublimating chemicals at supersonic speeds is that the adiabatic wall temperature rises with compressibility. Since the chemicals are affected by this wall temperature, rates of sublimation are higher than what would be considered normal at the freestream temperature. The relationship between the adiabatic wall temperature and the freestream is

$$T_{aw} = T_\infty\left[1 + K\left(\frac{\gamma - 1}{2}\right)M^2\right] \tag{7}$$

where γ is taken as 1.4 and K is the recovery factor. For a laminar boundary layer, the recovery factor is approximately 0.84, whereas for a turbulent boundary layer, the recovery factor is approximately 0.88. The suggested practical temperature ranges presented here are based on the experiences of the author and on other published flight results.

As previously mentioned, the freestream velocity effects the sublimation rate of a particular chemical. Based on the author's experience, suggested practical velocity ranges for each of the selected chemicals are presented in Fig. 4. These ranges are valid for sea-level standard day conditions. It is important to remember that the solid bar represents typical limits with standard coating thicknesses. Naphthalene can be used up to approximately 150 fps. Biphenyl works well in the low subsonic range of 100 fps to 500 fps, whereas acenaphthene is useful from 250 fps on up to transonic speeds of approximately 800 fps. A practical velocity range for fluorene would start from around 500 fps and go up to supersonic speeds.

Interpretation of Chemical Patterns

The transition mechanism or mode can be determined by analysis of the chemical patterns which develop. Typical patterns for four modes of transition are shown in Fig. 5. The developed pattern is shown as white in the laminar region and black in the turbulent region when the chemical has completely sublimated. Tollmien-Schlichting instability transition is characterized by a ragged transition line, as shown in the upper pattern of the figure. A crisp, straight transition front is indicative of the presence of laminar separation. When there are streamwise striations in the chemical coating followed by a very jagged transition line, crossflow or Görtler instability is the transition mechanism. The fourth type of transition pattern is formed by three-dimensional roughness elements. A typical shape would be a thin trail behind the element quickly followed by a turbulent wedge, usually having an included angle of around 15 deg.

Sublimating Chemical Flow Visualization Examples

Sublimating chemicals have been used extensively in recent years by NASA Langley personnel to document boundary-layer transition locations in flight on a variety of aircraft. Complete documentation of the results of the flight tests is presented in Ref. 8. The sublimating chemical technique has been used successfully on all surfaces of an aircraft, including wings, fuselages, empennages, and propellers.

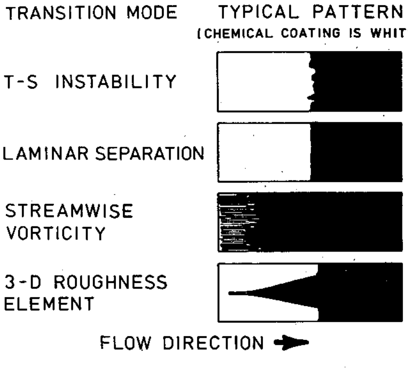


Fig. 5 Transition mode characteristics in sublimating chemical patterns.

Figure 6 shows a chemical pattern on the lower surface of a wing. The unit Reynolds number for the test was $R' = 1.9 \times 10^6$ ft^{-1}, and the chemical was acenaphthene. The figure shows the effect of insect strikes, propeller slipstream, and roughness in the form of inspection cover plates, screws, and selected tape trips on boundary-layer transition. There were several additional insect strikes which did not cause transition, whereas the ones shown did, as indicated by the turbulent wedges in the chemical pattern. The middle inspection cover had an aft-facing step, which caused boundary-layer transition. Although it cannot be seen very clearly, the inspection cover near the wing root caused transition because of the screw heads holding the plate on, rather than by the step height. Two additional turbulent wedges appear from intentional tape trips, which served to calibrate the photograph. Another noticeable effect is that the propeller slipstream caused the mean transition front to move slightly forward. The natural transition front shows the smooth, uniform pattern characteristic of laminar separation.

Another example of how well the sublimating chemicals can indicate the different modes of transition is illustrated in Fig. 7. This test was conducted on a business jet winglet at a Mach number of $M = 0.50$ and a unit Reynolds number of $R' = 2.1 \times 10^6$ ft^{-1}, using acenaphthene. On the upper span of the winglet, the transition front at $x/c = 0.65$ is characteristic of a laminar separation mode of transition. A roughness particle that prematurely tripped the boundary layer is evident in the mid-span region. A third mode of transition appears in the lower-span region. Between 5 and 10% chord, there is a manufacturing joint with an aft-facing step and several screw slots. The screw slots were not smoothed over and, consequently, in the one region, they caused premature transition. In the lowest

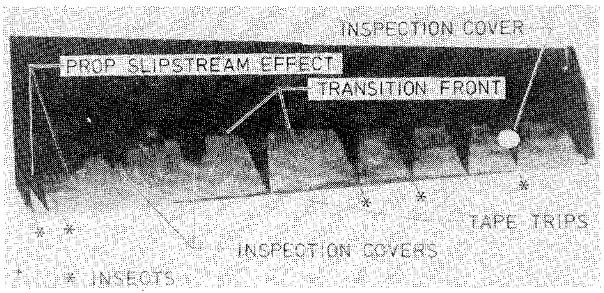


Fig. 6 Boundary-layer transition on a wing lower surface indicated by sublimating chemicals (acenaphthene), $R' = 1.9 \times 10^6$ ft^{-1}.[8]

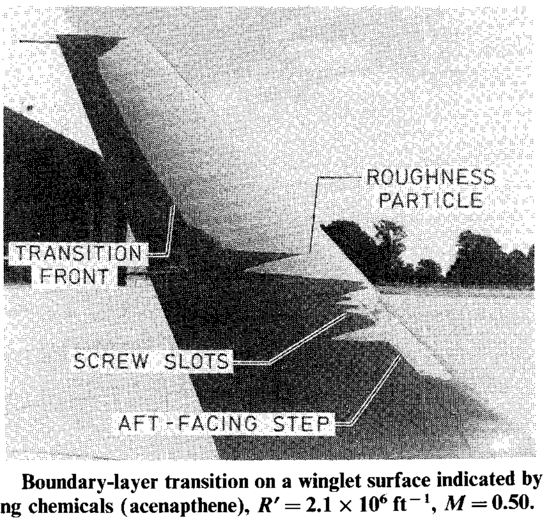


Fig. 7 Boundary-layer transition on a winglet surface indicated by sublimating chemicals (acenapthene), $R' = 2.1 \times 10^6$ ft^{-1}, $M = 0.50$.

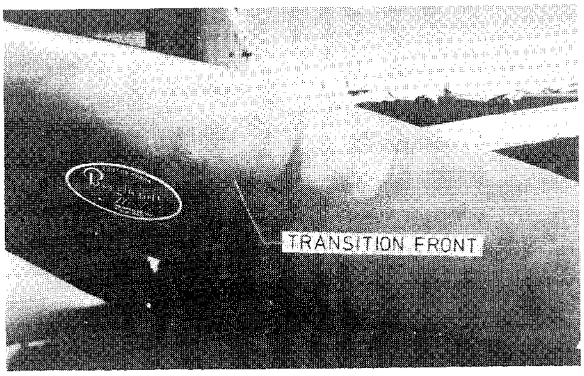


Fig. 8 Boundary-layer transition on the suction side of a propeller indicated by sublimating chemicals (acenaphthene), $R' = 2.77 \times 10^6$ ft^{1}.[8]

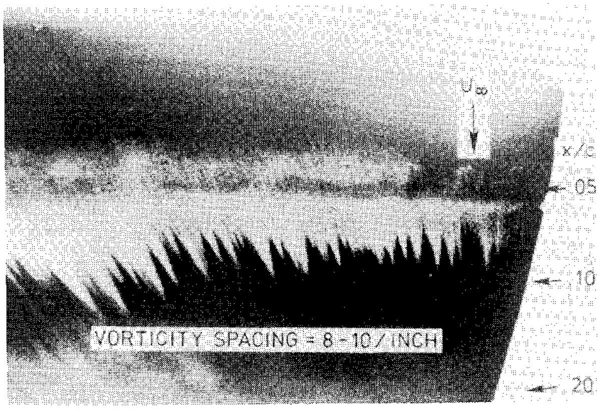


Fig. 9 Crossflow vortices indicated by sublimating chemicals (acenaphthene), $\Lambda = 27$ deg, $R' = 2.4 \times 10^6$ ft^{-1}.

region of visible chemicals, the aft-facing step was the cause of premature transition.

As noted previously, it is possible to measure the extent of laminar flow on a rotating propeller. Figure 8 shows an example of the suction side of a propeller and its boundary-layer transition location. An example of using sublimating chemicals for indicating crossflow vortices is shown in Fig. 9. The figure shows the development of crossflow vortices in the laminar boundary layer on the lower surface of a 27 deg swept wing at $R' = 2.4 \times 10^6$ ft^{-1}. Prior to causing boundary-layer transition, the vortices were spaced at 8–10 per inch.

Health Hazards

There are several precautions which should be followed in order to insure safe use of sublimating chemicals. The chemicals discussed here were selected because of their low health hazards. However, these chemicals should still be treated with respect. Persons within close use of the chemicals should wear an organic-vapor-type respirator (carbon filter). Eye and skin contact should be avoided whenever possible. Rubber gloves are recommended for handling. Always provide adequate ventilation when applying the chemicals. Biphenyl and naphthalene have been found to have low short-term and low long-term toxicity. Currently, fluorene and acenaphthene are known to have low short-term toxicity; long-term toxicity has not been extensively studied. The American Society for Testing and Materials, or a materials safety data sheet from the chemical supplier, can provide further health safety information on these and other chemicals.

A safety alert has been announced regarding the use of 1,1,1-trichloroethane and other halogenated hydrocarbons in pressurized fluid systems having aluminum or galvanized wetted parts. Under certain circumstances these solvents can corrode the aluminum or galvanized part. In pressurized spraying systems, this corrosive action could result in a pressure vessel explosion. Unless a stainless steel canister and spray gun are used, a siphon cup sprayer should be used when applying the chemical with a halogenated hydrocarbon solvent. Aluminum parts should be inspected regularly for corrosion. It is the author's experience that 1,1,1-trichloroethane does not harm composite or metal test surfaces. Some paints, namely the low cost spray enamels or laquers, may soften when cleaned with the solvent. Acetone can be used as a solvent; however, it does affect fiberglass and plexiglass and is a greater fire hazard than 1,1,1 trichloroethane. Proper cleaning of any fluid system will minimize the potential hazard. Further information on potential corrosion hazards should be obtained from the manufacturer of the spray equipment.

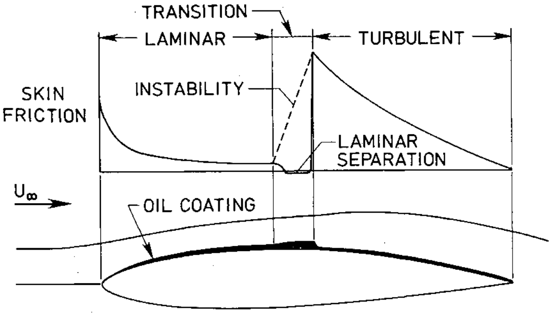


Fig. 10 How oil flows indicate boundary-layer transition.

Oil Flow

Description of Technique

Oil flows provide a second useful means for visualizing the state and nature of the flow over a surface. Oils can indicate regions of laminar and turbulent flow, regions of separated flow, location of shocks, and the location of laminar separation bubbles. One advantage of oil flows over sublimating chemicals is the ability to detect laminar separation bubbles.

The technique of applying and using oils differs somewhat from that of sublimating chemicals. The oil is brushed onto the surface to be tested. The aircraft is then flown to the desired flight conditions and held there until an oil pattern has developed. The oil will flow in the direction of the surface flow, collecting in regions of reverse flow, as shown in Fig. 10. Rapid movement of the oil will occur in regions of high skin friction and shear. Temperature has a large effect on the flow characteristics of the oil. The oil becomes less responsive at lower temperatures occurring at higher altitudes. This requires that the flight test conditions be held longer to insure that the oil patterns have adapted to the flowfield.

Unlike sublimating chemicals, any photographs of the developed pattern must be taken during flight at the desired test conditions, since transition patterns in oil coatings are difficult to preserve through offcondition flight regimes. For this same reason, the use of a less viscous oil may not help the low-temperature effect, since the climb portion of the flight would generally remove the thinner oils. Because the oil continuously responds to the flow conditions, multiple test conditions can be accomplished during a single flight.

For most flight conditions the use of a 1 : 1 mixture of AMS/Oil Para-Synthetic and Mobil 1, combined with a pigment to provide a contrast with the surface, has been recommended.[3] Suggested pigments include ferric oxide (FeO_2) for visualization on lighter surfaces and titanium dioxide (TiO_2) for contrast on darker surfaces. Useful ratios of pigment to oil are 1 : 10 for ferric oxide and 1 : 1 for titanium dioxide. The pigment should be completely dissolved in the oil before applying to any surface. Further information on the use of oil flow can be obtained from Ref. 3.

Oil Flow Visualization Examples

Some of the results of Curry et al.[3] in using oils for in-flight flow visualization are reproduced here. Figure 11 shows an oil

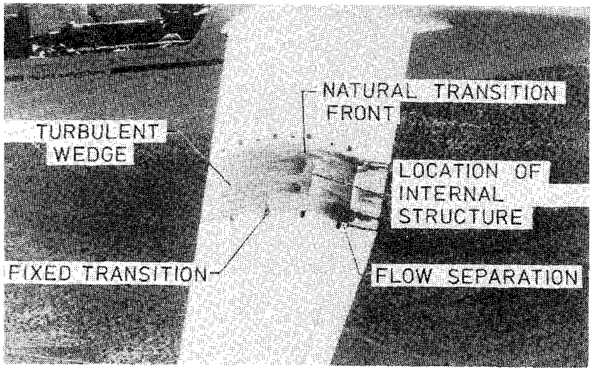


Fig. 11 Boundary-layer transition indicated by oil flows, $R' = 0.63 \times 10^6$ ft^{-1}.[3]

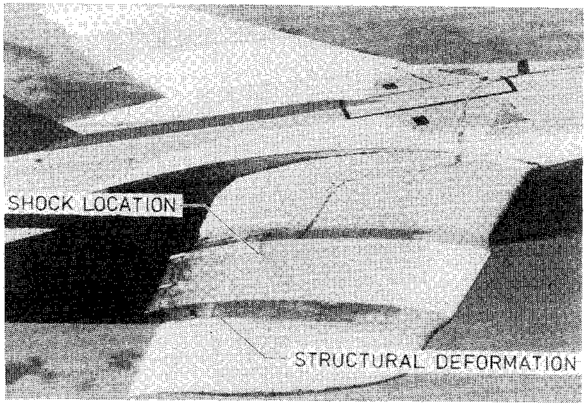


Fig. 12 Shock wave location indicated by oil flows, $M = 0.85$, $R' = 2.9 \times 10^6$ ft^{-1}.[3]

flow pattern indicating boundary-layer transition. The unit Reynolds number for this test was $R' = 0.63 \times 10^6$ ft^{-1}, and the oil was the mixture of AMS/Oil and Mobile 1 recommended above. The effect of fixed transition followed further downstream by a region of flow separation is also shown. An example of a shock location indicated by oil flow is shown in Fig. 12. For the faster speed, $M = 0.85$, $R' = 2.9 \times 10^6$ ft^{-1}, a more viscous oil was used.

Conclusions

Combined use of both oil flows and sublimating chemicals provides extensive boundary-layer data for use in design validation or certification flight testing. Each method of flow visualization has its advantages and disadvantages. Oil flows can be used to determine boundary-layer transition, shock wave locations, regions of separation flow and surface flow direction for several conditions during the same flight. However, oil flows must be photographed in flight following pattern development, and are somewhat untidy. Sublimating chemicals are useful for visualizing boundary-layer transition patterns from several modes of transition, including Tollmien-Schlichting instability, laminar separation, crossflow instability, and transition due to roughness. With the advent of new aircraft utilizing laminar flow for drag reduction, flow visualization is a valuable diagnostic tool to supplement other analytical measurements.

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