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Aerodynamic Effects of Aircraft Ground Deicing/Anti-Icing Fluids

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This article presents the results of flight and wind-tunnel investigations of the aerodynamic effects of aircraft ground deicing/anti-icing fluids on a Boeing 737-200ADV. The flight tests were performed in Kuopio, Finland, and the wind-tunnel tests were performed at the NASA Lewis Research Center Icing Research Wind Tunnel (IRT). Both types of commonly used fluids, those characterized by Newtonian and nonNewtonian viscosity behavior, were evaluated. Results of the tests indicate that the fluids remain on aircraft surfaces until well after liftoff and may cause measurable lift loss and drag increase, depending on the temperature, dilution, and specific characteristics of each fluid. A secondary wave of fluid which occurred at takeoff rotation was observed. Capillary wave action within the secondary wave is considered to be the source of the fluid's adverse aerodynamic effects at high angles of attack. Wind-tunnel testing and computational fluid dynamics analysis indicate that the fluid effects are airplane configuration dependent. This article also describes how results from these tests, other data, and airplane performance analyses were used to define an aerodynamic acceptance test for the fluids.

Nomenclature

C = longitudinal fraction of chord length
C_D = coefficient of drag, three-dimensional
CDSA = stability axis coefficient of drag, three-dimensional
C_{LAERO} = coefficient of lift, aerodynamic only
$C_{L\alpha W8}$ = coefficient of lift, three-dimensional, at 8-deg wing angle of attack
C_{LMAX} = maximum coefficient of lift, three-dimensional
C_{lMAX} = maximum coefficient of lift, two-dimensional
CLSA = stability axis coefficient of lift, three-dimensional
C_M = coefficient of pitching moments, three-dimensional
C_P = coefficient of pressure
EG = monoethylene glycol
ETHY = monoethylene
GLY = glycol
$h_{c.g.}$ = height of the c.g. above the runway
MIL SPEC = military specifications
PG = propylene glycol
PROPY = propylene
TEMP = temperature
t = time, s
U_∞ = freestream velocity
u = local velocity
V_{keas} = velocity, knots equivalent airspeed
V_R = takeoff rotation velocity
V_{S1g} = one g stall speed
V_2 = takeoff safety speed
X_{NF} = center of normal force in fraction of chord length
Y/C = vertical fraction of chord length
α = angle of attack, deg
α_B = body angle of attack, deg
α_W = wing angle of attack, deg
δ^* = boundary-layer displacement thickness
δ^*_{DRY} = dry surface boundary-layer displacement thickness
δ^*_{FLUID} = wetted surface boundary-layer displacement thickness
μ = absolute viscosity

I. Introduction

CIVIL aviation regulations in many countries require that commercial aircraft be free of ice, snow, or frost prior to takeoff. Protection of aircraft on the ground from accretion of frozen contaminates has become a major airline operational problem because of the negative economic effects of inclement weather-related schedule interruptions and as the time spent in queues waiting for takeoff during inclement weather has become longer at increasingly crowded airports.

Use of nonNewtonian pseudoplastic fluids containing glycol freezing point depressants to anti-ice aircraft on the ground is becoming a common industry practice. These thickened fluids, commonly referred to as Type II fluids, evolved from European airlines' requirements for fluids which provide anti-ice protection well beyond the limited anti-ice capability of glycol and water mixtures that have traditionally been used to deice aircraft. However, at cold operational temperatures both types of fluids can become highly viscous making them a potential aerodynamic contaminant. Because of reported airplane incidents and observations that deicing/anti-icing fluids did not always flow off lifting surfaces prior to liftoff, airlines and Boeing during the early 1980s questioned whether these fluids caused adverse aerodynamic effects. These doubts persisted even though the safety record supported the industry practice of using deicing/anti-icing fluids without concern for possible adverse aerodynamic effects.

Since 1982, wind-tunnel and flight investigations of the fluids have been performed to evaluate possible adverse aerodynamic effects. Results of these investigations, described herein, have led to marked improvements in the flowoff characteristics of Type II fluids, criteria for airplane performance when the fluids are used, and a standard for acceptable fluid flowoff characteristics. Along with promulgation of North American and international standards for the fluids, ground equipment, and deicing/anti-icing procedures (to accompany those already existing in Europe), the ground work is being laid for

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more effective aircraft ground deicing/anti-icing and for a significant enhancement worldwide in commercial aviation safety as related to aircraft ground deicing/anti-icing.

II. Background

Some of the fluids used to deice and anti-ice aircraft have unusual rheological properties. Also, analysis of airfoil and wing characteristic with fluid present is an area of aerodynamics that has received little attention. Therefore, the following provides a short description of the deicing/anti-icing fluids and briefly describes the fluid dynamic phenomenon which were addressed during the investigation. In addition, a summary of earlier wind-tunnel investigations is presented to provide the background which resulted in the activities described in this article.

A. Aircraft Ground Deicing/Anti-Icing Fluids

Two basic types of fluids are used to deice and anti-ice large commercial air transports. Use of a mixture of hot water and glycol-based freezing point depressants to deice aircraft is a common industry practice.[1–4] These mixtures are economical and easily applied, but provide limited anti-icing protection. Undiluted, or neat, formulations of these commonly called Type I fluids usually contain a minimum of 80% glycol, and the viscosities of these fluids have a Newtonian behavior (i.e., viscosity is principally a function of temperature only). Type I fluids have a relatively low viscosity except at very cold temperatures. At colder temperatures, viscosity of Type I fluids can vary significantly, depending on the glycol used and the dilution with water. Type I fluids are eutectic with the minimum freezing point or onset of crystallization, occurring approximately at a mixture of 60% glycol and 40% water. Monoethylene glycol has been widely used in the U.S. and has a low viscosity. Diethylene, triethylene, and proplyene glycol-based Type I fluids are used in Europe and are becoming more common in North America. At colder temperatures these latter glycols exhibit viscosities much higher than that of monoethylene glycol.

The other basic type of deicing/anti-icing fluids, Type II, is characterized by nonNewtonian viscosity behavior (i.e., viscosity is a function of temperature and shear stress). In the neat formulation these fluids have a minimum glycol content of 50%. Type II fluids are sensitive to storage and handling but provide markedly improved anti-icing protection compared with Type I fluids. Type II fluids may be further classified if they meet specific standards, such as those promulgated by the Association of European Airlines (AEA).[3] These nonNewtonian fluids are characterized by extremely high viscosity that dramatically decreases with increasing shear stress, approaching viscosity levels of Type I fluids at shear stress levels associated with typical takeoff and climb speeds of large commercial air transports. Fluid designers are able to control other characteristics of Type II fluids such as the variation of viscosity with temperature, flowoff behavior, and the affinity of the fluid to absorb melted precipitants into solution. Type II fluid products tend to have unique characteristics as compared to "generic" Type I fluid products. Figure 1 illustrates typical viscosity characteristics of Type I and II fluids.

Technology for a third type of deicing/anti-icing fluid is beginning to emerge. These fluids are Type I fluids with additives which apparently prevent adhesion of ice, snow, or frost to aircraft surfaces. The anti-icing capability and operational feasibility of this third category of fluids are yet to be established.

B. Fluid Dynamics Considerations

Analysis of a wing or control surface that has been wetted with a fluid film is a difficult multiphase fluid dynamics problem. Addition of the fluid introduces a second boundary layer which must be considered in evaluating the aerodynamic characteristic of a surface.

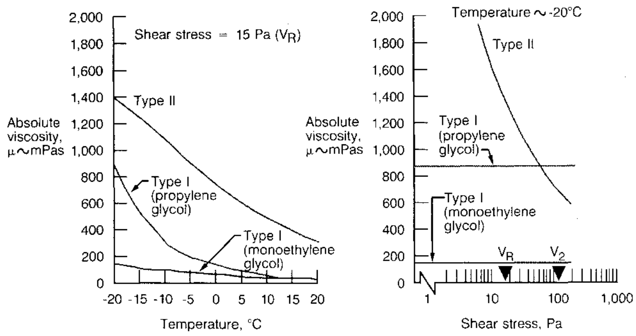

Fig. 1 Undiluted aircraft ground deicing/anti-icing fluids characteristics.

Generally, adding a fluid film to an airfoil will adversely affect the stability of the airfoil's boundary layer and decrease the airfoil's aerodynamic efficiency. Shearing of the fluid from the airfoil's surface will extract energy from the airstream boundary layer, and surface roughness resulting from the fluid flowoff will further weaken the airstream boundary layer. The weaker, thicker boundary layer changes the airfoil's effective contour and aerodynamic characteristics. Adverse aerodynamic effects of minute roughness near the leading edges of wings are well-known and documented.[5–7] Fokker and Boeing have verified the applicability of this general description of the fluid aerodynamic effects by measuring the thickened boundary layer on wind-tunnel models and then using the effective airfoil shape in computational fluid dynamics (CFD) codes to duplicate lift losses measured in the wind tunnel.

Realizing the need to develop analytical capabilities to evaluate the fluids in addition to empirical studies, the mathematically difficult problem under the auspices of the NASA Lewis Research Center has been addressed.[8]

Finally, an understanding of fluid scaling parameters is important because a comprehensive full-scale flight test evaluation of deicing/anti-icing fluids is economically impractical. Following commonly accepted industry practices for addressing the complex issue of scaling low Reynolds number wind-tunnel results to full-scale, correlation was established between fluid effects that were measured during full-scale flight and small-scale wind-tunnel tests. This correlation permitted full-scale estimates to be made from the results of an extensive wind-tunnel evaluation of the fluid effects.

C. Early Wind-Tunnel Investigations

Responding to airline concern for possible adverse aerodynamic effects of Type II fluids used at that time, Boeing performed small-scale wind-tunnel evaluations of the fluids during 1982.[9] Flow visualization studies of the fluid flowoff characteristics were observed on a 0.25-m (10-in.) chord airfoil in the Boeing icing wind tunnel. Force and visual flow data were also obtained on a 0.61-m (24-in.) chord two-dimensional model using nonNewtonian fluids that were modified to simulate their viscosity at −18°C (−0°F) while being tested at about 35°C (95°F) in the uncooled Boeing research wind tunnel. Results of these tests indicated that at cold temperatures both neat Type I and Type II fluids did not flow off the wing prior to liftoff velocities, with the remaining residue forming a rough, reticulated surface, causing a measurable lift loss and drag increase.

Beginning in 1984, the AEA sponsored a research program with the von Karman Institute for Fluid Dynamics to further investigate the fluid effects without the test limitations that questioned the validity of the Boeing results.[10–12] Neat Type I and neat unmodified Type II fluids were tested at operational cold temperatures using a large 1.5-m (4.92-ft) chord two-dimensional model. Results of these tests generally agreed with those from the Boeing tests. However, questions remained concerning the model scale and three-dimensional effects. Because of these remaining questions Boeing was asked by the AEA to perform a flight test investigation of the fluid effects.

III. Flight Test

Boeing and the AEA, with assistance from three fluid manufacturers, performed a flight test evaluation of deicing/anti-icing fluids at Kuopio, Finland from January 11–20, 1988. A Boeing 737-200ADV was provided rental-free by Lufthansa Airlines in behalf of the AEA. Boeing instrumented the aircraft and performed the test. The AEA hosted the testing in Europe and provided the ground equipment to apply the fluids, as well as technical assistance. The fluid manufacturers, Hoechst A. G., Kilfrost Ltd., and Union Carbide Canada Ltd., provided the fluids at the test site.

A. Test Description

The objectives of the flight test were to evaluate the aerodynamic effects of ground deicing/anti-icing fluids on a large jet transport and to establish a full-scale data base for extrapolating data from a planned, more comprehensive wind-tunnel investigation. The primary goal of the flight test was to obtain data for assessing the fluid effects on lift.

Four neat deicing/anti-icing fluids were tested: 1) a Hoechst AEA Type I, fluid 1; 2) an obsolete Type II fluid for which wind-tunnel data were available, fluid 2; and 3) two Type II fluids, fluid 3 manufactured by Hoechst which was representative of Type II fluids used by the airlines at the time of the test and fluid 4 manufactured by Union Carbide. All fluids were dyed by the fluid manufacturers with a 0.005% concentration of Rhodamine 6G fluorescent dye after determining that the dye did not affect the rheological properties of the fluids. The dye improved visibility of the fluid flowoff characteristics and allowed the use of ultraviolet photographic and backscatter laser techniques to measure fluid depth and roughness.

The aircraft was equipped with an inertial reference system (IRS), and a high-speed pulse code modulation data recording system was used for recording gross weight, c.g., engine parameters, air speed, acceleration, ground speed, distance, and angular data from the IRS. An airborne data acquisition and monitoring system provided onboard engineering analysis of acquired data. Video and photographic records of the fluid flowoff characteristics were made. A complete description of the aircraft instrumentation is provided in Ref. 13.

Test objectives were achieved by determining lift curves in ground effects with and without deicing/anti-icing fluids. A series of takeoffs was performed at flaps 5 with sealed slats, and at flaps 15 with slotted slats over a range of attitudes. Fluids were applied using in-service procedures: a two-step procedure in which the aircraft wing and horizontal stabilizer were first deiced using a 50:50 mixture of hot water and AEA Type I fluid and second anti-iced with an application of an undiluted cold Type II fluid. The fluids were applied by experienced personnel using a Finnair EFI 20000 vehicle, as shown in Fig. 2. When testing the Type I fluid, the fluid was applied cold and undiluted without a deicing cycle, except for the first takeoff of the day, which required deicing. The thrust and weight of the aircraft were scheduled to maintain approximately constant takeoff ground roll time and speed so that all fluids experienced the same shear stress and had the same time to flow off the wing. Exceptions were made to evaluate the effects of different shear stress and flowoff time. The aircraft was rotated early to stabilize at the desired attitude and then allowed to accelerate and liftoff.

B. Results

Figure 3 illustrates typical lift curves that were obtained. The data clearly show that the lift is lower with fluids on the wing than for the dry baseline, and that the lift loss increases with increasing angle of attack. Data obtained using a normal, continuous takeoff rotation indicated that use of the fixed attitude takeoff technique did not affect the test results.

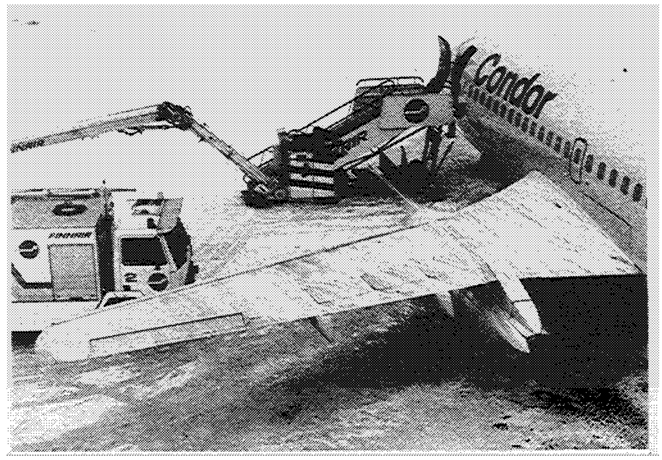

Fig. 2 Application of anti-icing fluid.

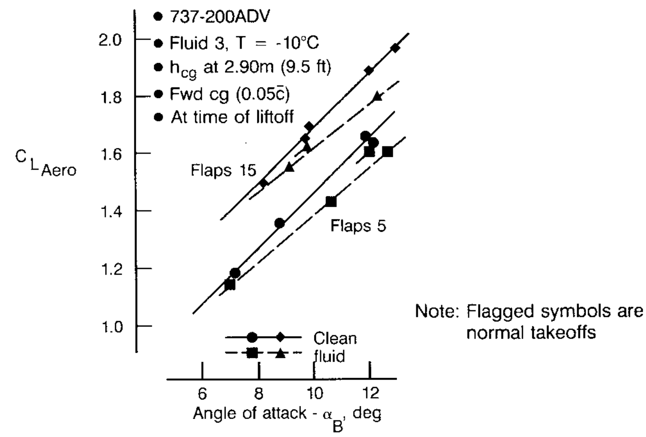

Fig. 3 Typical flight test lift curves with and without fluid.

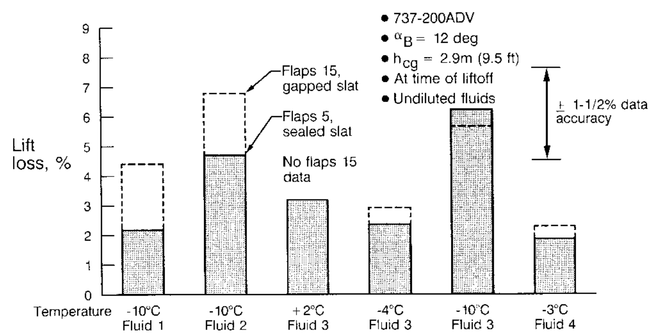

Fig. 4 Flight test results for effect of fluids on lift.

Test results for all the fluids are summarized in Fig. 4 for a liftoff attitude of 12 deg, which is a typical one-engine-inoperative takeoff climb attitude for the 737-200ADV. Because of prevailing ambient temperatures, data were obtained over a temperature range of 2°C (36°F) to −10°C (14°F). Based on an evaluation of the measured parameters, the estimated uncertainty of the fluid lift effects is ±1.5%. The test results show that both neat Newtonian Type I and non-Newtonian Type II fluids cause measurable losses in lift at the temperatures encountered during the flight test. Also, at −10°C (14°F), the lift loss associated with the Type I fluid was less than that for the Type II fluids. In general, there was evidence that the lift loss resulting from the fluid was larger at flaps 15 than at flaps 5.

Limited assessments of flowoff time, liftoff speed, and fluid exposure time revealed that reasonable variations of these parameters had no measurable effects on the test results. A flight with Type II fluids applied only to the left wing produced no noticeable effect on airplane handling characteristics as reported by the pilots.

A valuable cue to understanding the mechanics of the fluid related lift loss was revealed by photographs of the fluid flow-off which were obtained during special nighttime takeoffs with the fluid's dye florescence excited by cabin-mounted ultra-violet lamps. Figures 5a and 5b are photographs of the Type II fluid 3 obtained at 8 s after brake release and at liftoff. Increased fluorescence in the photographs corresponds to increased fluid depth. Initial movement of the fluid is evident in Fig. 5a, with the fluid surface becoming rough with wave activity. Figure 5b clearly shows a significant secondary wave of fluid moving aft from the wing's leading edge. The source of the fluid contained in the secondary wave can be hypothesized from airfoil pressure (velocity) distributions, calculated using a full potential flow two-dimensional panel method CFD program, shown in Fig. 6. At the takeoff ground roll attitude the local pressure coefficients, hence velocities, are low near the wing's leading edge when compared to the local velocities at liftoff attitudes. The subsequent low shear stress during the takeoff ground acceleration is hypothesized to leave a film of fluid near the wing leading edge that is subsequently "scrubbed" from the wing once the higher shear stress develops at the liftoff angle of attack. Also, movement of the wing's leading edge stagnation line toward the lower surface as the angle of attack increases probably sheds fluid that had accumulated along the stagnation line during the takeoff acceleration ground roll. Capillary waves within the secondary gravity wave are apparently rough enough to cause the higher lift loss observed at the increased angles of attack. This hypothesis suggests that the fluid aerodynamic effects are configuration-dependent, as evident from the flaps 5 and 15 data shown in Fig. 4. Also, the aerodynamic effects of the secondary wave are probably attenuated as the wave moves aft and the fluid residue in the leading edge area is reduced.

C. Flight Test Conclusions

General conclusion drawn from results of the 737-200ADV flight test were as follows:

1) The neat fluids cause a measurable loss in lift, similar to the results of earlier Boeing and AEA wind-tunnel tests.

2) The fluid effects are configuration-dependent.

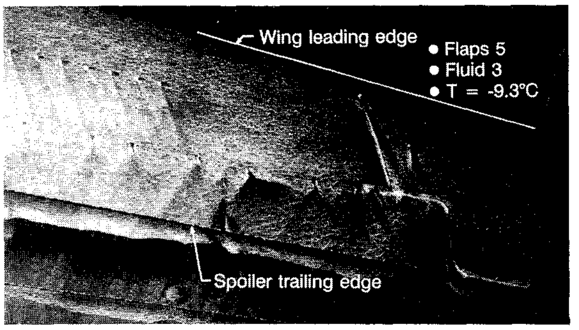

Fig. 5a **Fluid 8 s after brake release.**

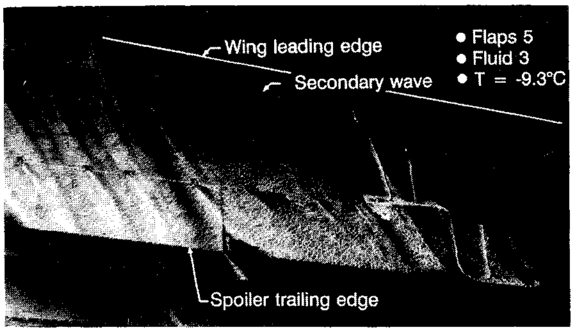

Fig. 5b **Fluid at liftoff.**

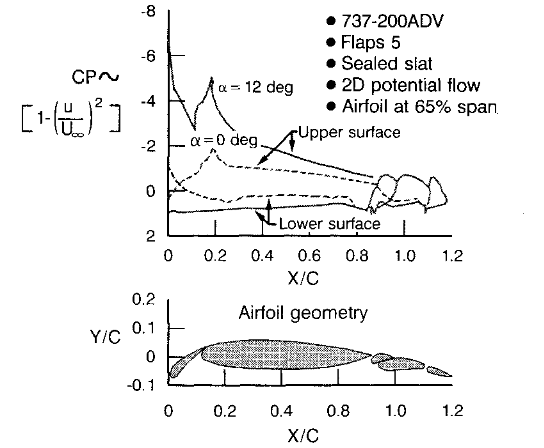

Fig. 6 Calculated pressure coefficient (velocity) distributions on two-dimensional model.

3) Effects of the fluid on airplane handling qualities can be small.

4) A secondary fluid wave flows aft immediately after rotation for takeoff.

5) Fluid effects are transitory.

IV. Wind-Tunnel Test

Wind-tunnel evaluations of the fluids were performed in two phases at the NASA Lewis Research Center Icing Research Wind Tunnel (IRT) during early 1988 and early 1990. The testing were joint efforts of Boeing, NASA, the AEA, and various fluid manufacturers. Boeing provided the wind-tunnel models and conducted the tests in cooperation with NASA. The NASA Lewis Research Center provided and operated the IRT. Documentation of the test results was performed jointly by Boeing and NASA. The AEA monitored the tests. Fluids were provided by a variety of fluid manufacturers. The following will principally address results from the 1990 entry into the IRT.

A. Test Description

Primary objectives of the wind-tunnel tests were as follows:

1) Validate use of the wind tunnel for investigating the aerodynamic effects of deicing/anti-icing fluids.

2) Determine the effects of the fluids on maximum lift.

3) Expand the testing envelope in controlled, cost-effective laboratory conditions to include a range of temperatures, airplane configurations, measured parameters, and fluids.

4) Obtain information to better understand the aerophysics of the fluid aerodynamic effects and to establish acceptance standards for ground deicing/anti-icing.

5) Provide fluid manufacturers opportunities through aerodynamic testing to develop technology for improving fluid flowoff characteristics.

Because the subject of aircraft icing is the primary objective of the IRT and because of earlier NASA Lewis Research Center dialogue with industry which indicated that aircraft ground icing was an area where NASA could contribute to flight safety, NASA Lewis was receptive to a joint wind-tunnel test program with Boeing.

The NASA Lewis IRT layout is shown in Fig. 7. Tunnel temperature can be varied from 27 to −29°C (81° to − 20°F) in the 6.1-m- (20-ft-) long test section. Boeing provided force balances, a data acquisition system, and photographic and video equipment to supplement the Lewis IRT data system and instrumentation.

Figures 8 and 9 show details of the models tested. The 0.46-m (1.5-ft) chord two-dimensional model was a 0.18 scale model of the 737-200ADV airfoil at approximately 65% semispan. The model was mounted to turntables and balances located within a pair of splitter walls. The three-dimensional model

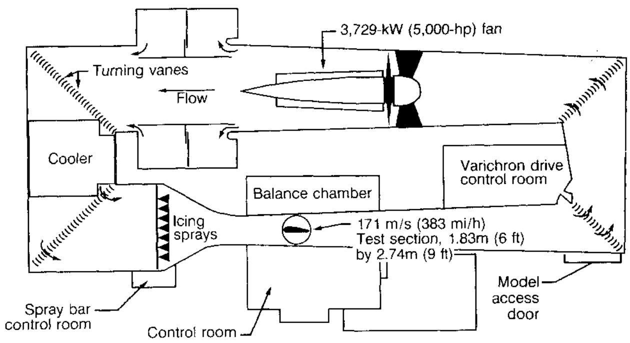

Fig. 7 NASA Lewis icing research tunnel.

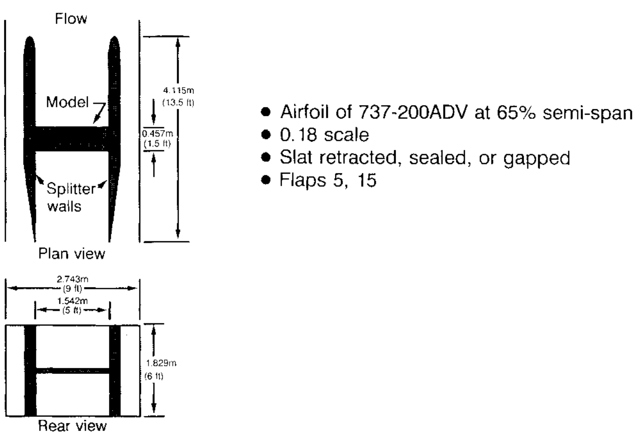

Fig. 8 Two-dimensional model.

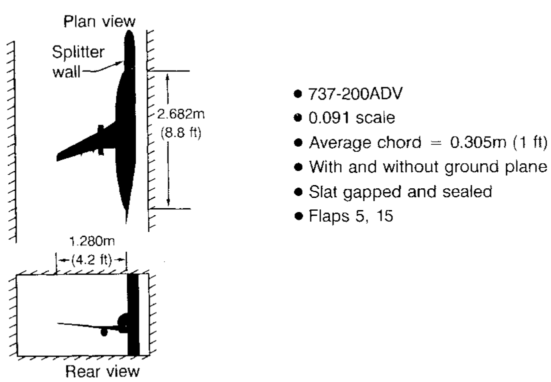

Fig. 9 Three-dimensional half-model.

Fig. 10 Two-dimensional model configurations.

was a 0.91 scale half-model of the 737-200ADV which was mounted to one of the splitter walls by a turntable and balance. Most of the three-dimensional model testing was performed with a ground plane in place. The models provided the capability of testing the configurations shown in Fig. 10, however, most of the testing was performed at flaps 5 with sealed slats and flaps 15 with the slotted leading edge.

After the model was cleaned, wiped with a cloth damped with a 50:50 water and Type I fluid mixture, and the fluid specimen poured from a 2L container and leveled to the desired film depth, the fluid film was exposed to the cooled wind tunnel environment for 5 min under essentially static conditions. The 5-min exposure time allowed the temperature of the precooled fluid specimen to come into equilibrium with the temperature of the model and wind tunnel. Also, the exposure time was representative of time required during the flight test phase for an aircraft to taxi to a runway for takeoff after deicing/anti-icing had been completed. The wind-tunnel flow velocity was linearly increased to 69 m/s [135 knots equivalent air speed (keas)] in approximately 30 s and the model was rotated from the taxi attitude (0 deg) to the desired attitude at a rotation rate of 3 deg/s at 25 s after the start of the tunnel flow. The tunnel-flow velocity increase and model rotation simulated the shear stress history that would be experienced during a typical all-engine-operating takeoff for a large commercial jet transport. Data were continuously acquired from the start of the tunnel flow to 30 s after the model was rotated to the maximum pitch angle for the test run. Data acquired using a pitch-and-pause technique verified that accurate data could be obtained using the more efficient continuous-pitch data acquisition technique. The typical on-line data plot shown in Fig. 11 illustrates the testing technique used and the force data acquired.

B. Results

Only major conclusions from phase I (1988) test results are presented since results of the initial wind-tunnel investigation are well-documented elsewhere and since the results of phase II testing are more germane for the fluids currently in use by the airlines. A detailed description is provided for results from phase II (1990) wind-tunnel test that are of general interest. Additional testing was performed during phase II to evaluate new and experimental deicing/anti-icing fluids. All the data from phase II will be provided in a forthcoming NASA report on the test.

1. Phase I IRT Entry (1988)

One of the important results of phase I testing was gaining confidence in using wind-tunnel data to evaluate the effects

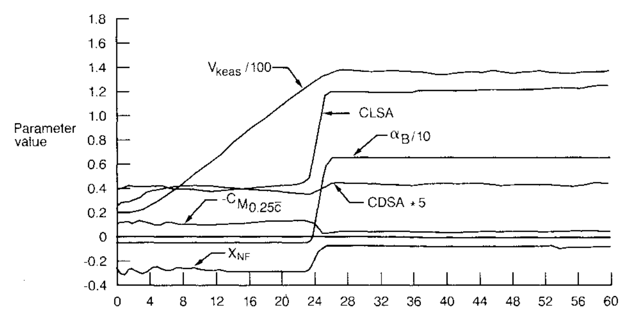

Fig. 11 Typical on-line data plot.

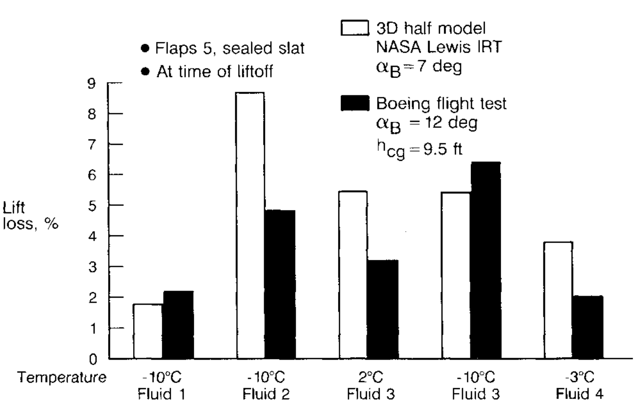

Fig. 12 Comparison of 737-200ADV three-dimensional half-model lift loss with flight test results.

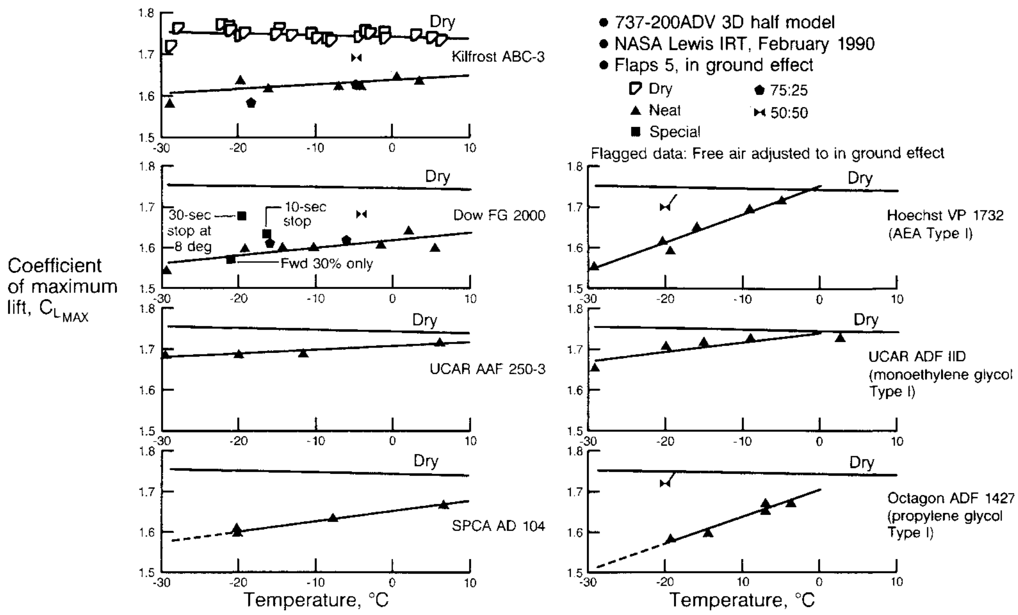

Fig. 13a Fluid effect on maximum lift.

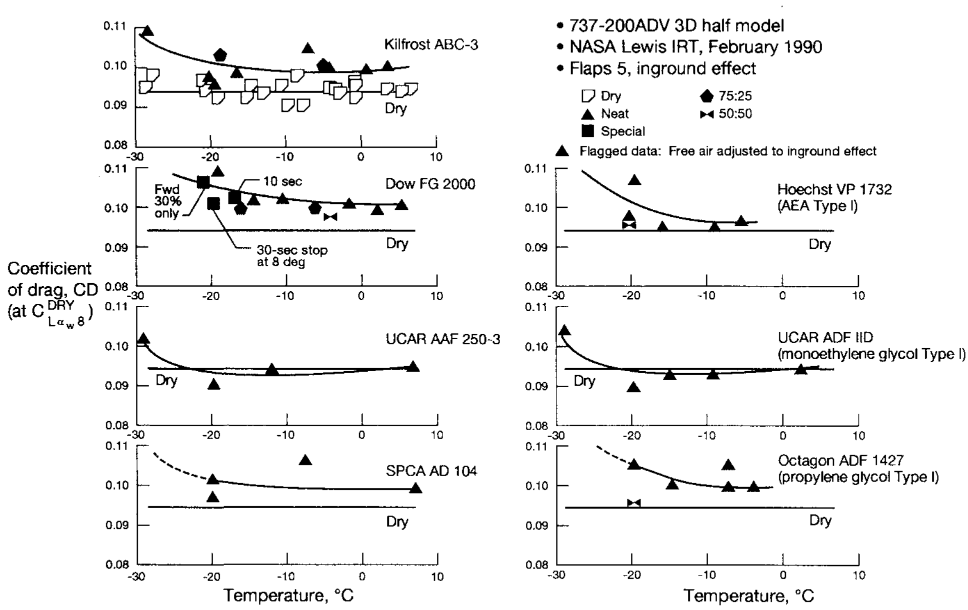

Fig. 13b Fluid effect on drag at dry wing 8-deg angle-of-attack lift.

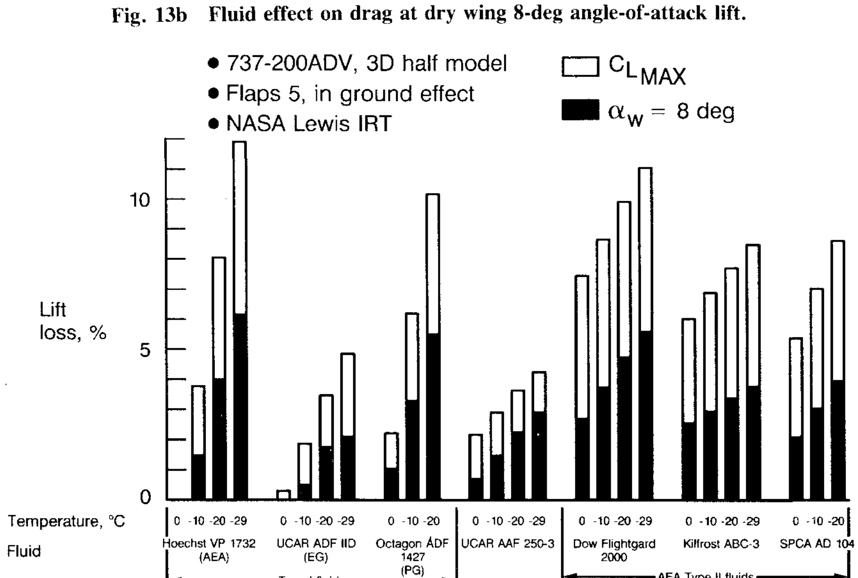

Fig. 14 Lift loss due to undiluted deicing/anti-icing fluids at liftoff.

of the fluids. By testing the same deicing/anti-icing fluids used during the flight test program on the 737-200ADV three-dimensional model, the correlation between full- and model-scale fluid effects on lift shown in Fig. 12 was obtained. Realizing the estimated ±1.5% data accuracy, the correlation suggested that the wind-tunnel lift loss results could be extrapolated to full scale on a 1:1 basis. Similar results were found for both lift and drag increments which resulted from distributed solid roughness during earlier Boeing flight and wind-tunnel evaluations.[7] Other results of phase I testing are presented in Refs. 14 and 15.

2. Phase II IRT Entry (1990)

The fluid manufacturers in a second entry into the Lewis IRT 2 yr after phase I and the opportunity to collaborate with NASA allowed the earlier limited data base to be expanded to include the following:

1) Aerodynamic evaluations of currently available undiluted and diluted Type II fluids.

2) An examination of the difference in effects between the various glycol *f* freezing point depressants used in Type I fluids.

3) Acquisition of data to support development of an aerodynamic acceptance test for deicing/anti-icing fluids.

4) Further aerodynamic experimentation for fluid manufacturers to develop technology for improved fluids.

5) A cursory look at the effect of precipitation on the flowoff characteristics of a Type II fluid.

Figures 13a and 13b are a synopsis of the 737-200ADV half-model data obtained with currently available deicing/anti-icing fluids. Maximum lift loss data extracted from Fig. 13a for neat deicing/anti-icing fluids are shown at specific temperatures in Fig. 14. In addition, Fig. 14 shows lift losses measured at 8-deg angle of attack, an attitude representative of an engine-inoperative takeoff climb at model Reynolds number. For the neat fluids shown, the monoethylene glycol-based Type I and Union Carbide AAF 250-3 Type II fluids are the least intrusive. At a representative cold day temperature of −20°C (−4°F), the aerodynamic effects of Kilfrost ABC-3 and SPCA AD 104 Type II fluids are similar to the neat European AEA Type I fluid. Note that the Dow Flightgard 2000 fluid is a Type II fluid manufactured in the U.S. under the guidelines of Hoechst A.G., manufacturers of the AEA Type II fluid 1704 LTV 88. However, the effects of the AEA Type I diminishes rapidly with increasingly warmer temperatures. The comparatively high variability of the neat proplyene glycol Type I fluid lift loss with temperature is also evident. The comparative results of the neat monoethylene and propylene glycol Type I fluids reflect the viscosity differences between the fluids as shown in Fig. 1.

The transitory nature of deicing/anti-icing fluids is shown in Figs. 15a and 15b. These data along with the drag data of Fig. 13b proved useful when evaluating the effects of the fluid on airplane takeoff and climb performance.

The effects of dilution on maximum lift loss and the lift loss measured at 8-deg angle of attack for the neat and diluted Type I and II fluids are shown at specific temperatures in Fig. 16. Because of economics and the eutectic nature of glycol mixtures, Type I fluids are diluted before they are applied to aircraft. For this reason the diluted Type I fluid lift losses, which are significantly less than those of neat AEA and propylene glycol-based Type I fluids, are most representative of what would be encountered in operational use. Conversely, Type II fluids are used operationally either neat or diluted. The temperatures selected for display are representative of

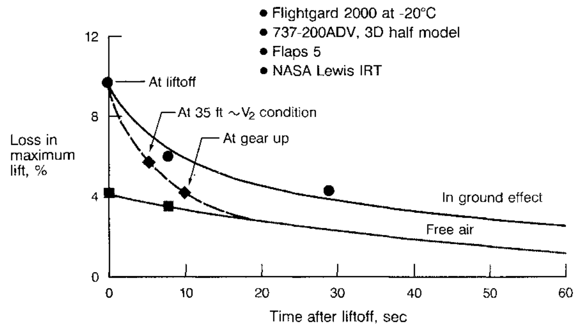

Fig. 15a Maximum lift loss variation with time.

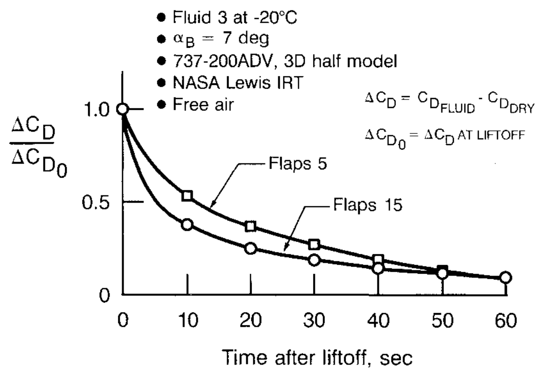

Fig. 15b Drag increase variation with time.

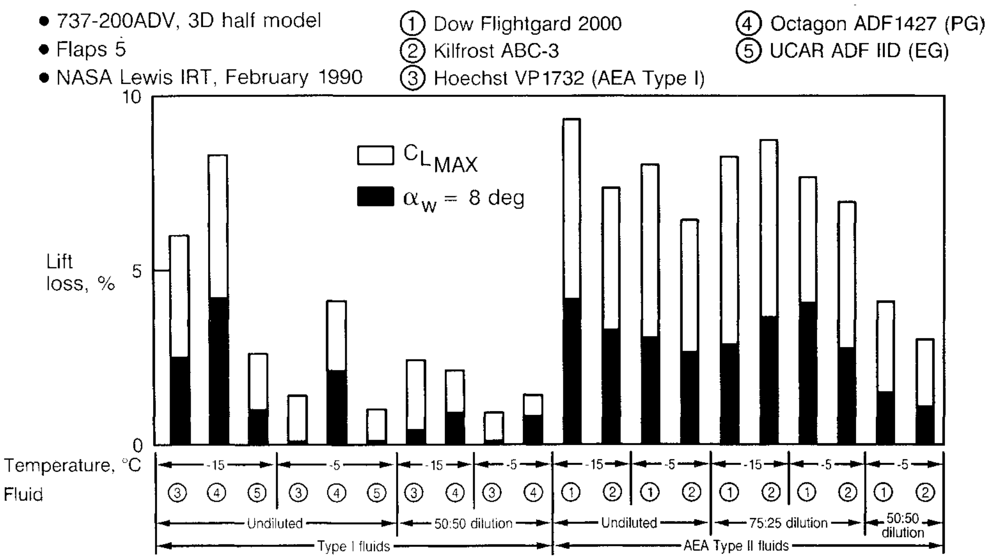

Fig. 16 Aerodynamic effects of deicing/anti-icing fluids at operational concentration.

the approximate lower limit temperatures for operational use of the particular dilution of the Type II fluids. Figure 16 shows that a 25% dilution of the Type II fluids did not result in significant maximum lift loss differences when compared to undiluted fluid results. The reason for the dilution investigation was a concern for the characteristic of some Type II fluids to have higher viscosity when diluted approximately 25% with water. Results of the investigation suggested that the adverse aerodynamic effects due to the increased viscosity was counteracted by the favorable change in elasticity of the diluted fluid.

The effect of precipitation on the flowoff behavior of Type II fluids were evaluated on the two-dimensional model by spraying water over the model which was equivalent to 10 and 20% of the undiluted fluid that had been applied to the model. Results of this evaluation are shown in Fig. 16. At

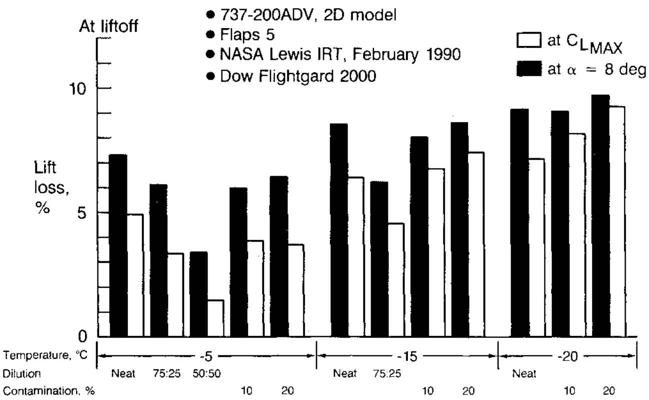

Fig. 17 Lift loss due to fluids with simulated precipitation.

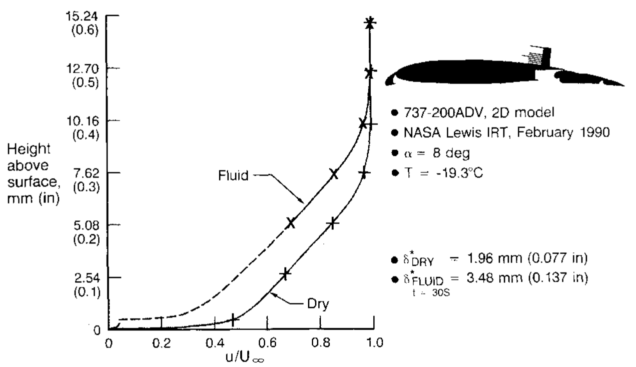

Fig. 18 Two-dimensional model boundary-layer velocity profile.

the colder temperatures the lift losses are either higher with the sprayed water than equivalent water that had been mixed into solution with the Type II fluid, or the lift loss did not diminish with the simulated precipitation. Video recordings revealed that at the colder temperatures the simulated precipitation formed a sheet of ice on top of the deicing/antiicing fluid layer rather than being absorbed into the solution. This evaluation is not considered conclusive but does suggest that further study is needed.

Results shown in Fig. 17 for the two-dimensional model, indicate percentage lift losses at 8-deg angle of attack that are larger than those at maximum lift. This trend is different from that observed on the three-dimensional model and indicates the importance of three-dimensional testing.

Boundary-layer data were obtained on the two-dimensional model using a rake of 10 total and 1 static pressure probes which was located at the trailing edge of the airfoil's fixed trailing edge. The effect of the fluid on the boundary-layer profile is clearly evident in Fig. 18. Data below 5.08 mm (0.2 in.) were not obtained with fluid on the model because the lower total pressure probes were plugged to prevent fluid contamination. The boundary-layer displacement thicknesses were computed for several of the currently used deicing/anti-icing fluids, using boundary-layer velocity profiles based on the measured total pressures and the local static pressure.

If the hypothesis is valid that the mechanism of the fluid effect on the aerodynamics of the wing is premature growth of the boundary layer, then a correlation between the prematurely thickened boundary layer and the aerodynamic affects can be anticipated. Figure 19 illustrates the excellent correlation obtained with the two-dimensional model between the boundary-layer displacement thickness with fluids and the resultant lift loss at an 8-deg angle of attack. Because the two-dimensional model airfoil is the critical (relative to stall progression) 737-200ADV wing section and assuming that the thickened boundary layer measured at an 8-deg angle of attack was an indicator of the affect of the fluid at maximum lift, then an acceptable correlation between the two-dimensional model boundary-layer thickness and the three-dimensional model maximum lift loss can also be anticipated. This correlation is shown in Fig. 20. These results indicate that the fluid effects on the boundary-layer thickness is an indicator of the fluid effects on airplane performance.

C. Wind-Tunnel Test Conclusions

Conclusions drawn from the 737-200ADV wind-tunnel test include the following:

1) Fluid effects can be evaluated in the wind tunnel and the results can be extrapolated to full scale with reasonable confidence.

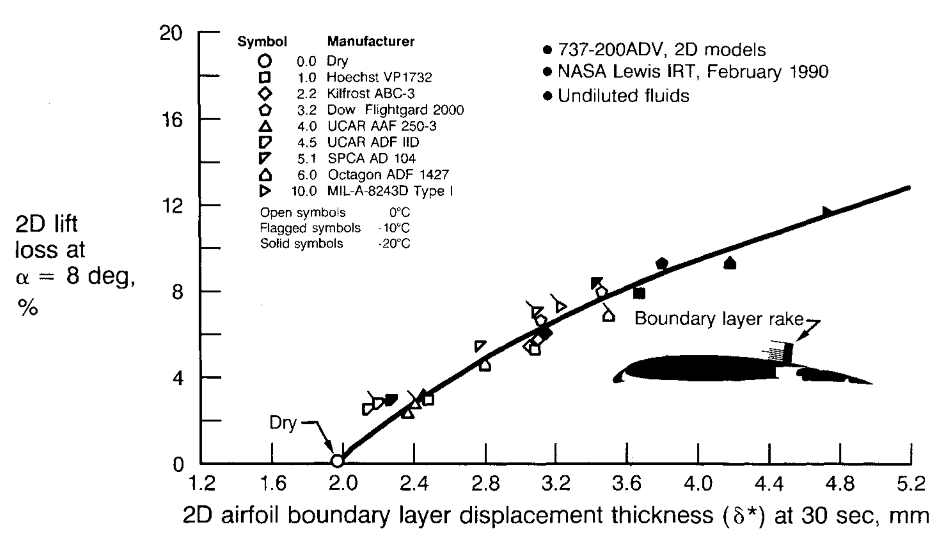

Fig. 19 737-200ADV two-dimensional lift loss/boundary-layer displacement thickness correlation.

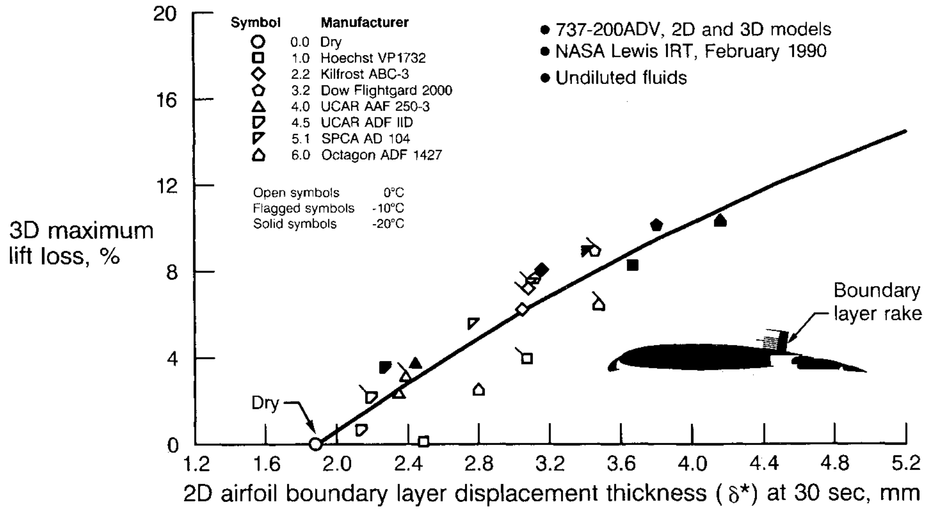

Fig. 20 Lift loss/boundary-layer displacement thickness correlation.

2) Dependent on temperature, Newtonian Type I and nonNewtonian Type II fluids produce measurable adverse aerodynamic effects.

3) For the 737-200ADV three-dimensional configuration, lift loss at maximum lift are greater than that at lower angles of attack.

4) Fluid aerodynamic effects are transitory.

5) The fluid effects vary with airplane configuration.

6) Aerodynamic effects of the fluids correlate well with boundary-layer thickening caused by the fluids.

7) Aerodynamic effects of the fluid vary with specific fluids and viscosity is not the only governing rheological parameter.

V. Aerodynamic Acceptance Test

Traditionally, aircraft have been deiced, anti-iced, and dispatched without concern for airplane performance effects. Whatever effects the fluids had on airplane performance were considered within the safety margins provided by airworthiness and operational regulations. The previous discussion clearly shows that the transitory aerodynamic effects of the fluids are not negligible for airplane configurations similar to the 737-200ADV.

Therefore, an international group was formed during 1988 under the auspices of the Aerospace Industries of America Transport Committee (AIA TC) to consider the aerodynamic effects of the fluids. The AIA TC 218-4 group consisted of active representatives from Airbus Industrie, Boeing, British Aerospace, Fokker, and McDonnell Douglas, with assistance from the AEA and the von Karman Institute for Fluid Dynamics. The result of the group's efforts was the definition of an aerodynamics acceptance test which establishes minimum standards for deicing/anti-icing fluids' flowoff characteristics.

A. Airplane Performance Considerations

With all engines operating, the effects of deicing/anti-icing fluids on airplane performance are considered negligible. However, with an engine failure at the critical engine failure speed V_1, and when the aircraft is operating at minimum allowable performance levels, adverse aerodynamic effects of the fluids can become more evident and significantly affect takeoff and climb performance for airplane designs similar to the 737-200ADV. Because of the low probability of a performance-limited airplane having an engine failure at V_1 with the fluid present, previous unrestricted use of deicing/anti-icing fluids has had an excellent operational record. However, airworthiness regulations do require consideration of an engine failure at V_1 when scheduling airplane performance. Prudence dictates that criteria be defined to insure adequate airplane performance when operating near minimum performance levels with a failed engine and the fluids present.

The criteria that has been established encourages proper aircraft ground deicing/anti-icing procedures, so that the intent of regulations requiring aircraft be free of ice, snow, and frost are met without undue takeoff performance adjustments. Underlying considerations of the takeoff performance criteria include the following: 1) aircraft safety is paramount; 2) the fluid effects are transitory; 3) diluted Newtonian fluids have been safely used without operational performance adjustments; 4) nonNewtonian fluids have been successfully used by European, Asian, and North American airlines; 5) both Newtonian and nonNewtonian fluids will be used, depending on anti-ice protection requirements; and 6) caution is required when considering use of fluids on a contaminated runway.

Specific aspects of the takeoff maneuver addressed by the criteria include 1) adequate margin between V_2 and the 1g stall speed; 2) adequate margins between liftoff and minimum unstick speeds; 3) adequate aft body runway clearance during takeoff; 4) adequate takeoff acceleration and climb capabilities; and 5) adequate maneuver capability to stall warning. Of these five criteria, the first is most critical. A minimum V_2 speed of 1.1 $V_{S_{1g}}$ was selected. The 10% V_2 speed margin to the 1-g stall speed compares with a 13% margin airworthiness requirement currently used for the nominal dry, clean wing. For aircraft whose normal V_2 speeds are at the minimum margin, 1.13 $V_{S_{1g}}$, the acceptable maximum lift loss resulting from reducing the minimum margin V_2 speed to 1.10 $V_{S_{1g}}$ for the fluids is 5.24%. For aircraft whose V_2 speed margin to the 1-g stall speed is larger, the concern for adverse effects of the fluids on stall speed is diminished. The acceptable 5.24% maximum lift loss defines a criterion for acceptable fluid flowoff behavior.

B. Fluids Aerodynamic Acceptance Test

In light of the results of the flight and wind-tunnel evaluations of the deicing/anti-icing fluids and the influence of the fluids on airplane performance, the AIA TC 218-4 group established an aerodynamic acceptance test for the fluids.

Research performed at the von Karman Institute indicated that fluid flowoff behavior could be observed on a flat surface in a small cooled wind tunnel which was capable of operational takeoff speeds and temperatures. Also, correlation was shown between lift losses measured on two-dimensional wind-tunnel models and the flat plate fluid boundary-layer displacement thickness.[16] These results suggested that a relatively simple, cost-effective aerodynamic acceptance test for ground deicing fluids could be established by measuring the fluid's boundary-

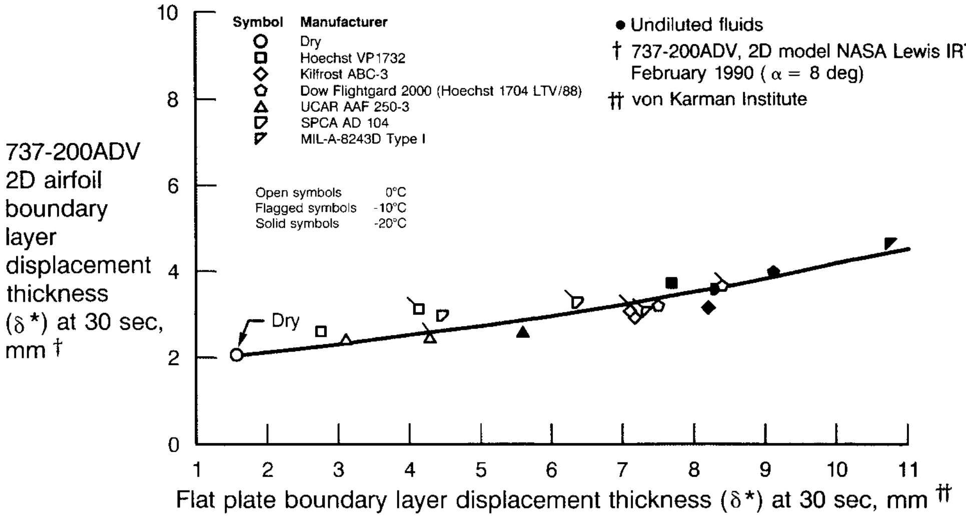

Fig. 21 Flat plate/two-dimensional airfoil correlation of boundary-layer displacement thickness.

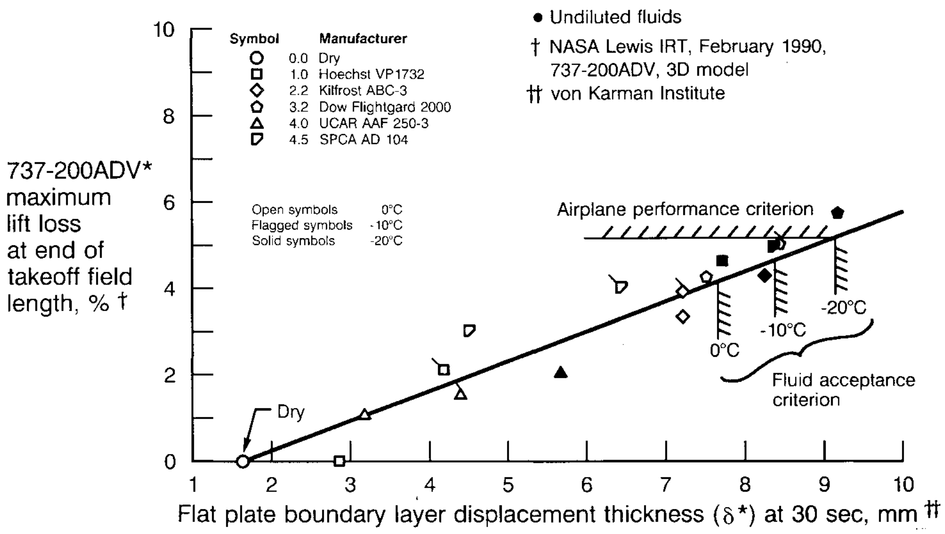

Fig. 22 Airplane performance/fluid acceptance correlation.

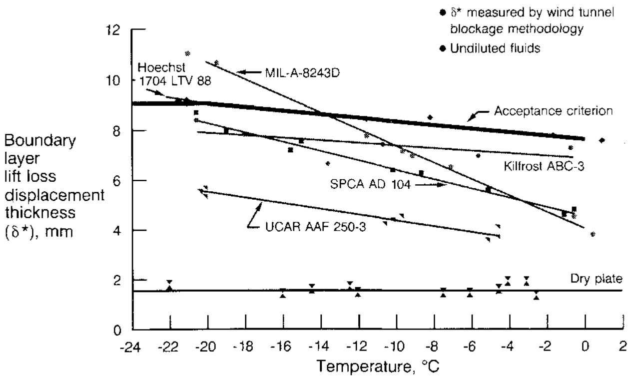

Fig. 23 Aircraft ground deicing/anti-icing fluids acceptance criterion.

layer displacement thickness on a flat plate in a small cooled wind tunnel.

Further validation of the aerodynamic acceptance test was provided by the force and boundary-layer data obtained during the 1990 re-entry into the NASA Lewis IRT. Figures 19 and 20 have illustrated correlations between lift losses measured on the two-dimensional and three-dimensional 737-200ADV wind-tunnel models and the boundary-layer displacement thickness measured on the two-dimensional model at an 8-deg angle of attack. Figure 21 illustrates the correlation between the two-dimensional model fluid boundary-layer thickness measurements and the flat plate fluid boundary-layer thickness measurements made at the von Karman Institute. The correlations shown in Figures 19, 20, and 21 suggest that 737-200ADV lift losses resulting from a fluid can be directly correlated witn the fluid's boundary-layer displacement thickness measured on a flat surface. This correlation is shown in Fig. 22.

Based on the allowable maximum lift loss of 5.24%, the 737-200ADV correlation shown in Fig. 22 indicates that a maximum fluid boundary-layer displacement thickness of 9.15 mm would be acceptable. Boundary-layer thickness measurements of several currently used deicing/anti-icing fluids, shown in Fig. 23 indicate that the fluid boundary-layer thickness tend to become thinner at warmer temperatures. This trend suggested that requiring a thinner boundary-layer displacement thickness at the warmer temperature would be prudent in that lower lift losses would be required at temperatures when contaminated runways might be encountered. The resultant fluid boundary-layer displacement thickness acceptance criterion is shown in Fig. 23. Details of the acceptance test are provided in Ref. 17.

Compliance with the acceptance test is considered a minimum requirement for acceptable aircraft ground deicing/anti-icing fluids. An airframe manufacturer may impose additional requirements which reflect considerations for airplane designs that are different than the 737-200ADV and for performance criteria not addressed by the acceptance test. The acceptance test is being incorporated as a requirement by fluid specifications promulgated by the AEA, the Society of Automotive Engineers, and the International Standardization Organization. In addition to the von Karman Institute, the University of Quebec at Chicoutimi currently has provided facilities and services to perform the test.

VI. Conclusions

Flight and wind-tunnel tests have shown that, dependent on temperature and specific fluid characteristics, Types I and II ground deicing/anti-icing fluids can measurably affect airplane lift and drag. Limiting the adverse aerodynamic effects of the fluids is considered prudent. An aerodynamic acceptance test standard has been established and is being incorporated into recognized fluid specifications to insure that fluids used by airlines to deice/anti-ice large commercial air transports have acceptable flowoff and aerodynamic characteristics.

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