Anti-icing Fluid Flow Off Process on a Wing Section during Simulated Taxi and Take-off

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Flow off process of a Type IV non-Newtonian anti-icing fluid was studied in Aalto University Low Speed Wind Tunnel during winter period 2011-12. Wind tunnel model used was a single element two dimensional fixed attitude wing section with a chord of 1.8 m. Wind tunnel test section is 2 m x 2 m. Conducted tests consisted of take-off simulations with approximately linear acceleration up to speed of 60 m/s (120 kt) and taxi simulations with constant speeds up to 15 m/s (30 kt). Results showed that during high airspeed taxi a detrimental premature flow off is possible. Comparison between one-step and two-step de-icing treatment showed no significant differences in fluid flow off properties. Tests generated some data on anti-icing fluid wave formation and propagation that may be useful in theoretical research.

Nomenclature

BLDT	=	boundary layer displacement thickness
C_f	=	friction coefficient
c	=	chord
FPET	=	flat plate elimination test
[illegible]	=	fluid shear rate
HOT	=	hold over time, time following an anti-ice treatment within which take-off has to be commenced
RGB	=	red (R), green (G) and blue (B) values of a digital image pixel. Max value =255, min value = 0
n	=	viscometer rotational speed
OAT	=	outside air temperature
TI	=	Type I fluid
TIV	=	Type IV fluid
TOGA	=	take off go around thrust = maximum available thrust on take - off and go ï around
x/c	=	chordwise relative coordinate, leading edge x/c=0, trailing edge = 1 (or 100 %)
v/V	=	local velocity ratio of airspeed on the airfoil surface; v=local airspeed, V= wind tunnel airspeed

I. Introduction

AIRCRAFT manufacturers have widely adopted an attitude to allow the use of deicing/anti-icing fluids complying with SAE Aerospace Standard AS5900[1]. This is a standard defining the test methods for aerodynamic acceptance of SAE AMS 1424[2] (Type I) and SAE AMS 1428[3] (Type II, III and IV) fluids. AS 5900 standard method is a wind tunnel test for a flat plate treated with the applicant fluid. This test is also known as FPET (Flat Plate Elimination Test). In FPET the acceptance criteria is boundary layer displacement thickness (BLDT) growth generated by the deicing/anti-icing fluids at the end of a simulated take-off run. According to material standards AMS 1424 and 1428 another acceptance criteria is that the total fluid flow off should be at least 74 % at the end of FPET-test.

Basis of FPET test lies on a lengthy correlation chain from measured lift loss during test flights (B737-200ADV) to growth of displacement thickness on a flat plate[4-7] . At the time when the present acceptance test for deicing/anti-icing fluids was created the fluids in the market differed essentially from the present fluids. Present Type II fluids are completely different from what they used to be in early 1990s and Type IV fluid appeared to the market several years after the acceptance test was adopted.

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After introduction of Type IV fluids several problems related to them have been reported by operators. Regardless of these problems not until quite recently[8-10] have there been published wind tunnel or flight tests studies to evaluate Type IV fluid effects on wings or wing sections. Basically the present acceptance test relies on studies conducted with fluids that have not been in the market for more than 15 years. Most of this research work covered only one type of wing/wing section geometry (B 737-200 ADV).

Some flight safety issues associated with the present Type IV fluids have emerged since the development of AS 5900. Fluid residue problems related to pitch control were encountered already in mid 1990s[11] and there still continue to appear reports on elevator control problems related to Type II and Type IV fluids[12]. In addition to these reported problems there has been some latent concern among the operators about Type IV fluids. One issue is the possible premature anti-icing fluid flow off during high airspeed taxiing (i.e. including the head wind effect). Another issue not addressed in any study known by the author is the effect of two-step de-icing treatment (deicing with Type I and anti-icing by Type IV) compared to effects of neat or water diluted anti-icing treatment on aerodynamic performance. Yet the standard practice to deice a contaminated wing with precipitation prevailing is always a two-step treatment. Type I fluid is obviously assumed to be totally drained out of the wing after the Type IV anti- icing treatment though factually the fluid on the wing is some kind of mixture of these two.

In AS5900 as in the majority of related research, the duration of ground roll in a simulated take-off run have been selected to be 30 s based on Boeing flight test data[4]. However revenue flight recordings[À] of more than 100 flights during winter period 2003-4 in Finland revealed that in case of Airbus 321, take-off run durations were in most cases well below 30 s. When TOGA thrust was applied at take-off ground roll endurances were between 19 to 25 s. This issue has also widely been omitted in the past publications.

A number of theoretical studies considering the behavior of deicing/anti-icing fluids subjected to airflow[13-17] have been published since early 1990s. Different methods of solving the Orr-Sommerfeld equations governing the two phase flow are in focus in most of these studies. Also experimental research has been published contributing theoretical studies[13]. These studies however are limited to flat plate cases due to mathematical complexity of the theoretical problem. Present paper includes data on wave formation and propagation on a two dimensional wing section that may be useful for verification purposes in theoretical research.

This study is first part of a two stage research program initiated in the beginning of 2012 at Aalto University to address some of the issues listed above. In this study wind tunnel tests were conducted at Aalto University 2 m x 2 m Low Speed Wind Tunnel using a fixed two-dimensional wing section model with a chord of 1.8 m. The second stage of the program will be finalized before the end of June 2013.

II. Objectives

The objectives of present study were to:

- Analyze anti-icing fluid behavior on a wing section surface during a simulated take-off run
- Determine flow off properties of the selected fluid on a wing section
- Detect possible premature fluid flow off during high airspeed taxi and if possible identify a threshold speed below which there will not be detrimental flow off during taxi
- Estimate the effect of Type I fluid to the flow off properties in a two-step treatment compared to the neat Type IV treatment

The main parameters varied in tests were initial fluid thickness and airspeed gradient (acceleration) during the simulated take-off run. As there is no possibility for temperature control in Aalto University Low Speed Wind Tunnel the prevailing outside air temperature had to be accepted as a daily changing ñfixedò parameter.

III. Test Arrangement

A. Wind tunnel

Aalto University Low Speed Wind Tunnel is a closed circuit wind tunnel with test section dimensions of 2 m x 2 m and test section length of 4 m. The flow uniformity in the test section is < 0.14 %, and turbulence level <0.1 %.

The massive concrete structures of the wind tunnel ducts are outside the facility building. This makes the tunnel structure an efficient heat sink during winter time and the fan power dissipated during the short period of a take-off

[À] Koivisto, P., ñA System Identification Analysis of Deicing Treatment Effects on Take-off Performance of Finnair A 321-fleet during winter period 2002-2003ò, Presentation for Postgraduate Seminar on Flight Mechanics at Aalto University Department of Applied Mechanics 2012-2013.

run simulation does not increase the test section temperature significantly (< 2 º C). Temperatures in the test section follow roughly the daily outside air temperatures (OAT) which during the winter time are suitable for deicing/anti-icing fluid tests (near or below 0 º C).

B. Wing Section Model

Type II anti-icing fluid tests with a two dimensional wing section model[18] were conducted at the Aalto University Low Speed Wind Tunnel during winter periods 1984 -85. As the model still existed it was utilized in present research program too. The airfoil model had a chord of 1.8 m and it spanned from test section wall to wall. The original argument for a relatively large chord was to minimize scale-effects, and this argument naturally still holds. The model was mounted to a typical taxiing attitude of a transport aircraft. Two-dimensionality of the flow was confirmed by tuft tests before test runs. According to these tuft tests there were no signs of flow separation either.

Fig. 1 is a photograph of the model attached in the test section. The fluid behavior test area spanned over 600 mm and extended over full chord (green area with applied fluid in Fig. 1)

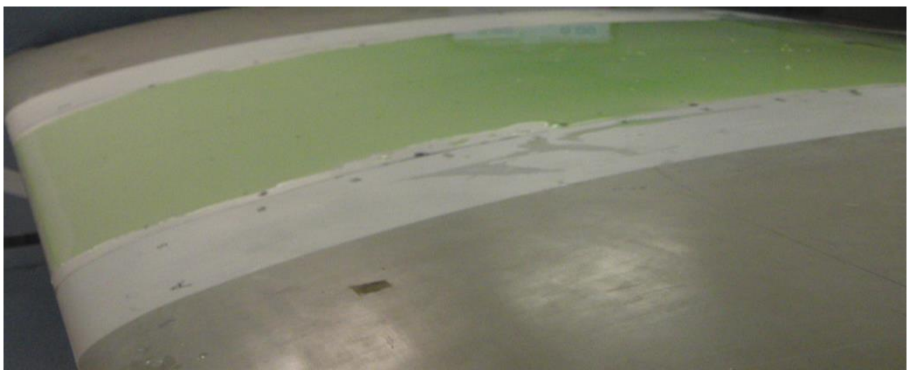

Figure 1. Wing section model in wind tunnel test section. *Fluid applied to the test area of wing upper surface. Test area spans over 600 mm and extends from leading edge to trailing edge.*

Airfoil profile of the model was a single element NACA 63-210. To duplicate a typical pressure distribution effect of a flap setting of 10º the airfoil mean line was folded downward by 5.5º at 65 % chord. The contour line was modified to retain a smooth contour shape. After the wind tunnel wall effect corrections[18] the resulting ñeffectiveò airfoil had a thickness of 10.4 % and an angle of attack of 0.3 º.

During winter period 2004-05 extensive wing upper surface temperature measurements[19] were conducted within the fleet of a Finnish operator. It appeared that the wing upper skin temperatures were seldom equal to outside air temperature (OAT) during an average turn-around. Temperature differences are caused by the very low temperatures of fuel remaining in wing tanks from the previous flight. As a rule of thumb these measurements concluded a wing skin temperature around 5ºC colder than OAT. The average OAT during the measurement period was -5ºC which means average wing upper skin temperatures of -10ºC. To simulate the skin temperature effects on the fluid properties the wind tunnel model of present study was equipped with a removable aluminum tank filled with a glycol coolant during the tests. The coolant tank extended chordwise from the leading edge to 60 % of the chord (Fig. 2). The rest of the chord was a plain aluminum plate without cooling. To monitor the fluid temperature on the wing section upper surface there was two K-type temperature sensors mounted on the skin of the wing model (Fig. 2).

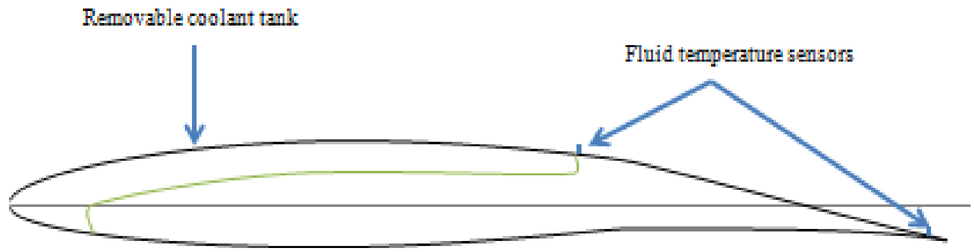

Figure 2. Cross-section of the wing model.

C. Data acquisition

In order to determine flow off properties for the applied anti-icing fluid the following manual measurements were made before and after each test run:

1) The amount of fluid applied before the test.
2) The amount of fluid scraped off from the wing surface after the tests
3) Pointwise fluid thickness before and after the tests using an Elcometer type of wet film thickness gauge. Thicknesses were measured at 5 spanwise lines with 20 points distributed evenly chordwise.
4) Skin temperature of the coolant tank in 12 chordwise positions

All test runs were videotaped through a window located on the roof of wind tunnel test section. From each test run single frames could be selected for image analysis. Wave formations were located and wave speeds calculated directly from individual video frames using the fluid depth measurement grid painted on the wing section surface as a reference.

To estimate the fluid depth development during test runs a new image analysis method was developed. As it was not an objective to measure the individual wave heights a fairly simple and low cost procedure could be considered. Type IV fluids are dyed with a green code color and it was used to determine the fluid depth. For this purpose the wing section upper surface was painted white to reflect light as evenly as possible. A MATLAB code was developed to read and process the RGB-values on individual video frame pixels. Spanwise RGB mean values were calculated for each chordwise pixel-column which after the grayscale intensity of these columns where determined as a vector sum of RGB-values (square root of sum of squares of R, G and B values).

A calibration plate painted white with grooves of known depths was utilized to define the calibration curve between grayscale intensities and fluid depth. This plate was located horizontally on the wing surface and videotaped before a test run. In addition to the calibration plate video frame two other calibration video frames were used to determine the zero fluid depth intensity and correction factors due to the curvature of the wing section surface:

- video frame of a clean wing section surface (zero fluid case)
- video frame of wing section after application of fluid before the test run (fluid depth distribution measured manually with wet film thickness gauge)

As Type I fluids are normally dyed orange it was not possible to use commercial Type I fluids in two-step tests. To enable the fluid depth determination method also in case of two-step de-icing treatment tests a special batch of green dyed Type I fluid supplied by the fluid manufacturer was used.

Wind tunnel speed, temperature and relative humidity were collected from the wind tunnel standard data acquisition system. Video tape time and data acquisition time were coordinated before each run to determine the prevailing wind tunnel speed for each individual vied frame. The two fluid temperature measurements (Fig.2) were recorded separately without time coordination to detect the average fluid temperature during each run.

D. Rheological Properties of the Anti-icing Fluid

In present study only one fluid was selected to represent the behavior of Type IV anti-icing fluids. The viscosity of the fluid batch used to the tests were determined with a Brookfield LV viscometer (spindle no LV2). The viscosity variation with shear rate (or in this case the viscometer rotational speed ***n***) is shown in Fig. 3. Viscometer rotational speed ***n*** in Fig. 3 can be converted to shear rate [illegible] using a recursive method of Ref. 20. Then the horizontal scale will be modified but the basic behavior is similar to Fig. 3, which shows the typical non-Newtonian behavior (shear thinning) of Type IV fluid.

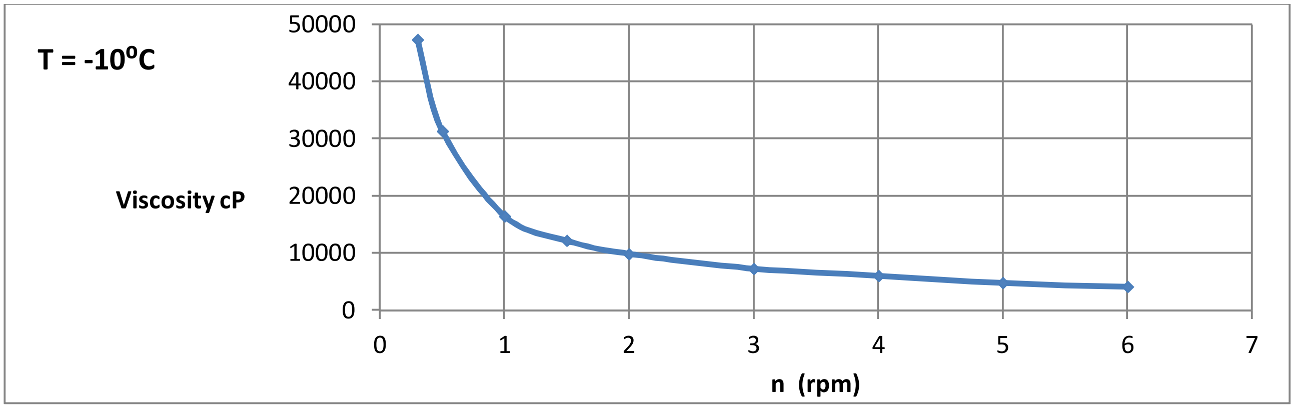

Figure 3. Viscosity variation with rotational speed of Brookfield LV viscometer (spindle no LV 2).

Probably not so typical for all Type IV fluids is the variation of viscosity with temperature for the selected fluid shown in Fig. 4. The variation of viscosity with temperature is quite modest at the range of temperatures between −10 ºC to −3 ºC (which appeared to be the range of fluid temperatures prevailing during the tests).

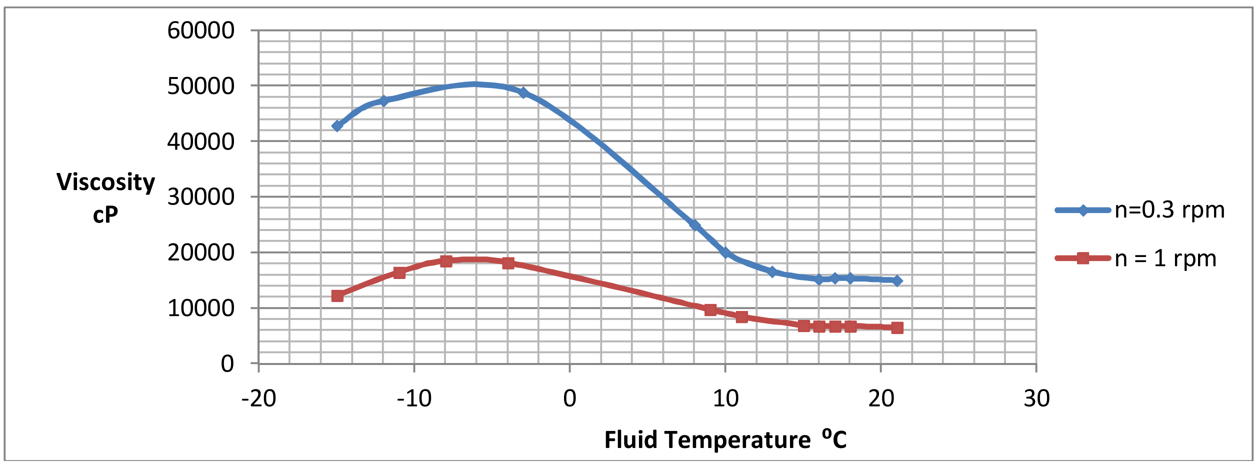

Figure 4. Viscosity variation with temperature for two viscometer rotational speeds: n=0.3 rpm (blue line) and n= 1 rpm (red line).

E. Assessment of Measurement Accuracy

Primary results of present study are related to fluid volumes and fluid layer thicknesses. The batchers used had a reading accuracy of 10 ml. Measuring accuracy of batchers left overŝ by weighing was 1 ml. When comparing the integrated pointwise thickness distribution values to batcher values the mean differences were within 5 %. Thickness gauge used for pointwise thickness measurements on wing section surface had an accuracy of 0.025 mm.

In case of thickness measurements from video frames the objectives for accuracy were related to the total volumes on the surface not individual wave heights. Random part of the error in video frames may be at least partially assumed to be evened out by the averaging process of RGB-values. Possible bias-error was at least partially corrected by the use of two calibration frames taken before the test. The only way to assess the accuracy of the method was to compare calculated volume from the last video frames to the volume measured after the test (pointwise measurements and off scraped volume). These values matched with an average accuracy of 10 %. The method is not very accurate, however sufficient to estimate the average fluid volume rate of change. By correcting the calculated curves by ratio of measured and calculated values before and after the test run the overall accuracy may be improved essentially.

Fluid wave speed values were calculated from video frames using the fluid thickness measurement point grid as a reference. All wave speeds were below 80 mm/s and the number of frames is 50 per second. Distance between two measurement points is 90 mm. By collecting only waves having approximately constant speed over two adjacent points the individual wave speed accuracy is at least 3 %.

F. Measurement Program

Test program were divided into two different types of tests: take-off run simulations with accelerating speed and so called taxi simulations where the tunnel speed were gradually increased. In take-off run simulations the tunnel speed were increased with approximately constant acceleration from a threshold value of 10 m/s to a maximum speed of 60 m/s and then decelerated to zero speed within 20 - 25 seconds. In previous studies with rotating models as well as in AS 5900 there is an additional constant speed phase included. In this study the rotation was not simulated and as all extra time after the maximum speed point will diminish the remaining fluid volume and reduce the resolution between individual tests the deceleration phase time was minimized. However one test were conducted with a 10 s constant speed phase after acceleration phase to estimate the influence of constant speed compared to 10 s slower acceleration without constant speed phase. The acceleration times from 10 m/s to 60 m/s varied between 19 s to 34s.

To identify a possible threshold taxi speed at which the anti-icing fluid begins to prematurely flow off the wind tunnel speed was gradually increased to a point when the fluid flow from trailing edge was obvious. Once the threshold speed was identified speed was kept constant for a period of several minutes to estimate the loss of fluid volume during a high airspeed taxi.

Test runs were conducted with several initial mean fluid thickness values. Mean thickness varied between 0.9 mm to 1.9 mm. There was some variation in local thickness values (mostly within 0.5 - 1 mm) due to the fact that part of the fluid drained off the leading and trailing edge before each test and due to the difficulty to distribute the fluid evenly on wing section surface.

The variation of temperatures was as follows:

- Wind tunnel air temperature: -2.6 ° to +4 ºC
- Coolant tank skin temperatures: - 18 ºC to 0 ºC

The idea of the coolant tank was partly to keep the fluid temperature within the range of small viscosity variation as there was no possibility for temperature control of the wind tunnel air. According to temperature measurements on wing section surface (Fig. 2) the fluid temperature were kept between -10 ºC to -3 ºC. Within this temperature range the fluid viscosity variations were relatively small (Fig. 4).

As pointed out in Ref. 21 the relative humidity of the wind tunnel air should be during deicing/anti-icing tests between 40% and 100% to avoid water loss from the fluid which would significantly alter the rheological properties of the fluid. During wind tunnel tests conducted for present study the relative humidity of wind tunnel air varied between 56 % and 82% the mean value being 68.6 %.

IV. Test results

Tests revealed some common features among all test runs. The flow off process seems to have a general pattern independent of test parameters. This pattern probably originates from wing section local velocity (pressure) distribution. An essential feature is that there is practically no fluid flow off without wave formation on fluid surface. This means that the wave formation plays a key role in fluid flow off process. The next two parts of this section details some general findings of anti-icing fluid behavior.

A. General Observations of Fluid Flow off process

Considering the flow off process of anti-icing fluid one distinctive feature was detected from the beginning of present study. This feature has actually been documented already in the first publications covering the research on earliest Type II fluids[4]: during the acceleration phase the flow off will be minimal before the fluid wave front reaches the trailing edge. As this phenomenon obviously governs the flow off process it is addressed more detailed in following.

The sequence of events is perceivable from the video frame series in Fig. 5. Though the times, volumes and thicknesses of the fluid changes the general picture of the process remains the same. Even the taxi tests revealed that without the wave front propagation to the trailing edge there will not be significant flow off. Fig. 5 shows how the fluid layer on the rear part of the wing section remains practically stagnant. While the wave front travels rearwards the last 35% of the chord forms a ñfluid basinò that begins to deplete not before the wave front reaches the trailing edge.

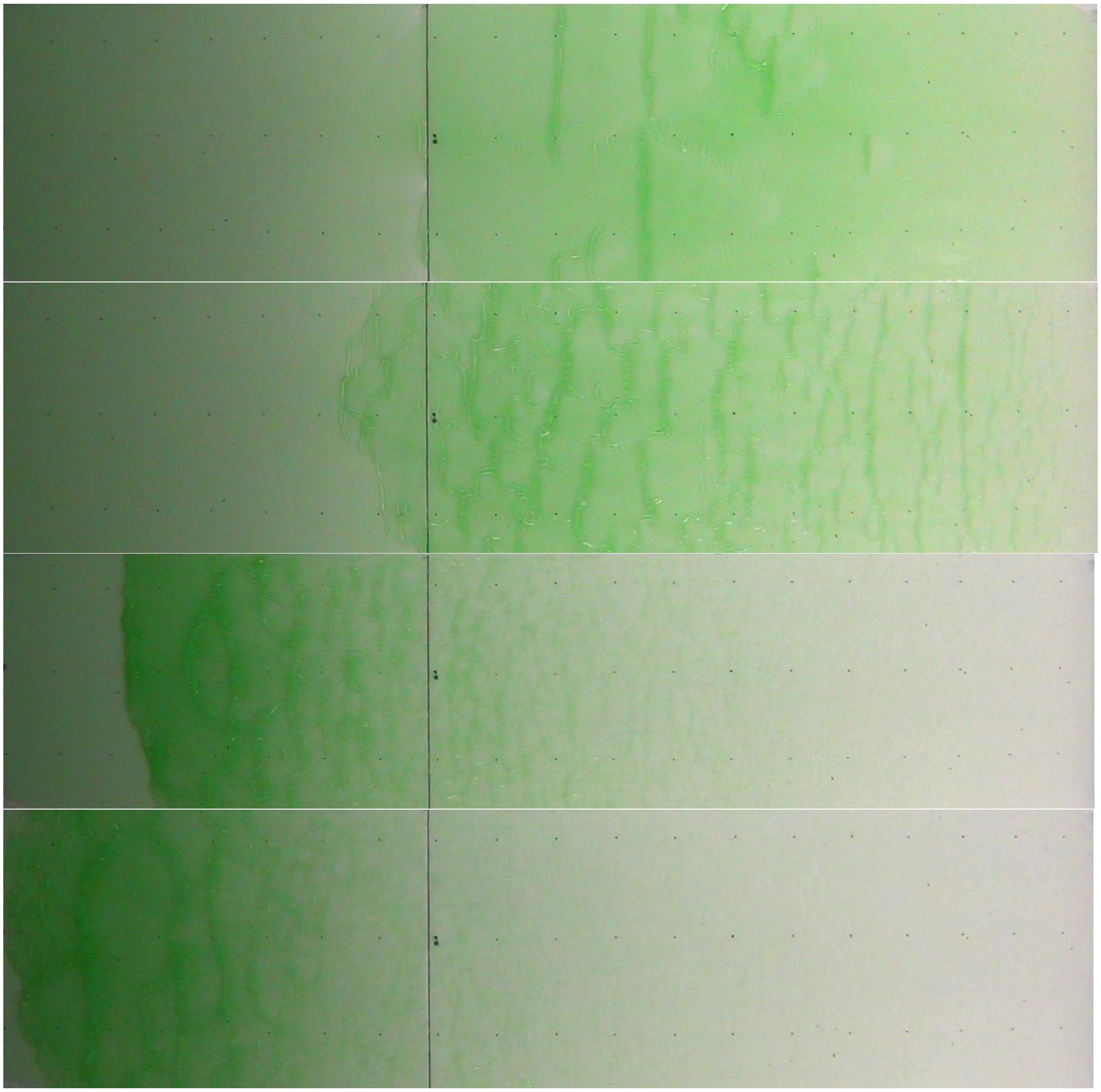

Figure 5. Videoframe sequence of a simulated take-off run. *Leading edge on the right. Numbering from top to bottom (time differences in seconds):*
1) First waves emerge (t=0),
2) Wave front starts moving (t=2.5 s),
3) Wave front on pressure rise area (t=8 s),
4) Flow off begins (t=10 s).

A counterpart for Fig. 5 in real world is Fig. 6. The wave front movement and the stagnant fluid behind it are clearly visible. In the 80 kt case of Fig. 6 flow off has begun at the wing tip area.

In Fig. 7 the flow off phenomena is illustrated by two measured thickness distributions (measured with wet film thickness gauge) after taxi simulations with different endurances (300 s and 400 s) at 15 m/s wind tunnel speed and one thickness distribution after a take-off simulation. According to Fig. 8 which illustrates the undisturbed potential flow speed distribution there is a clear pressure rise area (decreasing velocity) behind position x/c > 60 % . Fluid flow off behavior may be related to decreasing velocity at the rear part of wing section combined with boundary layer growth caused by wave induced roughness of upper surface. Local friction coefficients at the rear part may decrease due to these destabilizing effects on boundary layer. Low friction prevents the shear thinning effect and maintains the fluid stagnant at the rear part of wing section. As the front part of the wing section gradually clears of the fluid the boundary layer may recover to gain increased friction coefficients. The background of this mechanism should however be studied in more detail.

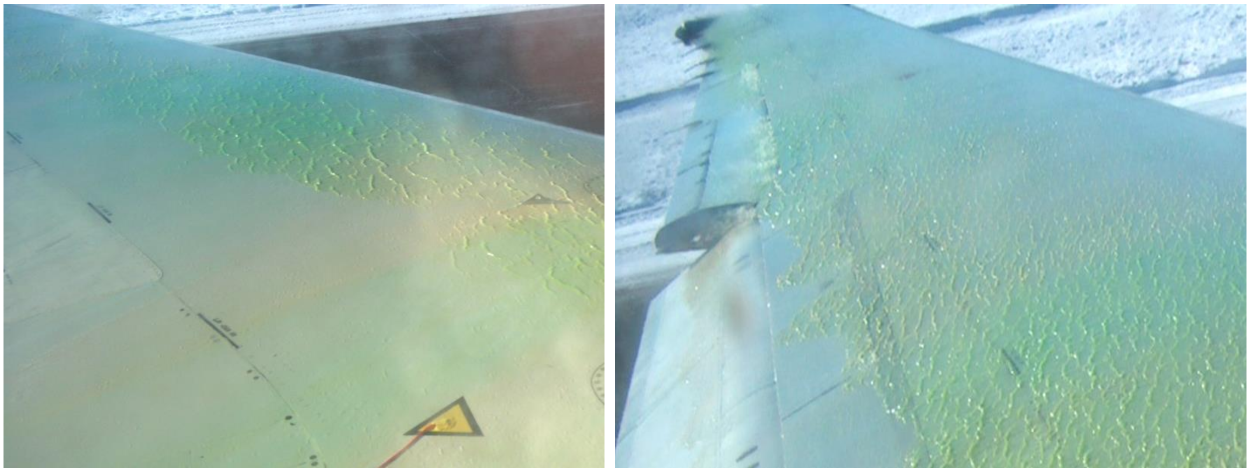

Figure 6. Wave front movement on a MD-80 wing on take-off.
1) 50 kt, *2) 80 kt.*

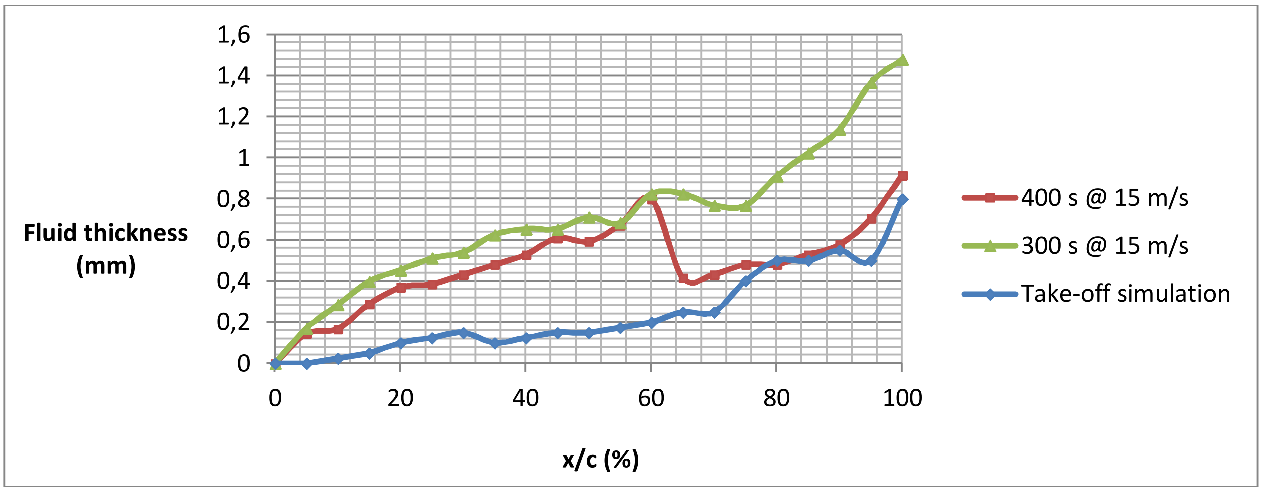

Figure 7. Wet film gauge measured fluid thickness distributions after two taxi tests and one take-off test.

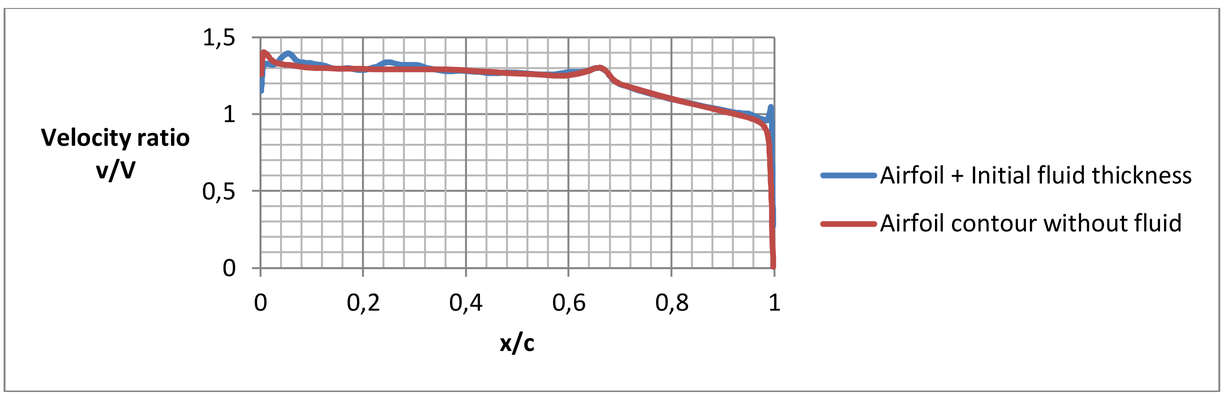

Figure 8. Test wing section upper surface relative airspeed distribution. *Airspeed distribution is calculated with an open source code (Jawafoil) and it represents potential flow without boundary layer effect.*

B. Formation and propagation of waves on fluid surface

Throughout the test program, independent of the parameters, the first standing waves on the fluid surface appeared approximately at the same wind tunnel speed. The chordwise positions of the first waves varied from 20% to 60%. However in 70% of the tests the initial wave appeared between 25% - 45% of chord, mean value of all tests being 32%. This chordwise variation of wave appearance position may be caused by varying velocity distribution caused by varying initial thickness distribution on the profile contour when fluid is added ï see Fig 8.

The wind tunnel speed at which the first standing or slow moving discrete waves appeared varied between 10 - 13 m/s mean value being 11.1 m/s. Converted to local airspeed at the surface of the wing section the variation was 13 - 16.9 m/s with mean value of 14.4 m/s. There seemed not to be correlation between the local airspeed at wave appearance and any other test parameter ï see Fig. 9.

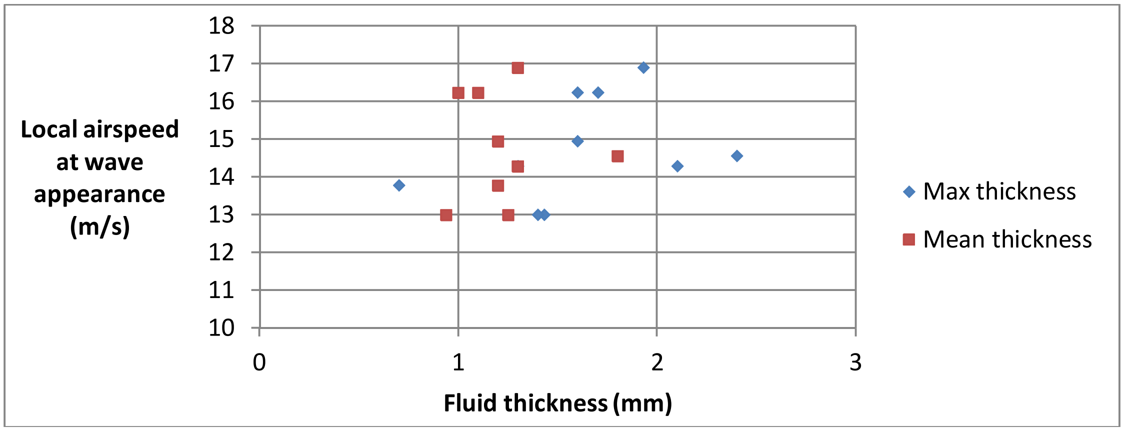

Figure 9. Variation of local airspeed at fluid wave appearance with fluid thickness.

Özgen, Carbonaro and Sarma[14] have reported initial wave appearance for a Type IV (non-Newtonian) fluid (not necessary the one used in present study) on a flat plate at tunnel speeds of 11.4 ï 12.9 m/s. In Ref. 14 there was a dependence between initial fluid thickness and airspeed of wave appearance. When comparing the local wave onset speeds on the flat plate of Ref 14 and on the profile of this study the maximum difference is approximately 30 %. The air velocity for wave initiation in Type II fluid on a flat plate was studied theoretically also in Ref. 20 where the onset velocity was 14 -15 m/s depending on fluid temperature.

Chordwise position of waves affects the wave propagation process. From leading edge to 60 % of the chord there was no clear observable wave front whereas at the rear part of the section there was a distinct build up of fluid with a wave front. Discrete wave propagation was easier detected on the front part of the wing whereas the fluid at the pressure rise area (>60 % of the chord) formed more or less a wavy ñfluid basinò. This ñfluid basinò had a clear front moving towards trailing edge in a pulsewise manner ï as is seen in Fig. 10.

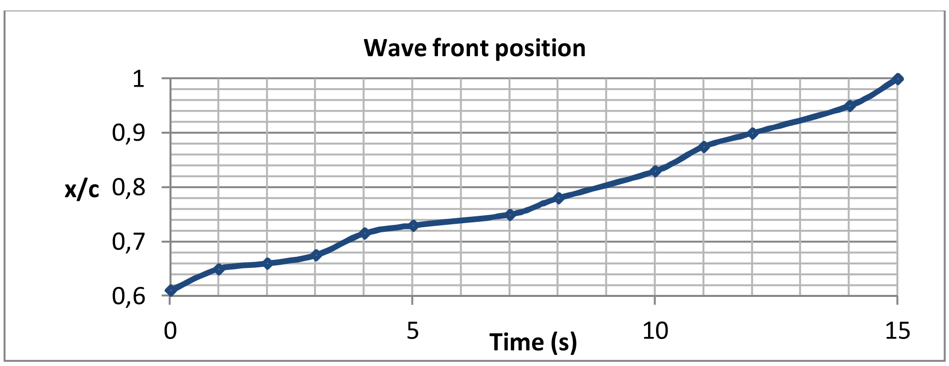

Figure 10. Variation of wave front position (behind 60 % of chord) with time.

Propagation of individual waves on the front part of wing section (forward of 60 % of chord) was intermittent varying from full stagnation to computable maximum speeds. Waves were mostly two dimensional however not in full span as seen in Fig. 5. Some temporary sweep angle in the direction of waves could be detected. Measured maximum wave speeds had a clear correlation with local airspeeds at the wing profile surface as may be seen in Fig.

11. It should be noted that as there was quite a lot scatter in data of Fig. 11 the scatter was between tests not within them. Still there was no clear correlation between maximum wave speed and any of the other test parameters than local airspeed. Another characteristic feature was a distinct maximum speed of waves (0.64 m/s) that were exceeded only in some sporadic cases. Note that in Fig.11 the wind tunnel speeds are converted to local profile airspeeds using the potential flow relative airspeed distribution of Fig 8.

Measured maximum wave speeds of Fig.11 match quite well with the ones reported by Papadakis, Strong and Wong[22]. However the wave speeds are described as a function of time instead of airspeed in Ref 22.

The non-Newtonian shear thinning feature is obviously in a key role of Type IV fluid behavior and flow off process. During a flow off there are most probably different layers of fluid with very different viscosities within the wing section upper surface. This makes the process as a whole quite complicated to tackle theoretically and it is apt to increase scatter in experimental test results.

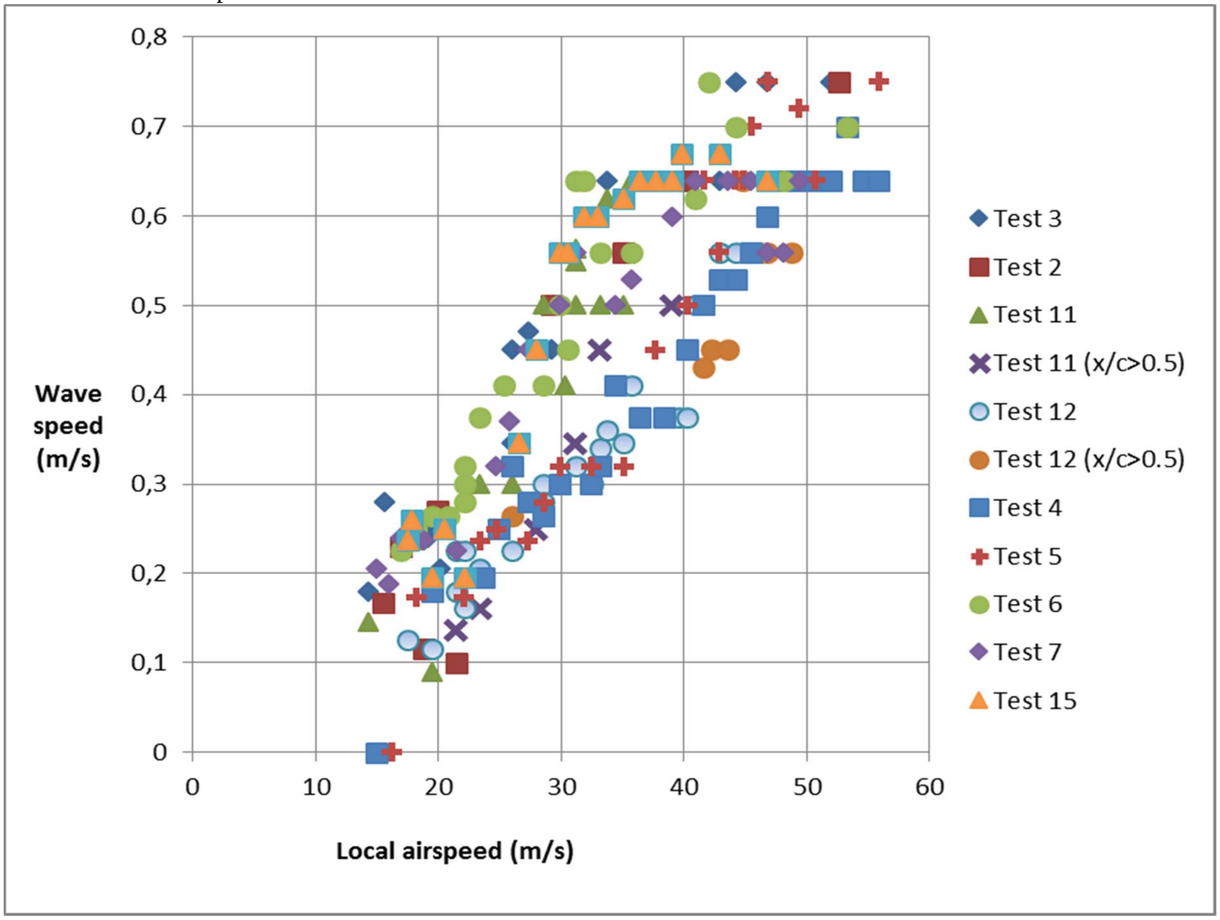

Figure 11. Correlation between maximum fluid wave speeds and local air speed on profile surface.

C. Take-off simulation results - effect of fluid initial thickness

Initial fluid mean thickness varied from 0.9 to 1.9 mm. Total fluid volume measured form individual video frames were converted to mean thickness by dividing with application area (see III. B.). Mean thickness value variation with time for different initial thicknesses during simulated take-off tests is presented in Fig 12.

One obvious result seen in Fig. 12 is the one reported in several studies[4,5,6,21] ï final fluid thickness is independent of the initial fluid layer thickness. Mean thickness values merge fairly well within 24 s from the start of take off simulation test. The final thicknesses of the two initially thinner fluid layers seem to differ more than final thicknesses of initially thicker and thinner layers.

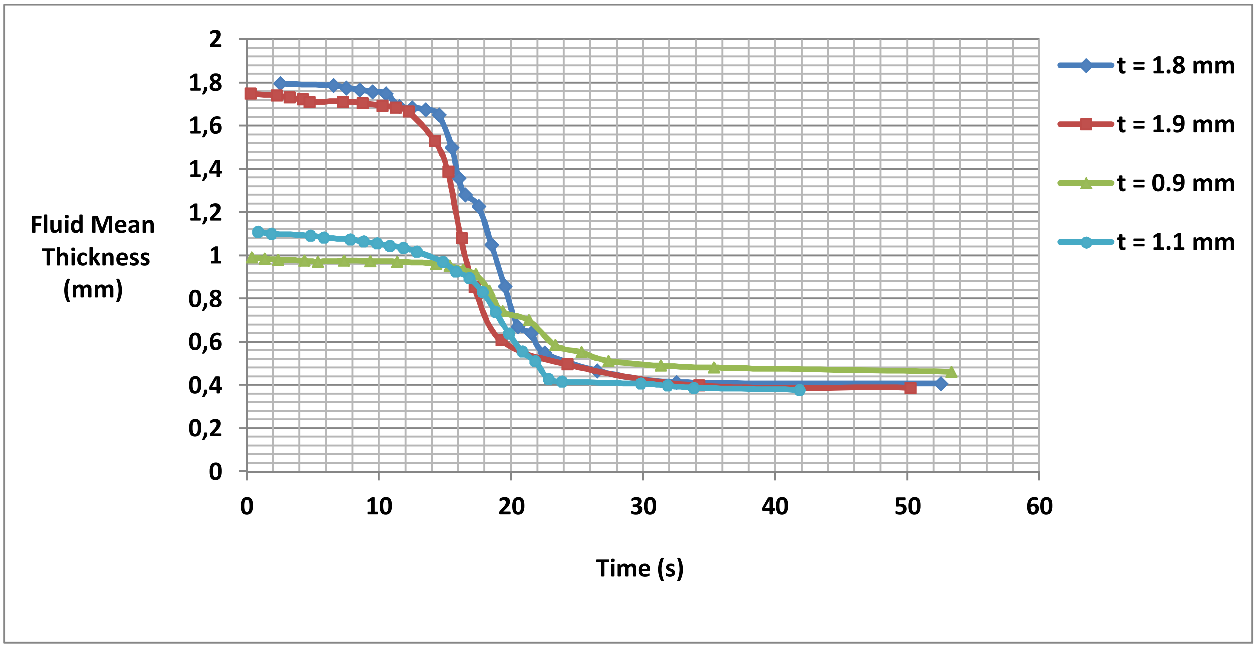

Figure 12. Fluid mean thickness variation with time for four different initial fluid thickness values during a simulated take off.

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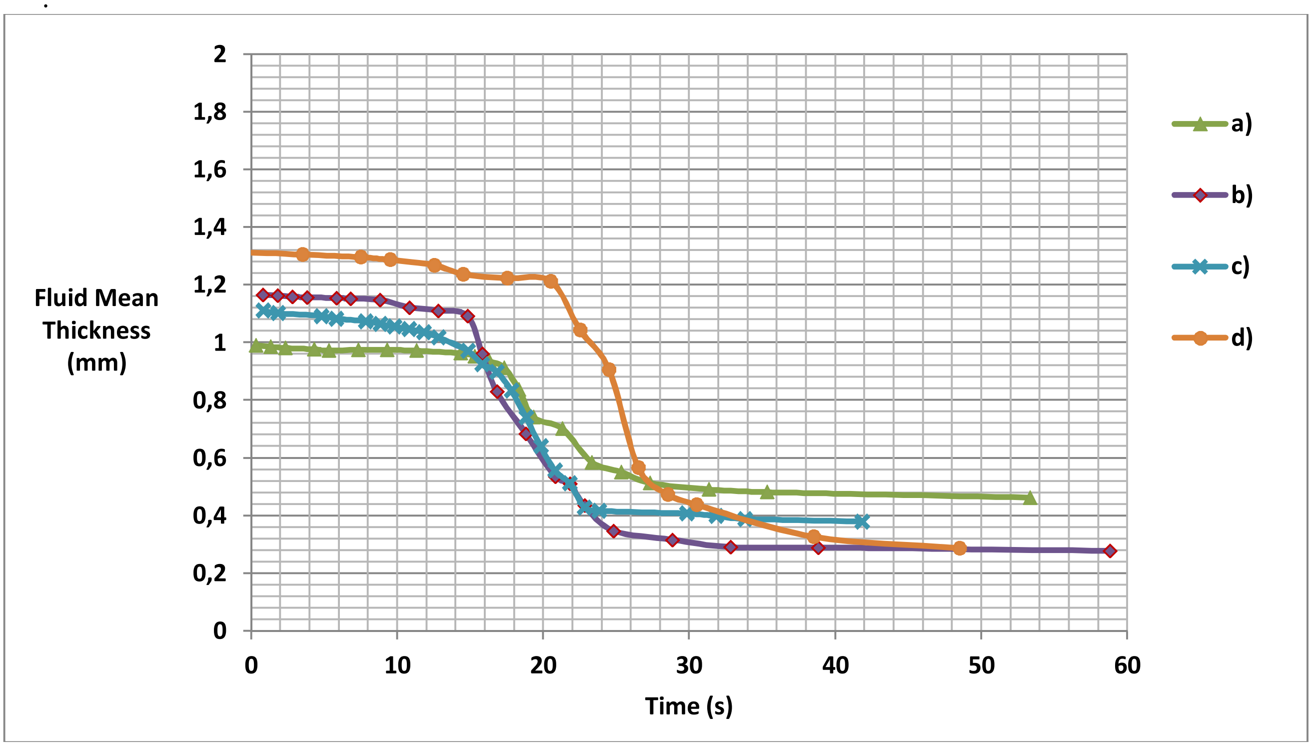

Figure 13. Fluid mean thickness variation with time for four different wind tunnel airspeed acceleration.

Case: a)Acceleration time (time from 10 m/s to 60 m/s) ***19.3 s,*** *initial thickness =0.9 mm,*
b)Acceleration time ***20 s*** *added to a constant speed of* ***10s****, initial thickness = 1.2 mm,*
c)Acceleration time ***24.8 s****, initial thickness = 1.1 mm,*
d)Acceleration time ***33.5 s****, initial thickness=1.3 mm.*

D. Take-off simulation results - effect of acceleration time

Effect of acceleration time to mean fluid thickness on wing section model is presented in Figure 13. Acceleration time is the time to accelerate wind tunnel speed from 10 m/s to 60 m/s. Initial thicknesses vary between tests from 0.9 to 1.3 mm but as noticed in previous chapter the initial thicknesses do not affect the final thicknesses.

There is a clear almost linear correlation between the final mean thickness and acceleration speed as can be seen in Fig. 14. Note that acceleration speed does not include any constant speed phase in Fig. 13 cases a), c) and d) as they have been conducted with an ñaccelerate stopò method to increase the resolution of results. And indeed the final thicknesses have significant differences considering the variations of acceleration times in reality (referred above) compared to the SAE AS 5900 standard acceleration time of 30 s.

Acceleration in 20 s added with a constant speed phase of 10 s leads to quite identical final thickness as an 33.5 s acceleration and stop ï however within a shorter time (see Fig. 14 cases b) and d).

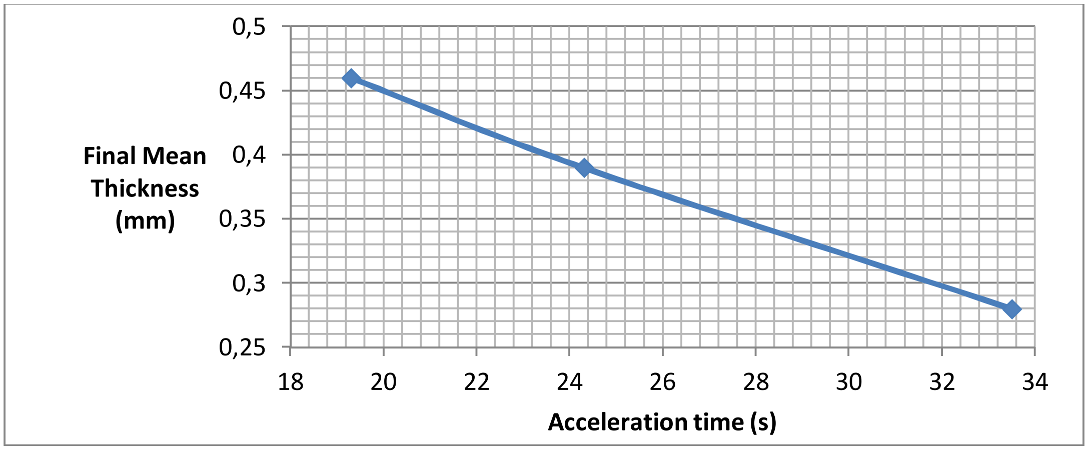

Figure 14. Final mean thickness variation with acceleration time.

E. Take-off simulation results - effect of two-step de-icing treatment

The two-step de-icing treatment was simulated by an initial application of diluted Type I de-icing fluid (30 %) before application of Type IV anti-icing fluid. Diluted Type I fluid is considerably thinner liquid than neat Type IV which caused it to drain off the surface much easier leaving only a very thin film of fluid on the wing. The mean thickness of Type I fluid after application was 0.37 mm. Though Type I fluid formed a thin layer, its proportion was 3-5 % of the total thickness which made it reasonable to study its effects on fluid flow off behavior.

According to Fig. 5 the effect of Type I fluid in two-step treatment is marginal. The test parameters, initial thickness and acceleration time, are almost equal with small deviations. This is in line with a generally adopted assumption, not based on any research before, that the anti-icing fluid layer squeezes the deicing treatment remains to a volume with diminishing effects on flow off properties.

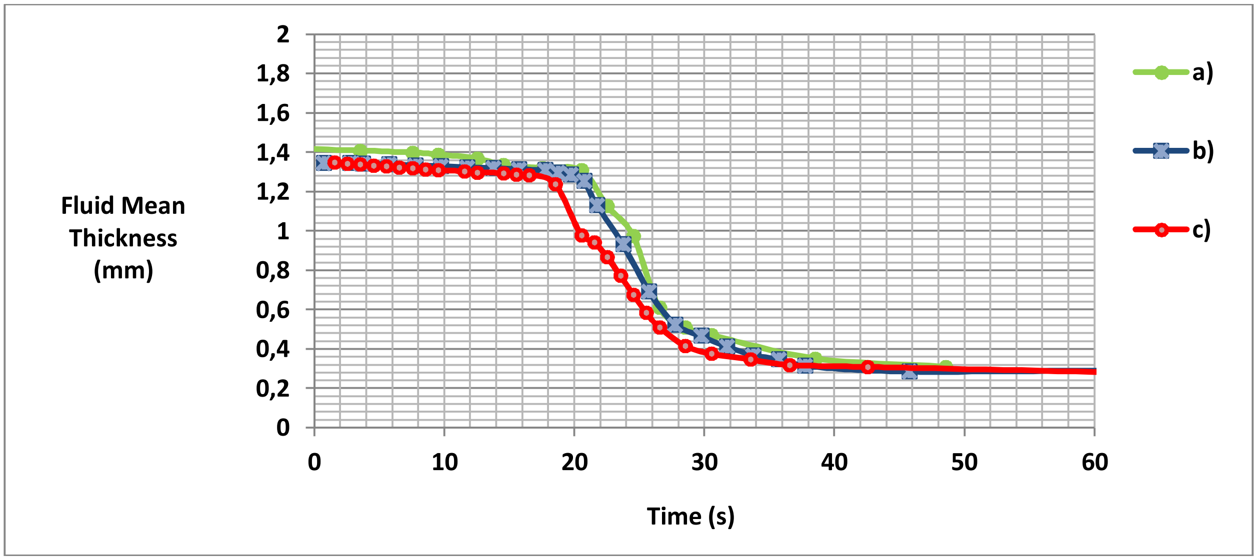

Figure 15. Fluid mean thickness variation with time for one-step (neat Type IV) and two-step (30 % diluted Type I and neat Type IV) deicing treatment:

a) One-step treatment ï initial fluid thickness 1.3 mm, acceleration time 33.5 s,
b) Two-step treatment ï initial thickness 1.2 mm, acceleration time 33,7 s,
c) Two-step treatment ï initial thickness 1.25 mm, acceleration time 32,5 s.

F. Taxi simulation results

In previous studies an implicit or explicit[20] assumption has been done that there is no significant flow off during taxi phase. However no experimental research on the issue has been found by the author. This study tries to address the effects of high speed taxi on premature fluid flow off. In this context high speed means high airspeed, it is: combination of standard taxi ground speed and a strong headwind. The taxi ranges may at some airports extend to distances which may well be equivalent to taxiing with 30 kt (15 m/s) airspeed for more than 15 min.

To discover the possibility for any detrimental premature anti-icing fluid flow off during taxi before take-off it is essential to find a threshold airspeed at which a significant flow off starts. In order to find this kind of a threshold airspeed the wind tunnel speed was increased by small steps and trailing edge flow off was constantly monitored.

The essential findings in fluid flow off process during taxi tests were as follows:

- The first waves appeared as documented above (during take-off simulations) at wind tunnel speeds of around 10 m/s (20 kt) which means converted to wing section local velocity of 13 m/s
- There was no significant wave front build up in the rear part (behind 60 % of chord) ï before wind tunnel speed of 14 ï 15 m/s (28 ï 30 kt)
- After this threshold speed of 14-15 m/s had been reached the detrimental flow off was a matter of time: as the wave front reached trailing edge a significant drain from the trailing edge started.

Results of taxi simulation tests have been collected to Fig. 16. It shows that taxiing at speeds exceeding 14 m/s (28 kt) for more than 4 min begins a process where premature flow off will be detrimental. During a 7 min taxi with airspeed of 30 kt or more will lead to mean fluid thickness less than a half of the initial thickness. This kind of a fluid flow off will certainly affect the Hold Over Time (HOT) of the fluid. Fig. 16 also reveals that there is no significant difference between one-step de icing treatment (neat Type IV) and two-step de icing treatment (30 % diluted Type I + neat Type IV) regarding premature fluid flow off.

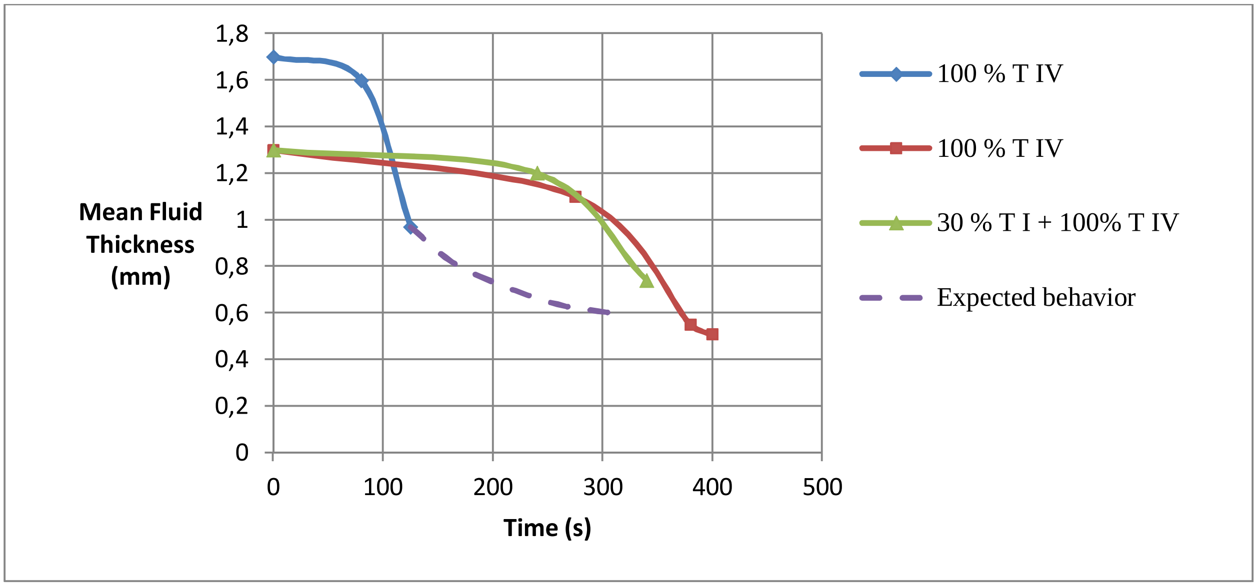

Figure 16. Mean fluid thickness variation with endurance at wind tunnel speed of more than 14 m/s.

V. Conclusion

Wind tunnel experiments were conducted at Aalto University Low Speed Wind Tunnel facility during winter period 2011-2012. Objectives were to study fluid behavior and flow off process in general during a simulated take-off, to detect possible premature flow off during taxi phase and to estimate the effect of two-step de-icing treatment on fluid flow off properties. A simple low cost videotape recording technique was applied to determine the variation of mean fluid thickness over the wing section surface Present study were limited to cover only one specific Type IV anti-icing fluid.

Take-off simulations were conducted using an ñaccelerate stopò-method to achieve better resolution in results than in the conventional ñ30s acceleration plus a constant speed phaseò ï method. The results considering general behavior and flow off properties of non-Newtonian Type IV fluids were consistent with the results reported earlier in the literature. Results considering two-step de-icing treatment compared to one-step anti-icing treatment showed no significant differences. This is in line with the adopted assumption within de icing practices that the Type I fluid will be displaced by the anti-icing fluid (Type IV). However it has to be noted that this study covers fluids only by one manufacturer.

An alarming result of present study is the detected premature detrimental flow off of anti icing fluid during taxi phase. According to this study the Hold Over Times of fluids will be fatally reduced during a sustained high speed taxi. Further research should be initiated with more than one fluid type to confirm the results. As the results have direct flight safety related consequences it should be considered to do full scale taxi tests with anti-icing fluids. It should be noted that expenses for full scale taxi tests are a fraction of flight tests. If full scale tests confirm the results of present study, taxi speed limitations have to be immediately considered thereafter.

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