Finnish Transport and Communications Agency

# A Brief Survey on Possibilities to Model the De/anti-icing Fluid Flow Off by an AdHoc Method

Pekka Koivisto, Aalto University

Traficom Research Reports

**18/2019**

Finnish Transport and Communications Agency

Date of publication
October 15th 2019

| | |
|---|---|
| Title of publication<br>**A Brief Survey on Possibilities to Model the De/anti-icing Fluid Flow Off by an AdHoc Method** | |
| Author(s)<br>Pekka Koivisto | |
| Commissioned by, date<br>Marko Sillanpää, December 5th 2013 | |
| Publication series and number<br>**Traficom Research Reports 18/2019** | ISSN (online) 2669-8781<br>ISBN (online) 978-952-311-344-2<br>URN http://urn.fi/URN:ISBN: 978-952-311-344-2 |
| Keywords<br>Aerodynamics, anti-icing fluids, deicing fluids | |

Abstract

This document is a short summary on the aspects and possibilities to simulate the complex phenomenon of flow off of an air driven de/anti-icing liquid from a flat plate by an AdHoc method. In this document AdHoc method means a simplified calculation method that is not applicable to any other flow condition but is simplified from the more general flow simulation models. The original objective of simplifying the driving aerodynamic forces acting on wavy liquid layer on a flat plate under an airflow had to be neglected however as the complex nature of airflow was revealed during a parallel CFD study that was a part of the same project (Icewing 3). To simplify the unsteady separated airflow with continuous vortex shedding on the top of the waves turned out to be out of the scope of this study.

Another trial to tackle the problem was to find a semi-empirical method using correlations discovered from the measurements. This method turned out to be more fruitful than the initial one. Although it is partly based on over simplifications of some of the correlations between the considered variables the closed form equation derived for time dependency for thickness of the fluid gives reasonable results. Despite some flaws in the equation it may be a good starting point for development of a refined AdHoc method.

| Contact person | Language | Confidence status | Pages, total |
|---|---|---|---|
| Erkki Soinne | English | Public | 17 |

| Distributed by | Published by |
|---|---|
| | Traficom |

# FOREWORD

This report is focused on anti-icing and deicing fluids behaviour, which is an important subject in aviation safety. The report is part of the Icewing research conducted by the Finnish Transport Safety Agency Trafi in 2014. Due to a mishap the publication of the report was missed and is done first now.

Helsinki, 15.10.2019

Erkki Soinne
Chief Adviser, Aeronautics

Finnish Transport and Communications Agency Traficom

## Table of Contents

# Nomenclature

| | |
|---|---|
| *AAT* | = Aerodynamic Acceptance Test |
| $c_w$ | = wave speed |
| C | = k*r*p/q (see below) |
| $C_2$ | = 0.02*C |
| *d* | = thickness of fluid |
| $d_0$ | = initial fluid thickness |
| h | = height of a wave |
| *k* | = wave shape factor |
| *L* | = length of flat plate |
| p | = proportionality factor |
| q | = proportionality factor |
| *OAT* | = outside air temperature |
| *Q* | = volume (in 2 D area) flow |
| *TI* | = Type I fluid |
| *TII* | = Type II fluid |
| *TIV* | = Type IV fluid |
| U | = velocity of air |
| V | = volume of liquid (in 2 D area) |
| w | = width of a wave |
| $\lambda$ | = distance between two isolated waves |

# 1 Background and Objectives

A widely adopted perception of the flow condition considered in this study is illustrated in Figure 1. Overwhelming majority of the previous literature on subject considers the problem to be simplified as follows:

- Under the free stream (with air velocity of $U_\infty$) there is a (laminar or turbulent) steady boundary layer of thickness δ
- At the interface of air and liquid both fluids have an equal speed of $U_i$
- Between the interface of air and liquid and the solid wall of a flat plate there is the liquid layer having a linear velocity distribution in vertical coordinate y

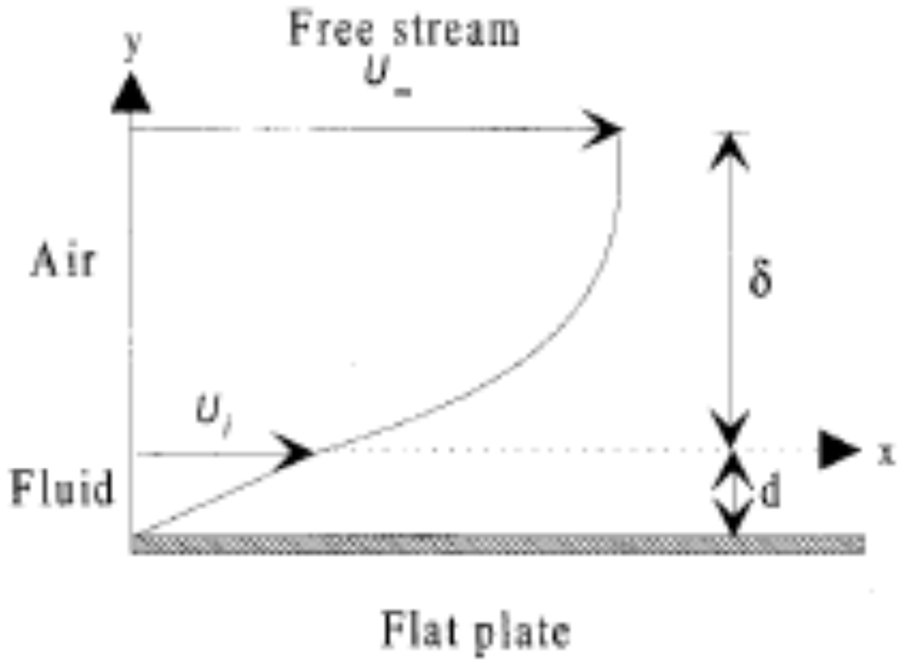


**Figure 1.** Configuration of the flow condition considered

The simplified model of Fig. 1 was initially the basis for a simplified AdHoc-model of this study. There are several published methods utilizing the idea of pure shearing force on the interface neglecting the wave formation[1,2]. However these methods do not lead to satisfactory results when compared to measurements. Reference 3 points out that instead of shear the pressure forces around the waves will be significant once the liquid layer is thick enough – quoting Ref. 3: *"When the film exceeds a certain critical thickness which is small percentage of the boundary layer thickness, then air pressure gradients drive the wave motion. Pressure driven waves are found to control mass flux within the film."*

The initial objectives of this study were:

- to model the pressure forces referred above by finding a separated or attached simplified boundary layer flow
- to model the liquid flow under the aerodynamic forces including the shape of the free surface
- to model the interaction of free surface and aerodynamic forces

It appeared quite soon that the last objective would be very complex though the wave speed is two orders of magnitude smaller than the air speed and could be therefore neglected.

The futility of the initial objectives was revealed at latest when the CFD results of the same problem showed that the airstream is far from the ideal one described in Fig.1. Figure 2 illustrates the flow above the waves according to LES-CFD-calculations. There is an unsteady flow with continuous vortex shedding from the top of the waves above the liquid layer. These vortices are sweeping the waves at a speed of two orders of magnitude faster than the waves are propagating.

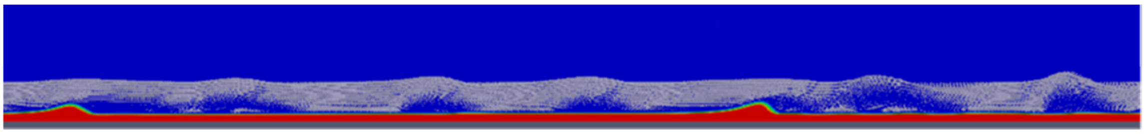

**Figure 2.** Vortex shedding of airflow (white arrows are airspeed vectors) over wavy liquid surface (red surface).

Another way to tackle the problem of AdHoc modeling was the use of measured data to find simplified correlations between some of the variables of the fluid flow and air flow. The data that is available for this purpose in some studies[4,5,6] consist of:

- wave speed variation with airspeed
- wave height variation with fluid thickness
- wave length (or separation of solitary waves) variation with fluid thickness

The data about the waves referred above are relevant only if the relationship between the total liquid volume flow and the wave data is known.

# 2 The Method of Correlations

The above mentioned CFD-calculations clarified not only the structure of the airflow but also the structure of fluid flow. It turned out that the liquid fluid convection was concentrated practically in whole on the wave motion. As is illustrated by Figure 3 (part of the Trafi report not yet published) the movement of fluid is concentrated in the wave whereas the fluid outside the wave is practically stagnant.

This fact enables the fluid volume flow to be estimated as soon as the wave form, length, height, speed and the distance between two adjacent waves are known. Also the critical air velocity at which the first fluid wave appears should be known. Note that in the case of this particular flow condition (flat plate with liquid film under airstream) the waves cannot be considered as a conventional wave group with constant wave length but more as a group of solitary waves with somewhat varying distance between the waves. According to experiments[5,6] there exist merging between waves and some of the waves fade away during their way on the surface. However the distance between the waves may be calculated as an average from the experiments and assumed to be constant in the AdHoc model.

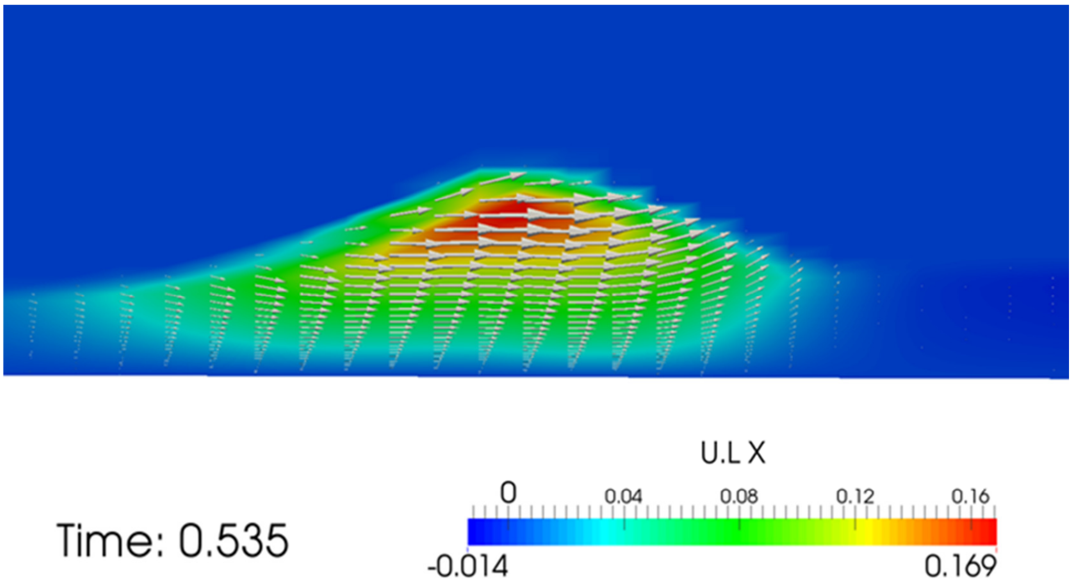


**Figure 3.** Liquid fluid velocity field in and around a wave.

## 2.1 Wave speed variation with air velocity

There are only two published experimental studies[5,6] where the wave speeds have been measured. In Ref. 5 the wave speeds have been measured on a wing section upper surface under an accelerating air velocity. Figure 4 illustrates the relationship between these parameters. There was a similar analysis done for the wing section of Reference 7. The results of these are partly collected to Figure 5.

The results shown in Fig. 4 and 5 pertain only to Type IV fluids. In Reference 6 there is several different Type I and Type IV fluids considered. However the test arrangements differ from the References 5 and 7. In Ref. 6 the tests are done with a flat plate duct and the airspeed has been increased slowly up to the point when first waves are detected and then stopped there. The results[6] of wave speed variation with initial fluid thickness is shown in Figure 6 for Type I fluid and in Figure 7 for TIV fluids. The air velocities corresponding the wave speeds of Ref. 6 are found in Figure 8.

A similar type of tests as described above (Ref. 6) were done also for a wing section in Ref 5. These results are illustrated in Figure 9. The correlation between wave speeds and initial thickness found in Figure 6 and partly in Figure 7 is totally absent in Figure 9. In addition the neat TIV and 50 % diluted TIV fluids have a wave speeds that differs one order of magnitude or more between the 25% diluted TIV and TI fluids. The TI fluid results are better in line with measurements in References 5 and 7 than with the TIV fluids in the same study.

The wave onset air velocity (the speed of air at which the first wave appear) varies according to Ref 6. between 6-13 m/s (flat plate) and according to Ref. 5 the local air velocity between 13-17 m/s (approximately 1.3 times the wind tunnel speed for the wing section).

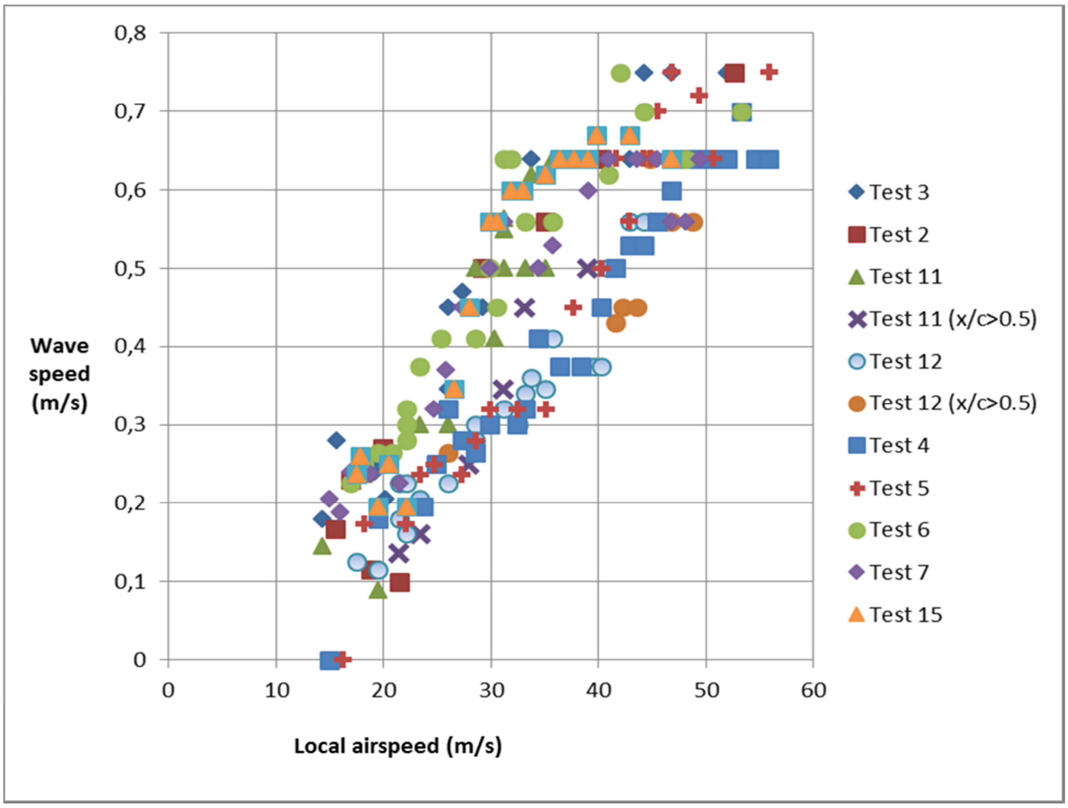


**Figure 4.** The wave speed variation with local air velocity on a wing section upper surface according to Ref 5. All tests done with a TIV non-Newtonian fluid.

A linear fit for wave speed ($c_w$) as a function of air velocity from data in Figures 4 and 5 may be written as:

$c_w = 0.0175*(U_{air} - U_{cr})$   Figure 4

$c_w = 0.022*( U_{air} - U_{cr})$   Figure 5

As a more general correlation formula one could use e.g.:

$c_w = 0.02*( U_{air} - U_{cr})$

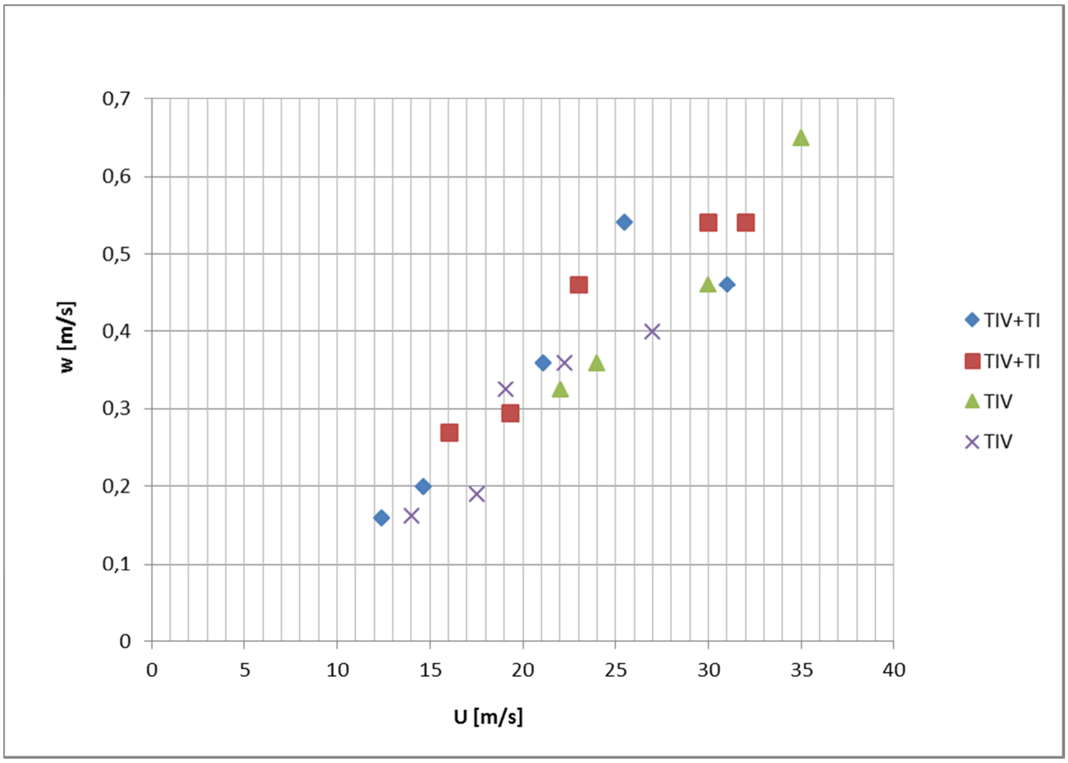


**Figure 5**. The wave speed variation with local air velocity on a wing section upper surface according to Ref 5. All tests done with a TIV non-Newtonian fluid or a mixture of TIV and TI.

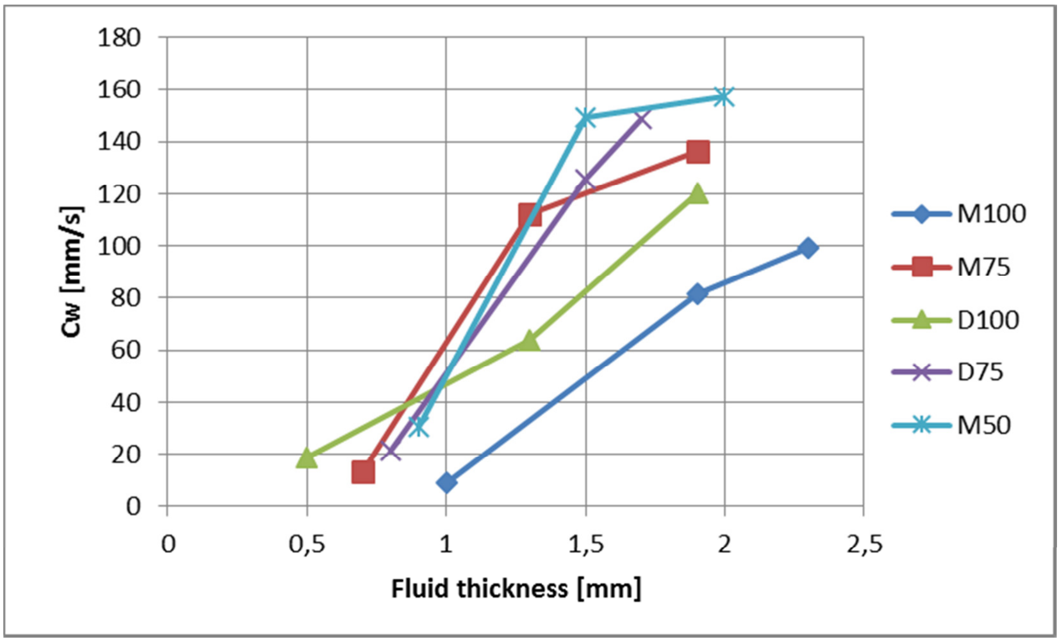


**Figure 6.** Wave speed variation with initial thickness of Ref. 6. All fluids are Type I. The number indicates fluid percentage in dilution where the rest is water.

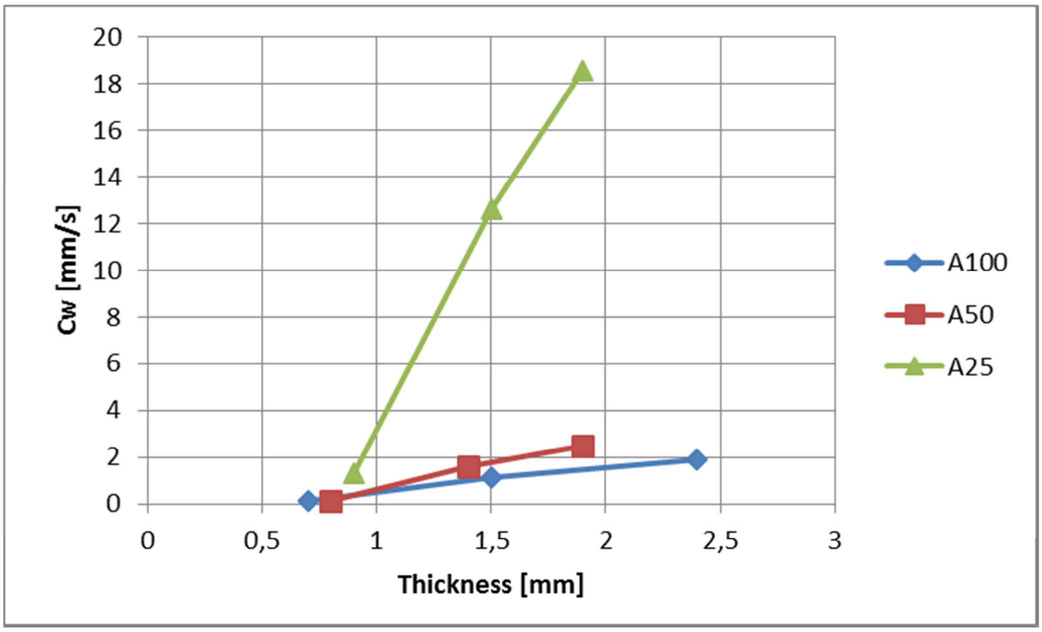


**Figure 7.** Wave speed variation with initial thickness of Ref. 6. All fluids are Type IV. The number indicates fluid percentage in dilution where the rest is water.

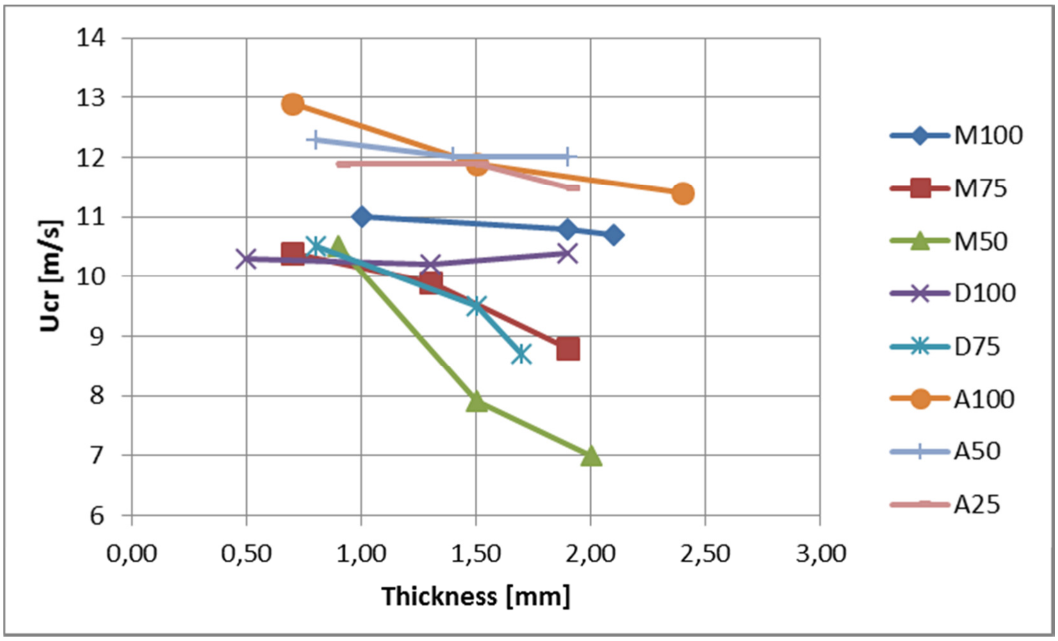


**Figure 8.** The variation of $U_{cr}$ with initial fluid thickness according to Ref.6. $U_{cr}$ is the onset air velocity at which the first fluid wave appears.

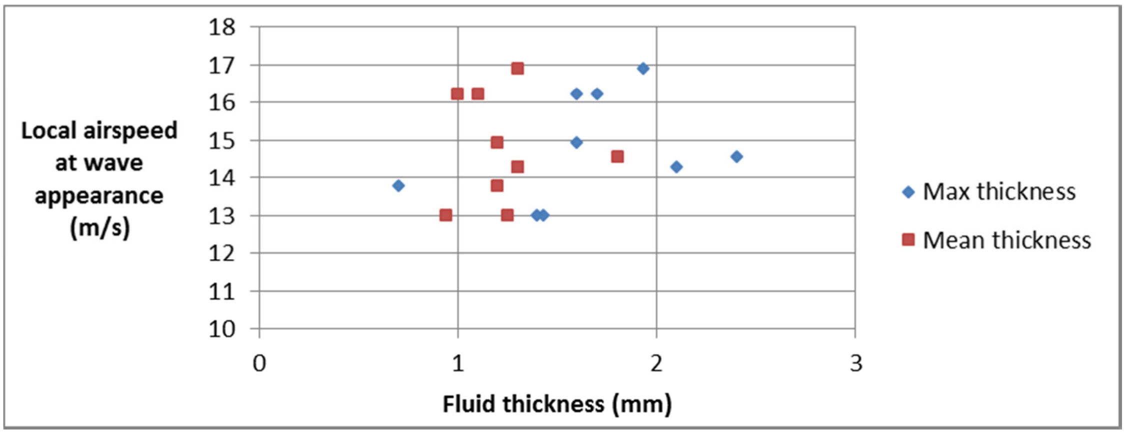


**Figure 9.** The variation of local wave onset air velocity with initial fluid thickness according to Ref.5. Onset air velocity is equivalent to $U_{cr}$ in Fig. 8.

## 2.2 Distance between waves

The distances between the fluid waves (λ) on a flat plate have been reported in references 4 and 6. By collecting the data from tables in Ref. 4 and 6 there appears some correlation between the distance λ and fluid thickness. The λ values collected from References 4 and 6 are presented in Figure 10. Note that for results of Ref. 4 and neat TI fluid of Reference 6 there appears a clear correlation however for TIV and diluted TI fluid of Ref 6. the correlation is weak or absent.

The study of Ref 5. includes also information on distance between waves (not published earlier). Data points from 4 separate video frames in two separate test case with differing initial fluid thicknesses (1 and 2 mm) on wing section upper surface have been collected to Figure 11. The correlation between distance λ and fluid thickness is obvious.

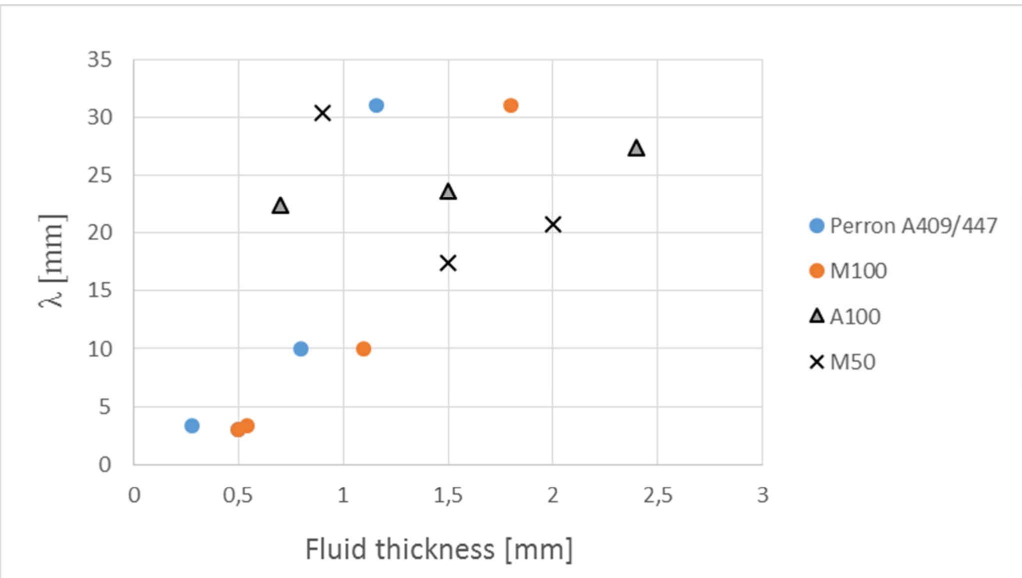


**Figure 10.** Variation of distance between fluid waves and fluid thickness. Fluids A409/477 (TIV fluids) are from Ref. 4 and fluids M100 (neat TI), A100 (neat TIV) and M50 (50% dilution of TI) from Ref. 6.

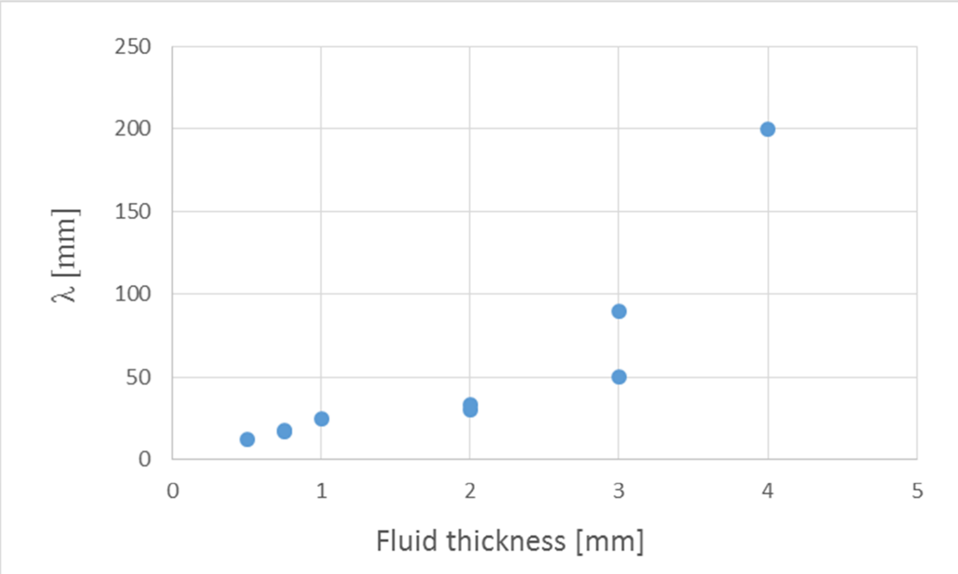


**Figure 11.** Variation of distance between fluid waves and fluid thickness[5].

If we focus on fluid thickness below 3 mm we may fit the data to a linear correlation as follows:

$\lambda = 21*d$ where $d = d(t)$ = instantaneous depth of fluid layer

## 2.3 Estimation of wave height and length

There is no information on measurements of wave geometry (height, length and shape) in author's knowledge. However some estimates may be done from the data of not yet published CFD-study referred earlier and the video frame data of Ref. 5. Using these two source of information one gets a rough estimate for length (w) of a single wave as being 4 to 8 times the height (h) of the wave.

As an average of wave height the CFD-calculations gives 2.3 times the instantaneous depth (d(t)) of fluid layer. This is most probably an over simplification but may be utilized without better knowledge. The multiplier may not be constant but probably varies with depth value.

The shape of the wave is a topic that naturally should be studied in more detail. However without losing generality the volume (in 2D case the area) of a wave may be written as:

$V\ [m^2] = k*h*w$

where k = shape factor of the wave (h = height and w=length)

We may to start our analysis with choosing k intuitively to be e.g. k = 0,33. This is approximately the shape factor of a sinus-shaped half wave.

## 2.4 Deriving an equation for fluid film depth as a function of time

In the flow condition considered in this study assuming all the previous information to hold, we assume the rate of volume (area in 2D) exiting the flat plate to be equal with frequency of waves exiting the plate times volume of one wave, which is:

$$Q\ [m^2/s] = (c_w / \lambda)*k*h*w \quad (1)$$

The initial volume of fluid on the flat plate is:

$$V_0 = d_0*L, \quad (2)$$

where $d_0$ is the initial (even) thickness of the fluid and L is the length of the flat plate. The instantaneous volume V(t) on the plate at time t is now:

$$V(t) = d_0*L - Q*t = d_0*t - (c_w / \lambda)*k*h*w*t \quad (3)$$

The thickness at the time point t is then:

$$d(t) = V(t) / L = d_0 - (c_w / \lambda)*k*h*w*t/L. \quad (4)$$

Taking into account the previously reasoned correlations of:

$h = r * d(t)$, $w = p * h$ and $\lambda = q * d$ where r, p and q are considered as constants we get:

$$d(t) = d_0 - c_w *k*r*p*t*d(t) /(q*L) = d_0 - c_w * C *d(t)*t/L$$

where $C = k*r*p / q$, so:

$$d(t) / d_0 = 1 / (1 + ( c_w*C / L) * t) \quad (5)$$

According to the reasoning above we can substitute $c_w = 0.02 * (U-U_{cr})$ which leads to:

$$d(t) / d_0 = 1 / (1 + t * C_2 * (U-U_{cr}) / L), \quad (6)$$

where $C_2 = 0,02*C$.

When inserting all the proportionality coefficients given above we can calculate the relative thickness variation ($d / d_0$) with time. In Figure 12 the relative fluid thickness variation with time has been calculated for a plate of length of 1.8 m under a constant air velocity of 15 m/s. If we take into account the difference in flow conditions between a flat plate and a wing section the results are somewhat in line with taxi test results in Reference 5.

Figure 13 illustrates the relative thickness when the air velocity above the plate is accelerated from zero speed to 60 m/s in 30 s with a constant acceleration of 2 $m/s^2$. There are three different lengths of flat plate considered. The differences in relative fluid thicknesses after 30 s are considerable. Explaining factor is the ratio:

$$(U-U_{cr}) / L, \quad (7)$$

where $U_{cr}$ is more or less a constant

so that the ratio U / L may be regarded as the basic explaining factor for the differences in curves in Fig. 13.

U / L may be regarded as a scaling factor as its contribution to thickness ratio is obviously significant. The ratio U / L may be thought as a sweeping frequency or the inverse L / U as a sweeping time – the time that an air element uses to travel past the flat plate. As it was assumed that wave speed is proportional to air velocity it seems obvious that this parameter is dominant in fluid flow off.

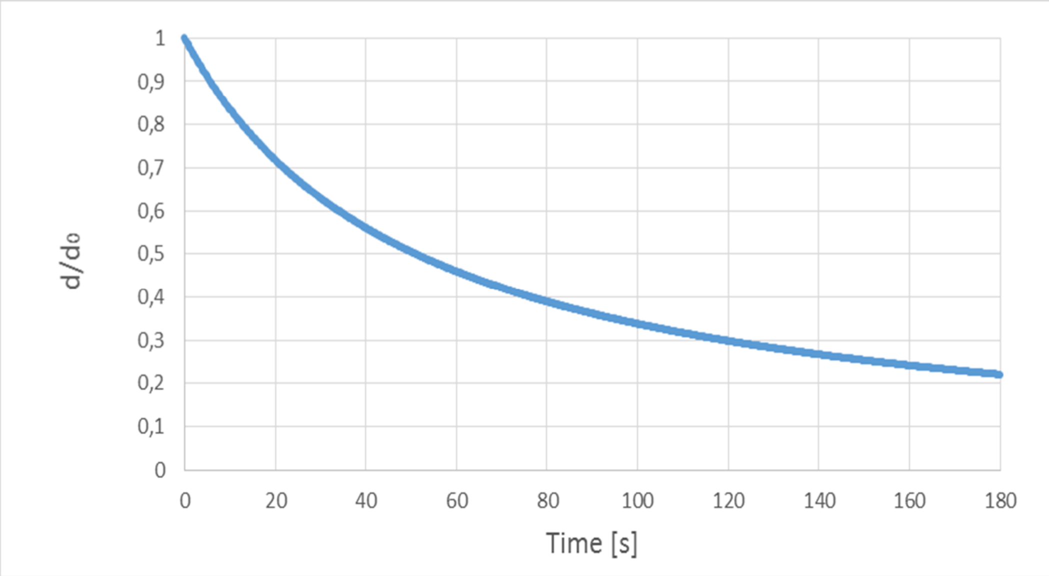


**Figure 12.** Variation of relative thickness of fluid with time on a flat plate of 1,8 m under on air velocity of 15 m/s

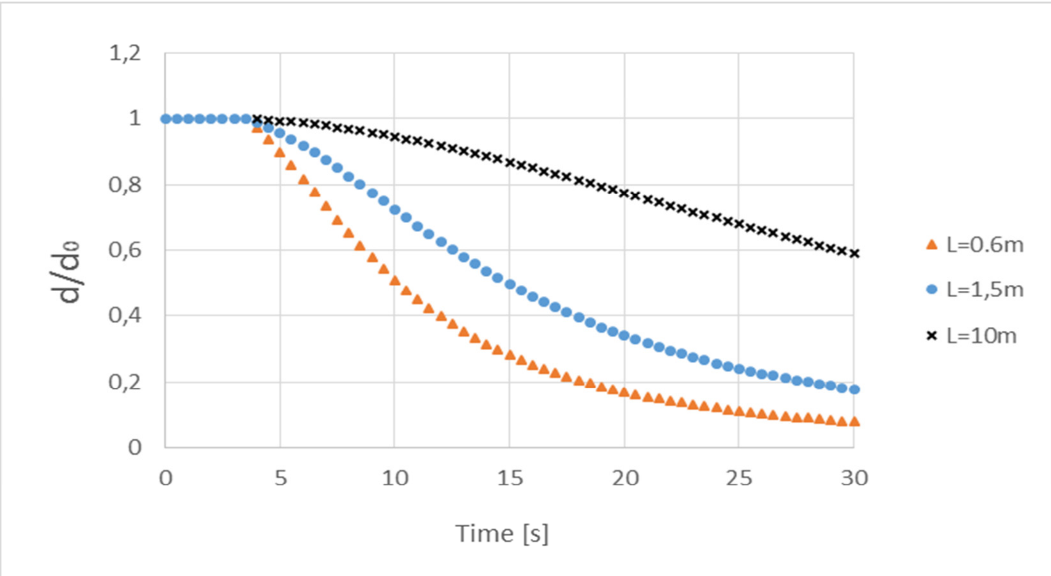


**Figure 13.** The variation of relative thickness with time in the case of accelerating air velocity (as per AS 5900: 2 m/s$^2$) and three different length of flat plate.

U / L may be regarded as a scaling factor as its contribution to thickness ratio is obviously significant. The ratio U / L may be thought as a sweeping frequency or the inverse L / U as a sweeping time – the time that an air element uses to travel past the flat plate. As it was assumed that wave speed is proportional to air velocity it seems obvious that this parameter is dominant in fluid flow off.

There is one obvious flaw in the result of equation (6). As most of the experimental studies considering the flow off from a flat plate or a wing[5] show that the final fluid thickness on a flat plate or on a wing section under an accelerating air velocity (as per AS5900) does not depend on the initial thickness of the fluid layer. In equation (6) the dependence is linear. As noted above there is a lot of over simplifications in the correlations between variables considered. For example the wave height is most probably not in a linear dependence with fluid thickness. The same applies to distance between waves as can be seen in contradicting results of Ref. 6. Once adopting more complicated interrelationships between parameters the equation (6) will most probably not be solvable in closed form but needs an iterative solution.

An obvious additional shortage of the method presented in this study is that it is not based on pure material properties such as densities, viscosities and surface tension but on measured interrelationships of wave motion on a flat plate. This means that the method does not give information about which material properties give the optimal result for fluid flow off.

However the discovery of sweeping time L / U as a scaling factor seems still to be relevant. There is two major discoveries behind the reasoning:

- The fluid transfer (convection) seems to be almost fully concentrated to waves which are more or less solitary in nature
- The wave speed seems to correlate quite well – at least on a wing section – with the air velocity. The linear dependence hold quite well up to air velocities of 50 m/s

With this background it is intuitively understandable that the relative thickness of the fluid depends on sweeping time L / U (or frequency U / L). The longer the plate the more time it needs to loose relative fluid thickness with same air velocity. This gives a new perspective for the scaled wind tunnel model results.

# 3 Conclusions

Possibilities to find an AdHoc calculation method to determine the fluid flow off from a flat plat subjected to air flow were studied. The initial objective to find a simplified calculation method using the basic equations for viscous flow were not found to be feasible.

The attempt to find calculation method using correlations between different parameters in flow discovered by measurements were more successful. Though there are some flaws in the method it may be regarded as a functional starting point for refinements. The discovery of a new scaling factor – sweeping time L / U – should be studied further. This and many other details in this study will be evaluated once the ongoing wind tunnel experiments on fluid flow on a flat plate will be completed as part of the research program Icewing 3. After the results of wind tunnel tests there are also better possibilities to refine the method developed in this study.

# References


1. Nelson, J.J., Alving, A.E., Joseph, D.D., "Boundary layer flow of air over water on a flat plate", Journal of Fluid Mechanics, 284, 1995

2. Dart N.P., "Numerical Analysis of Deicing Fluid Flow Off from Aircraft Wings", AIAA 2010 – 7838, Atmospheric and Space Environments Conference 2-5 Aug. 2010, Toronto, Ontario, Canada

3. Rothmayer A. and Tsao J., "Water Film Runback on an Airfoil surface.", AIAA 2000-0237, 38th Aerospace Sciences Meeting and Exhibit, 10-13 Jan. 2000, Reno, Nevada

4. Perron, E., Louchez P.R.and Laforte, J-L., " Introductory Analysis of Boundary layer Development on De/Anti-icing Fluid", Journal of Aircraft, Vol 33, No 1., Jan-Feb, 1996

5. Koivisto, P. "Anti-icing Fluid Flow off on a Wing Section During Simulated Taxi and Take-off Run", Trafi Publications 01/2013

6. Özgen S., Carbonaro M., Sarma G.S.R, "Experimental study of wave characteristics on a thin layer of de/anti-icing fluid" Phys. Fluids 14, 3391-3401, Oct. 2002

7. Koivisto, P. "Effects of Anti-icing Treatment on Lift Degradation during Simulated Take-off" Trafi Publications 25/2013.

**Finnish Transport and Communications Agency Traficom**

P.O.Box 320 FI-00059 TRAFICOM, Finland
Tel. +358 295 345 000

traficom.fi

ISBN 000–000–000–000–0
ISSN 0000–0000 (online)

TRAFICOM
Finnish Transport and Communications Agency