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PERFORMANCE DEGRADATION OF A SIMULATED ICE CONTAMINATED AIRFOIL BY SUPER-COOLED DROPLETS

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Keywords: *Aerodynamics, airfoil, ice accretion*

Abstract

An investigation was performed, by means of low speed wind tunnel testing, to study the aerodynamic effect of super-cooled large-droplet ice accretion on an advanced low-speed airfoil section. The ice accretion was simulated by placing strips of different shapes and different dimensions in the regions of expected accretion. This entailed that every strip was positioned at several locations on the upper surface of the airfoil. The influence on the basic aerodynamic characteristics was evaluated for each case. It was concluded, as for conventional sections, that the accretion, caused by large super-cooled droplets, severely degraded the aerodynamic performance. So the consequences of the phenomenon to flight safety are of extraordinary importance and also, for the advanced low-speed wings.

Nomenclature

C_L	lift coefficient
C_D	drag coefficient
C_m	pitching moment coefficient
c	airfoil chord (m)
Re	Reynolds number based on airfoil chord
x	longitudinal position of the accretion from leading edge (m) (Fig. 1)
α	angle of attack (degrees)

Ice accretion shapes

B	backward facing quadrantal, height 0.0133 c
F	forward facing quadrantal, height 0.0133 c
FH	forward facing quadrantal, height 0.025 c
S	sinusoidal, height 0.0133 c

1 Introduction

The different ice accretions and their influence on aerodynamic performance have been studied for decades and many important studies have been performed. Continuous attention to this phenomenon has to be paid because of its potential danger.

Recently a long time unknown form of ice accretion, caused by large super-cooled droplets, was detected. If an aircraft is flying at an altitude where the temperature is close to or below the freezing point of water, and it encounters a cloud containing large super cooled water droplets, very specific forms of ice accretion may appear [1]. That accretion may form in various ways, and particularly downstream of the ice protection system. This is, of course, at variance with the normal, and well-documented extensive works associated with leading-edge accretion.

With regard to ice accretion due to super-cooled large water droplets, and their degrading effect on the aerodynamic airfoil coefficients, the works of Bragg [2], [3], [4] together with the comprehensive FAA reports [5], [6] are examples of the work to date. Also, computational studies have been performed which were useful for the understanding of influence of the accretion on the flow field surrounding the airfoil [7], [8].

All the above works were concerned with the conventional, long-time studied, airfoils like the NACA 23012. The studies on such airfoils, with characteristics known in detail, have the advantage of detailed comparison of the different influences and phenomena. The present day designer, however, needs additional data for the advanced airfoils used on current aircraft. So, for example, the airfoils derived from NASA MS airfoil family, currently used on the general aviation aircraft, require the appropriate wind tunnel testing. That testing and the results thereof, is the subject of the presented paper. It is concluded that all the simulated ice accretions have a detrimental effect on airfoil performance. This study continues on from the research presented in [9].

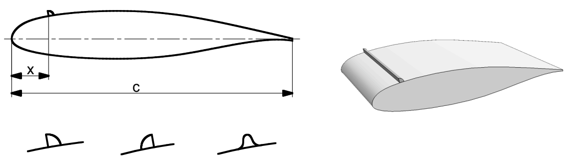

Fig. 1 Forward facing quadrantal(F&FH), backward facing quadrantal (B) and sinusoidal (S) accretions

2 Experiment

The influence of specific forms of the ice accretion was studied on an advanced low-speed airfoil section of 17% maximum thickness and was derived from NASA MS airfoils. The wind-tunnel model, depicted in Fig 1, was in the form of a rectangular wing with circular endplates. The span was 1.2 m and the chord 0.6 m. The model was suspended on a mechanical balance to measure lift, drag and pitching moment.

Four types of ice accretion shape were examined, and all shapes related to the large super-cooled droplets. In all cases, the simulated ice accretion was modelled by an appropriately shaped ridge on the upper surface of the airfoil and downstream its leading edge. The ice ridge was simulated by mouldings of appropriate cross-section made of plastics. The mouldings were as follows:

1) - quadrantal section, backward facing, of height of 1.33% of chord,(B)
2) - quadrantal section, forward facing, of height 1.33% of chord,(F)
3) - quadrantal section, forward facing, of height 2.25% of chord,(FH)
4) - sinusoidal section of height of 1.33% of chord.(S)

All of these shapes are depicted in Fig 1together with the aerofoils cross section. The first two ridge sections were of the shape recommended by the FAA US civil aviation authority (the FAA recommends one inch high ridge for tests on real aircraft). Each moulding was positioned on the upper surface of the airfoil at locations from 5% to 45% of chord.

The tests were performed in the 3m LSWT low speed wind tunnel at VZLU, Aeronautical Research and Test Institute in Prague. The wind tunnel used was an atmospheric type with open test section of 3 meters diameter.

3 Test procedure

All tests were performed at the Reynolds number 2.1* 10^6 and Mach number 0.15. The data were processed with all standard wind-tunnel corrections for airfoil testing applied. The uncertainties of C_L were ± 0.01, of C_D ± 0.0001 and of C_m ± 0.001.

The angles of attack tested were over a range from negative to positive as depicted in Fig 2.

A summery of the test points is as follows:

1) - Clean airfoil without ice accretion, the reference configuration
2) - Airfoil with low (1.33 %) positioned at 5 %, 25 %, 35 % and 45 % of chord
3) - Airfoil with high (2.25 %) forward facing quadrantal ice accretion (FH shape) positioned at 5 %, 25 % and 45 % of chord
4) - Airfoil with low (1.33 %) backward facing quadrantal ice accretion (B shape) positioned at 5 %, 25 % and 45 % of chord

5) - Airfoil with low (1.33%) sinusoidal ice accretion (S shape) positioned at 5 %, 25 % and 45 % of chord.

4 Results

Figure 2 depicts the comparison of the lift coefficient for the forward facing quadrantal ice accretion (F) positioned at various chordal locations. Most striking is the insignificant effect that the simulated ice accretions have at negative angles of attack. This could have been expected since, at these angles, the lower surface becomes the upper surface and vice versa. Accordingly, with the ridges effectively on the lower surface, in what would most likely be a favourable pressure gradient, no gross separations would occur. This is certainly not the case for positive angles of attack.

At positive angles of attack the accretion has a detrimental effect on performance for all chordal locations. This is most noticeable for the 5% of chord location where the accretion effectively stalls the aerofoil at 5^0 of incidence and the lift coefficient has a maximum value of approximately 0.4 compared to almost 1.6 at 19^0 of incidence for the clean configuration. It is hardly surprising that as the accretion ridge is moved backwards along the chord the very serious detrimental effect decreases, in terms of C_{Lmax}. None the less, the first three locations, up to 35% of chord, all show a break at approximately 5^0 of incidence. It is only the 5% location that shows no recovery.

It is very clear, that at the 5% location, the accretion causes gross separation without any re-attachment. In all probability due to it entering the pressure recovery region (i.e. adverse pressure gradient) at 5^0 of incidence as the pressure peak migrates towards the leading edge; as the incidence increases. As the accretion moves backwards toward s the trailing edge, the detrimental effect decreases.

When the accretion is placed at 45% of the chord, no break in the lift-curve slope can be observed and the configuration has the poorest performance over the first 5^0 of incidence. Towards the trailing edge, the fully developed boundary layer will be at its thickest and closer to separation than any other location. It is most probable that the accretion simply forces a fixed separation location for most on the positive incidence range until the sharp stall at about 17^0 of incidence.

Figure 3,4 and 5 depict the effect that the different shapes of accretion have on the lift coefficient whilst located at 5%, 25% and 45% of the chord. At the 5% location it is obvious that the larger (FH) accretion has the largest detrimental effect. Its lift coefficient shows a stall at about 3^0 and demonstrates the impact of secretion size. As is to be expected the forward facing quadrantal is poorer that the backward facing version because of the nature of the separated shear-layer that that emanates from the accretion tip. The shape that has the least detrimental effect is the sinusoid.

In Fig. 4 (location at 25% of the chord) the large accretion (FH) appears to be forcing significant separations over the entire positive incidence range until the stall. This is very like its smaller counterpart (F) when placed at 45% of the chord. Again the sequential improvement from FH to F to B to S is obvious. Figure 5 illustrates that, to varying degrees, all the accretions behave in a similar manner to F accretion in Fig.2 at the 45% of the chord. Again the S accretion is the least detrimental with the FH the worst. In fact, the FH accretion creates such a disturbance that its detrimental effect persists well into the negative incidence range.

The drag polars are presented in Figs. 6 to 9. Figure 6 depicts the effect of the F accretion when placed at different locations along the chord. Unlike the lift coefficient, the drag is effected at all incidences. This is probably due to the creation of a small separation zone behind the accretions that would be less significant to the lift than the drag. Again, the secretion at 5% chord is the worst and, over the entire incidence range, at 45% is the best albeit it has a higher drag at the lower incidences. Figures 7, 8 and 9 depict the effect of accretion shape at the 5%, 25% and 45% locations. At the 5% location all the trends are similar with the worst being the FH shape and the S the least detrimental. The significant effect of the FH shape at the 25% of the chord is obvious in Fig. 8.; with about an order of magnitude increase at a lift coefficient of 0.3. At the 45% location (Fig. 9), all the shapes display similar trends.

Figures 10 to 13 depict the pitching moment coefficient against incidence. Figure 10 depicts the effect of the F accretions location along the chord. Again the 5% location displays the largest deviation from the clean aerofoil and the 45% location the least. Figures 11, 12 and 13 depict the differences between the various accretions at 5%, 25% and 45% of the chord. At 5% all the accretion curves follow much the same shape and in the usual order. At 25%, the large separations caused by the FH shape create an earlier moment break. Again the FH accretion displays the largest deviation from the clean aerofoil.

For completeness Figs. 14 to 17 present pitching moment coefficient against lift coefficient. Figure 14is for the F accretion at various locations along the chord, whilst Figs. 15 to 17 display the performance degradation caused by the different accretion shapes at the5%, 25% and 45%. The effect of the accretions is, once again, all to obvious and in particular the FH accretion with the aerofoil at negative incidence where it produces a large nose down moment.

5 Conclusions

An experimental investigation was conducted to study the aerodynamic effect of simulated ice accretion, caused by the super-cooled large droplets on an advanced low-speed airfoil section. One of the accretion shapes corresponds to FAA recommendations. The following conclusions can be drawn.

1) These types of ice accretion strongly affect the lift, drag and moment of an airfoil. The maximum lift coefficient is significantly reduced, the drag is increased several times and the moment develops a pronounced “nose down” attitude.

2) The results are similar like to other airfoils and so conclusion (1) maybe considered as universally valid.

3) The detrimental influence of ice accretion is increases with proximity to the leading edge. Hence, the most dangerous case would be that of an accretion ridge immediately behind the de-icing device.

5) The greater the height of the accretion the larger the performance deterioration.

6) The forward facing quadrantal shaped accretion gave the worst performance deterioration.

7) The forward facing quadrantal is the shape recommended by FAA for use during the certification procedure. Accordingly, the FAA recommended case should cover the other shapes with a safety margin.

8) In general, the detrimental consequences of supper-cooled large-droplet ice accretions are extremely dangerous for current advanced airfoil designs.

6 Acknowledgements

This project was supported by the Ministry of Industry and Trade of the Czech Republic and by VZLU, Aeronautical Research and Test Institute in Prague.

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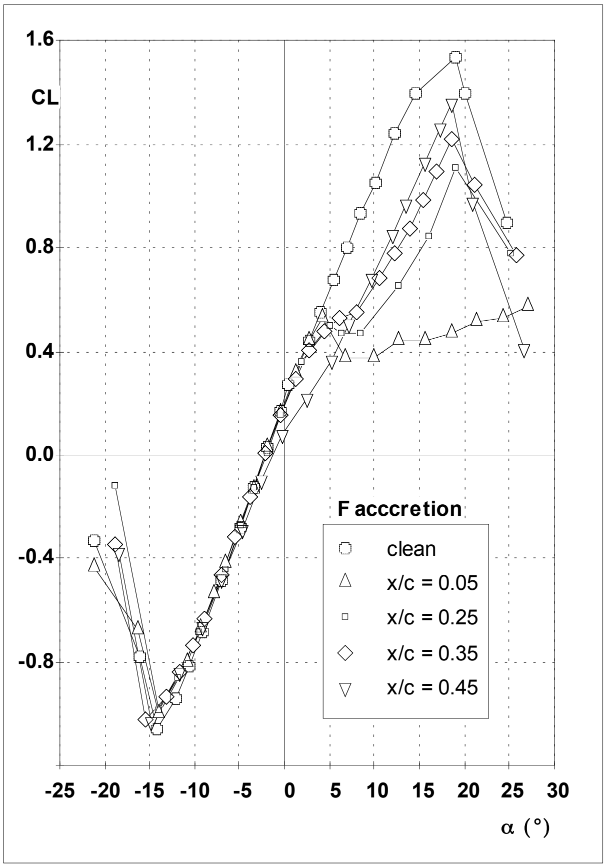
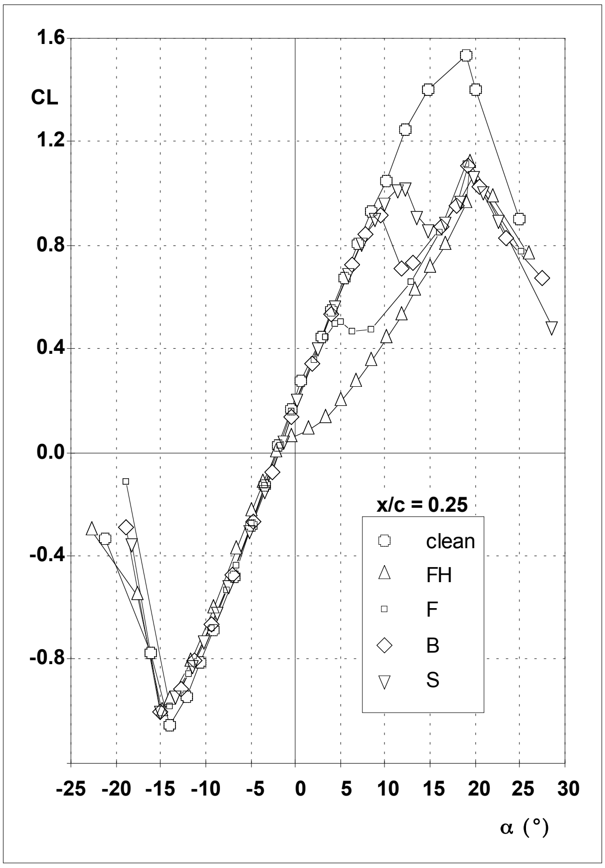


Fig. 2



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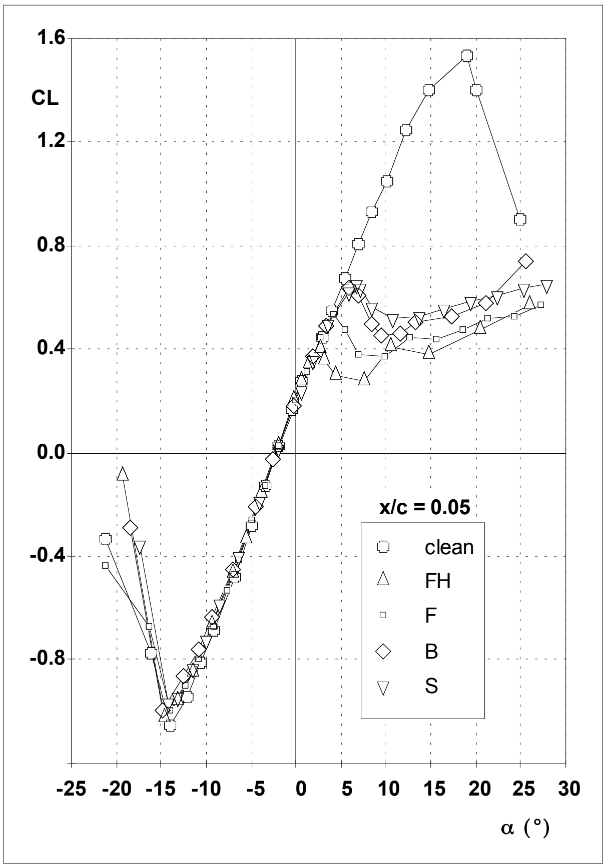

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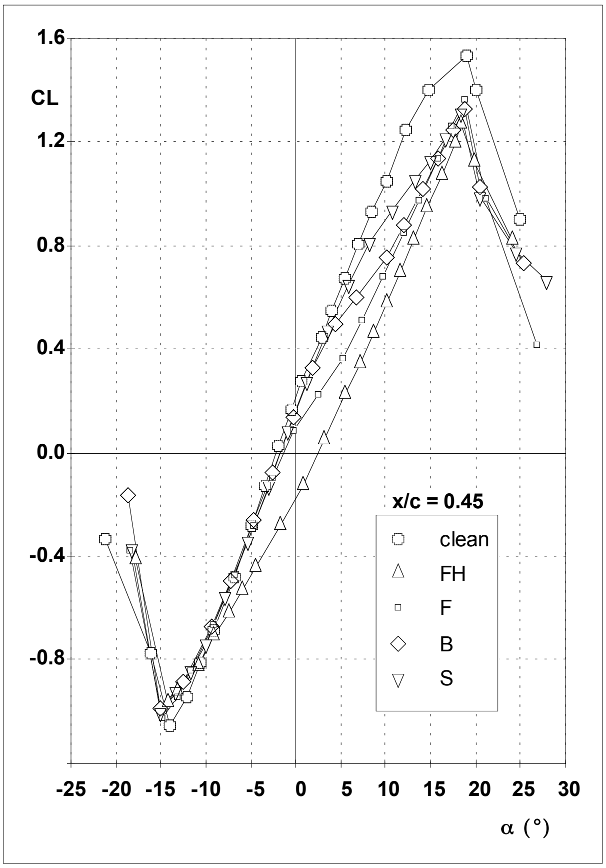

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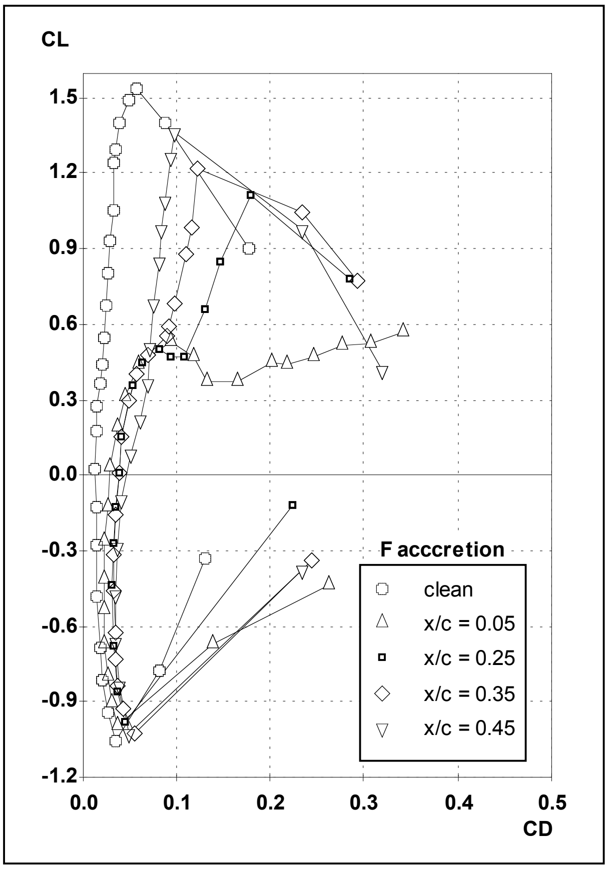

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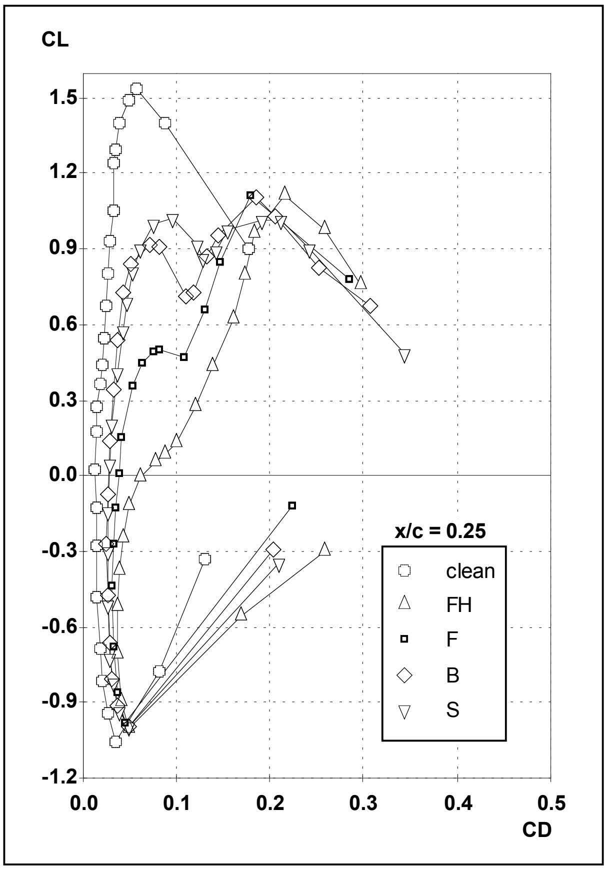

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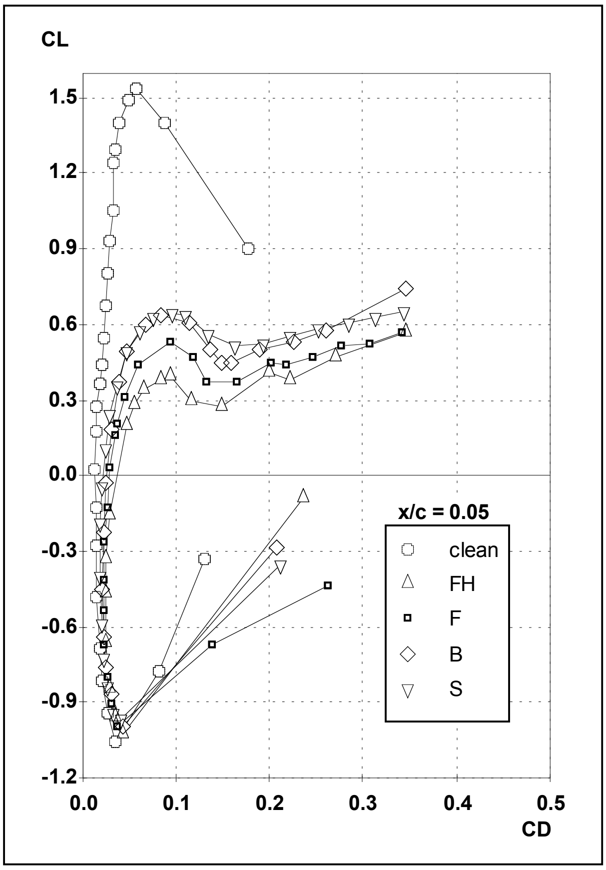

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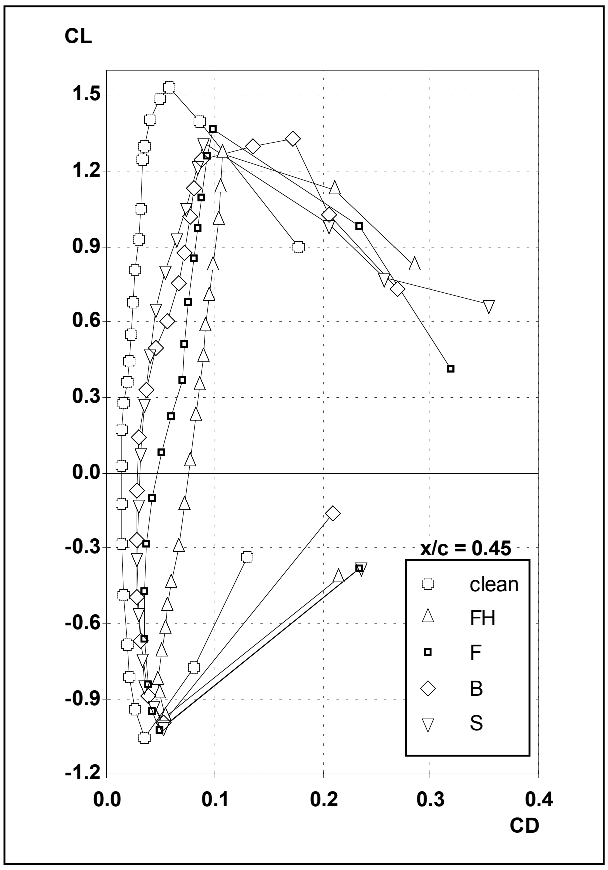
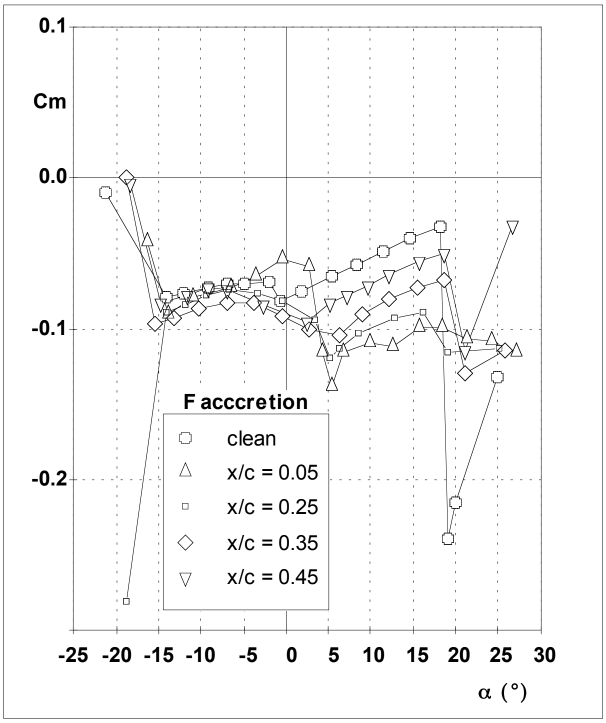


Fig. 9



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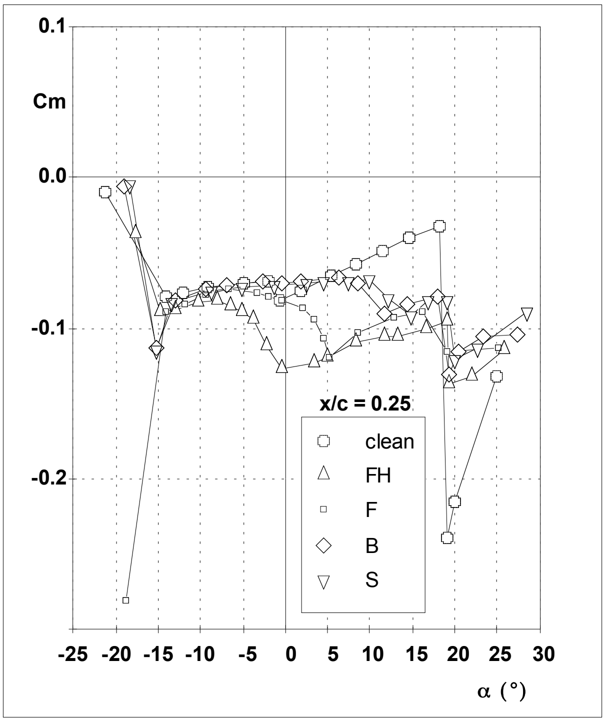

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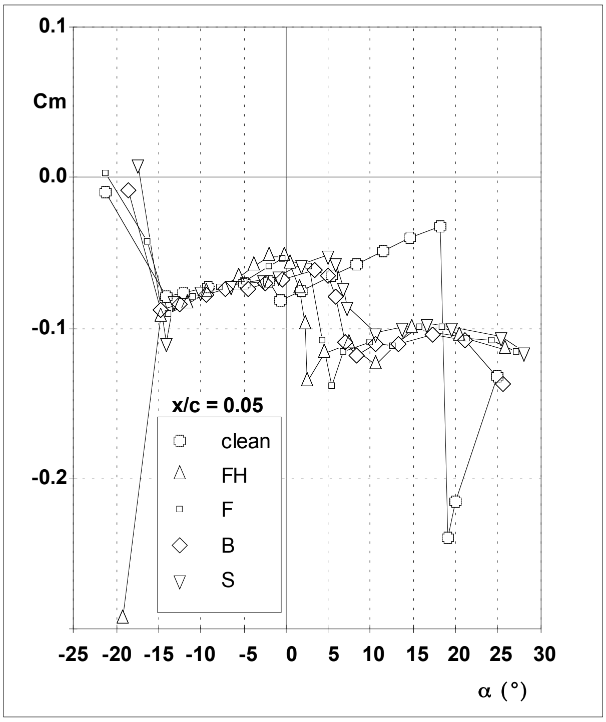
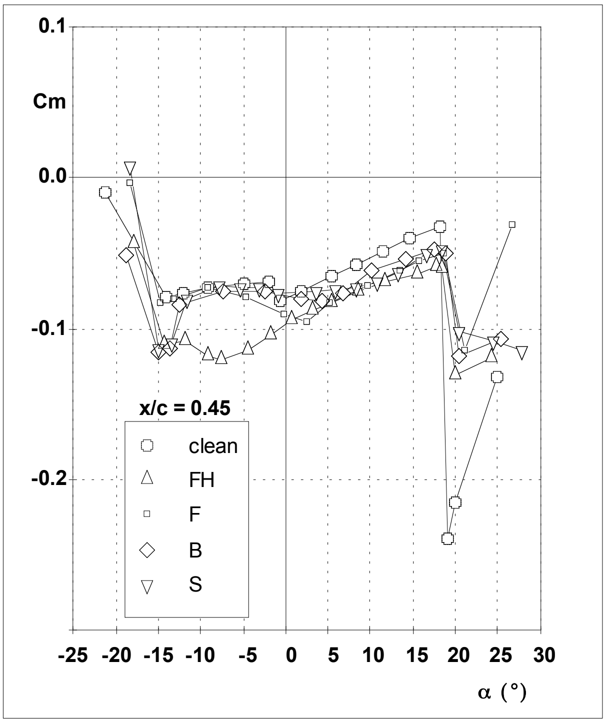


Fig. 11



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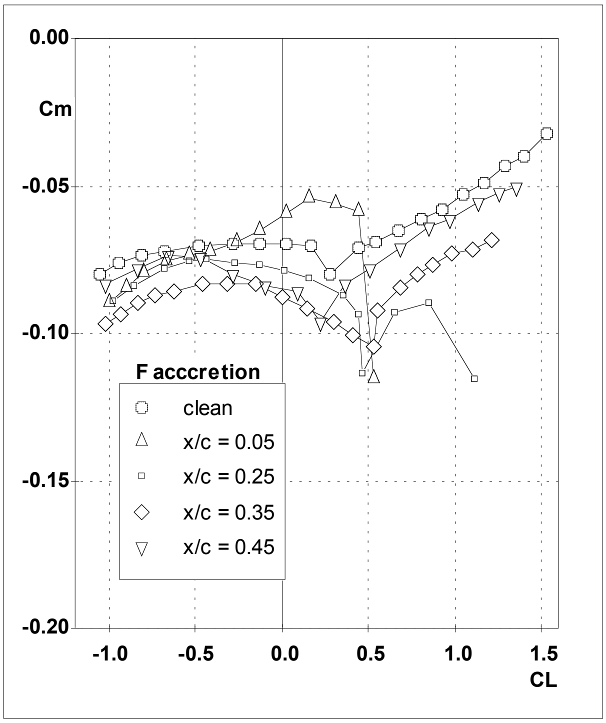

Fig. 14

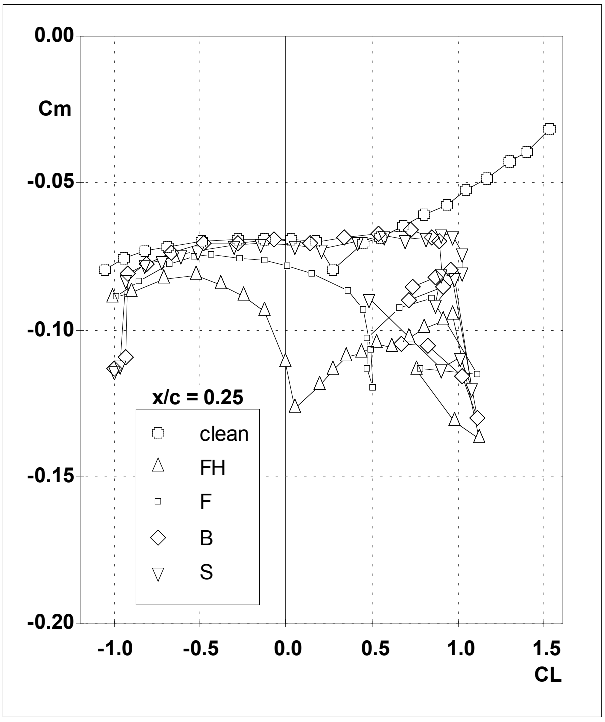

Fig. 16

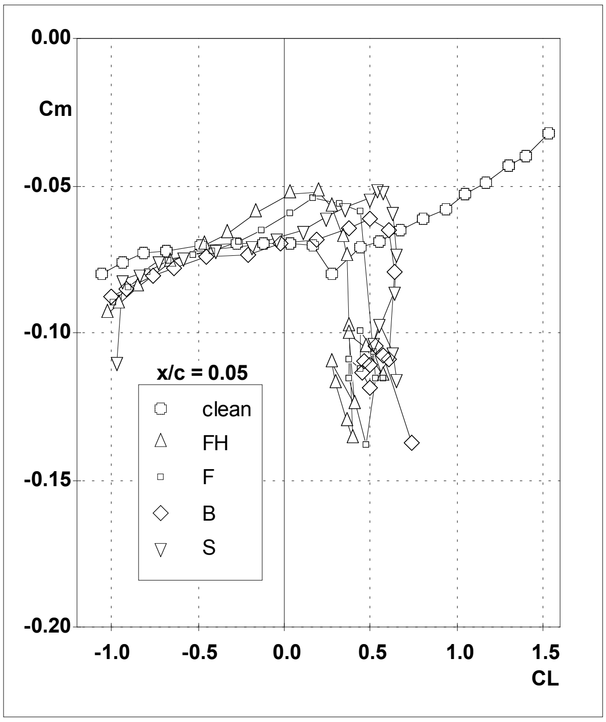

Fig. 15

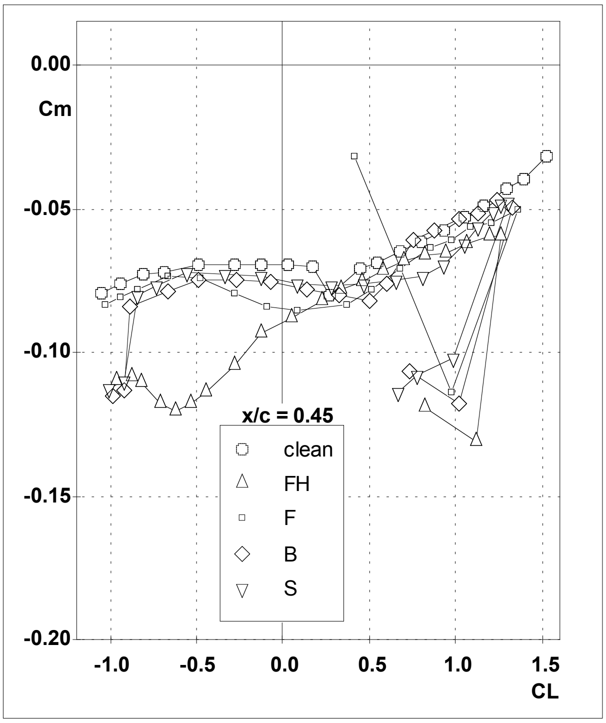

Fig. 17