EXPERIMENTAL STUDY OF CONTAMINATED AIRFOIL WITH FOWLER FLAP

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Abstract

Aerodynamic characteristics of a low-speed airfoil section with Fowler flap were studied in the low-speed wind tunnel. Consequences of different kinds of contamination of airfoil were examined – insect contamination, leading-edge ice accretions and ice accretion caused by supercooled large droplets.

1 Introduction

A phenomenon of shape deformation and then performance deterioration of an airfoil section caused by the flight in natural conditions is known from the beginning of the applied aviation. Ice accretion, insect contamination etc. and their different aspects have been observed, examined and evaluated for decades. The obvious importance for aircraft operations causes that the phenomenon and its consequences for aerodynamic performance have been continually studied.

Thousands studies concerning the formation of ice accretions and their influence on aerodynamic characteristics of an airfoil section were carried out. The exhaustive studies of the ice accretion are for example [1] or [2] and many others, in the field of ice accretions caused by large supercooled droplets for example [3], [4], [5]. The VZLU institute performed the experimental studies with simulated ice accretions in wind tunnel, for example [6]. This study is focused on the performance degradation of an advanced low–speed airfoil section with Fowler flap caused by insect contamination, by leading–edge ice accretion and by ice accretions caused by supercooled large droplets. The reasoning for the study was the fact that available studies supported the conclusion that the sensitivity of airfoils could strongly depend on their geometric shape and there was a lack of available information for new advanced airfoils similar to the studied case.

2 Nomenclature

c_D	drag coefficient
c_L	lift coefficient
c_m	moment coefficient
c_p	pressure coefficient
α	angle of attack
α_{CLMAX}	„stall“ angle of attack

3 Airfoil section and its shape deformation

An influence of the shape deformation of leading edge area on aerodynamic characteristics could be important for all flight regimes. As the contemporary advanced airfoils are developed for maximum efficiency at specific regimes, they could, as the consequence of “pushed” efficiency, be also very sensitive to shape accuracy. The extreme shape deformation that can occur as a consequence of extremely adverse weather conditions has been long-term studied, but in standard flight operations mild shape deformation by insect contamination during everyday operations is much more common. In the presented paper, the consequences of the both kinds of contamination on aerodynamic performance of an airfoil with Fowler flap were studied. The examinations were carried out for the cruise, the take-off and the landing flap position. The configurations with ice accretion on flap leading edge are often omitted in evaluation, so the attention was paid to them. The ice accretions were simulated both on the leading edge of the main airfoil and on the leading edge of the flap or on the flap only.

The examined airfoil was designed for low–speed general aviation aircraft, its relative thickness was of 16 %. The Fowler flap chord was 30 % of the airfoil section chord. The take–off setting of the flap was with 18 degrees deflection, the landing setting with 33 degrees deflection.

The insect contamination was simulated by means of small bulges of plastic deposited on the leading edge. The bulge dimensions and the density of bulges per meter corresponded to the typical summer insect contamination in the Central Europe. The density of bulges was 25 per meter and the height of the bulge was 2 mm.

The shape and position of leading-edge ice accretion were determined by special-purpose software developed by Hoření [7]. The software computed development sequence of "conventional" ice accretions, their comparisons with experimental results showed a very good correspondence. The ice accretion formations were established both on the main airfoil and on the flap, for the cruise, the take–off and the landing configurations at relevant characteristic angles of attack. The shapes of the accretions are in Fig. 1.

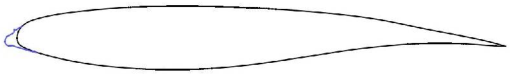

Fig. 1a. Leading-edge ice accretion, cruise configuration

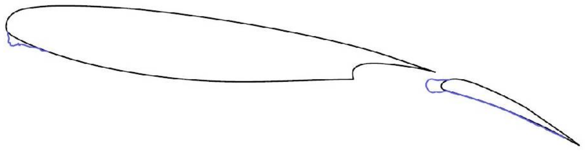

Fig. 1b. Leading-edge ice accretion, take-off configuration

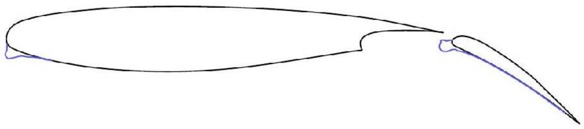

Fig. 1c. Leading-edge ice accretion, landing configuration

The ice accretion created by the supercooled large droplets was shaped according to the FAA recommendations as an accretion of forward-facing quadrantal cross-section. The height of the accretion was 2.25 % of the airfoil chord. The leading edge of the accretion was positioned at 15 % of the airfoil chord where the typical de-icing device is supposed to be no longer efficient (Fig.2).

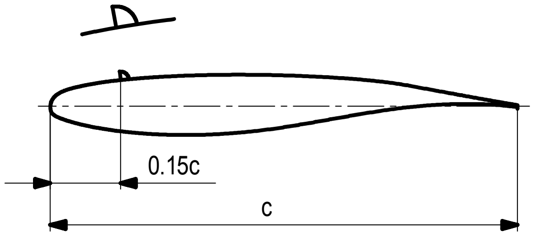

Fig. 2. Supercooled large droplets ice accretion

4 Model and wind-tunnel

The model (Fig. 3) was in the form of a rectangular wing of 0.6 m chord and 1.2 m span with the circular endplates of 1.08 m diameter. The ice accretion models were produced as shaped plastic ledges bonded at the appropriate positions on the airfoil model.

The tests were performed in a 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. The intensity of turbulence in the test section was 0.3 %, the irregularities in the velocity are 0.2 %. The wind-tunnel mechanical balance in the three-component mode was used for the forces and moments measurements. The uncertainties of C_L

were ± 0.01, of C_D ± 0.000 1 and of C_M ± 0.001. The pressure distribution measurement was with the uncertainty of c_p ± 0.01

5 Wind-Tunnel Testing

The wind–tunnel tests were performed for the cruise, the take–off and the landing configurations. The insect contamination was positioned on the leading edge of the main airfoil. The leading edge ice accretion was positioned both on the leading edge of the main airfoil and of the flap or on the leading edge of the flap only (this case was tested as the de-icing devices are commonly positioned on the leading edge of the main airfoil only). The accretion due to the supercooled large droplets was positioned on the upper surface at 15 % of the airfoil chord. For all testing cases, the forces, moments and pressure distributions were measured.

The following matrix contains all tested cases. C, T-O and L mean the cruise, the take-off and the landing configurations respectively, Ma and Fl mean the main airfoil and the flap respectively, Is, Icl and Ics mean the insect contamination, the leading-edge ice accretion and the supercooled droplets ice accretion respectively.

	C	T-O	L
Ma only	Ics	Ics	Ics
Fl only	Ic	Ic	Ic
Ma + Fl	Is, Icl, Ics	Is, Icl, Ics	Is, Icl, Ics

Reynolds number of all tests was $1.65 \cdot 10^6$, Mach number 0.15.

6 Results

6.1 Cruise

The results for c_L, c_D and c_m in the cruise configuration are presented in Fig. 3. It is visible that the mild insect roughness deteriorated the maximum lift coefficient as well as the value of α_{CLMAX} angle and the drag coefficient. Increment in c_D reached the extent that could be important for the efficiency of operation economic.

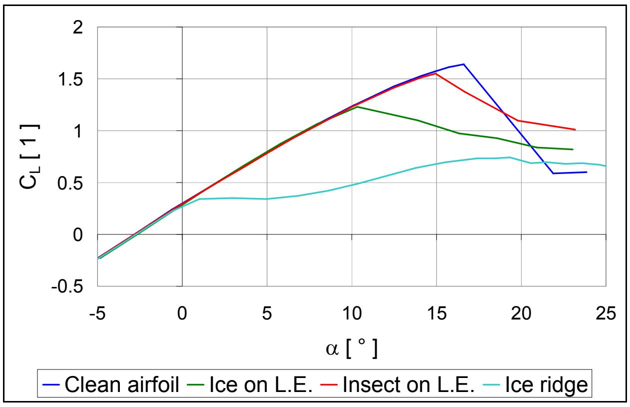

Fig. 3a. Lift curves for cruise configuration

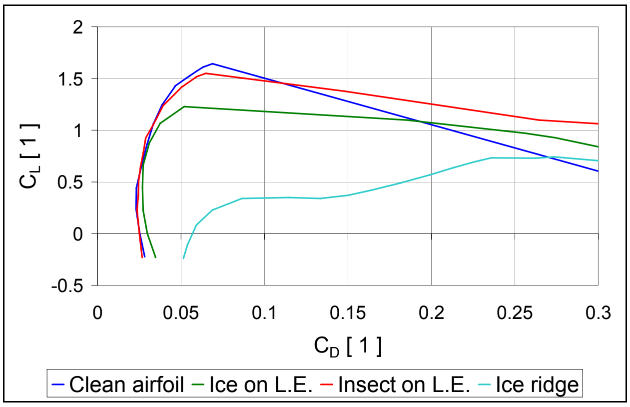

Fig. 3b. Polars for cruise configuration

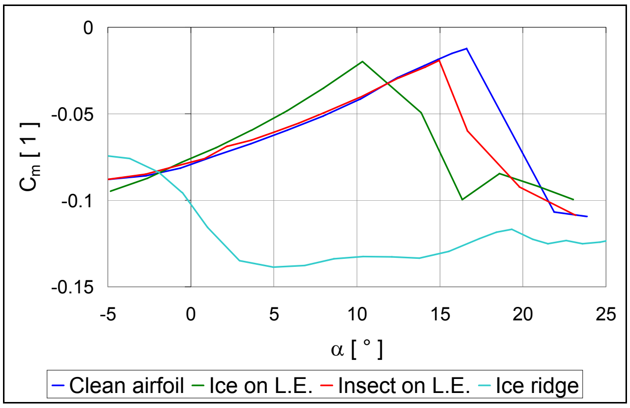

Fig. 3c. Moment curves for cruise configuration

The leading-edge ice accretion deteriorated the aerodynamic characteristics as anticipated, it means to the extent that could influence not only efficiency but also safety of flight. The maximum lift coefficient decreased from 1.64 to

1.02 and the angle α_{CLMAX} decreased from 16.7 to 10.3 degrees. The changes in the moment curve indicate also the shift of the airfoil aerodynamic focus towards its trailing edge, the airfoil develops to be autostable, the magnitude of the shift is approximately 4.5 % of the chord.

The accretion created by large supercooled droplets causes total degradation of aerodynamic performance of the airfoil. The stall (if we can distinguish the stall) occurs at angle of attack of 1 degree only at $c_L = 0.35$, the maximum value of lift coefficient of 0.85 accompanied by drag coefficient of 0.274 is reached at angle of attack of 19.3 degrees.

The Fig. 4 illustrates the development of the pressure distribution. The very moderate influence of the insects on the distribution is visible within the exception of earlier stall (by 2 degrees).

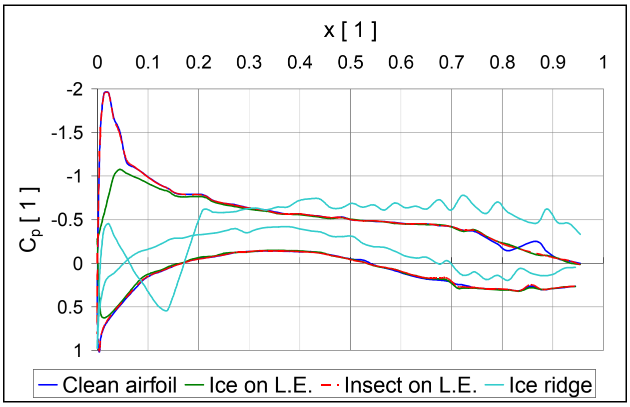

Fig. 4a. Pressure distribution at angle of attack of 3 degrees

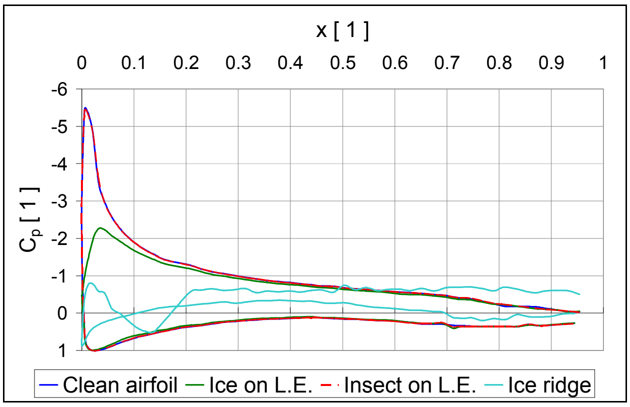

Fig. 4b. Pressure distribution at angle of attack of 10 degrees

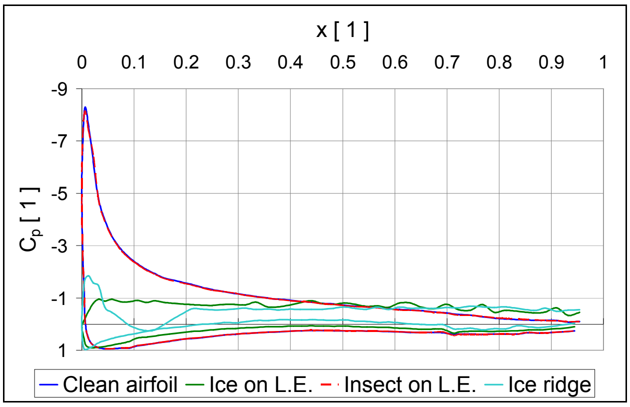

Fig. 4c. Pressure distribution at angle of attack of 15 degrees

By contrast, the significant changes caused by the leading edge ice accretions even for low angles of attack are strongly pronounced. The accretion caused by the large supercooled droplets changes the pressure distribution entirely, a relatively small ridge at upper side of the airfoil changes its shape entirely from the aerodynamic point of view and the desired aerodynamic performance of airfoil is lost totally.

6.2 Landing

The results of testing are presented in Fig. 5a to 5c. The insect contamination in spite of its relatively small geometric dimensions had significant consequences to the maximum lift coefficient as well as drag coefficient. The loss of maximum lift coefficient of 0.2 is similar like in the cruise configuration as well as the decrease of the α_{CLMAX} of 1 degree. But the increase of drag coefficient is higher than in the cruise configuration, the increase of drag is of the same magnitude as in the case of leading-edge ice accretion in the region of lift coefficients higher than 1.9.

The ice accretion on the leading edge of the flap only does not affect the maximum lift significantly but causes the increase of drag similar as insects or the ice accretion on the leading edge of the main airfoil.

The case of the leading-edge ice accretion on the main airfoil and on the flap is more performance deteriorating as expected, the maximum lift coefficient is reduced from 2.8 to 2.4 with α_{CLMAX} reduced from 11 to 9 degrees.

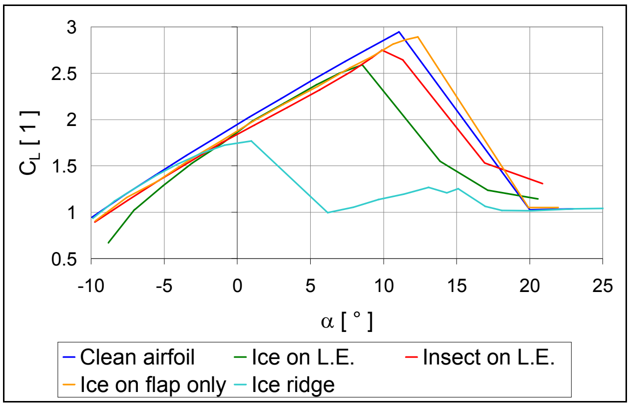

Fig. 5a. Lift curves for landing configuration

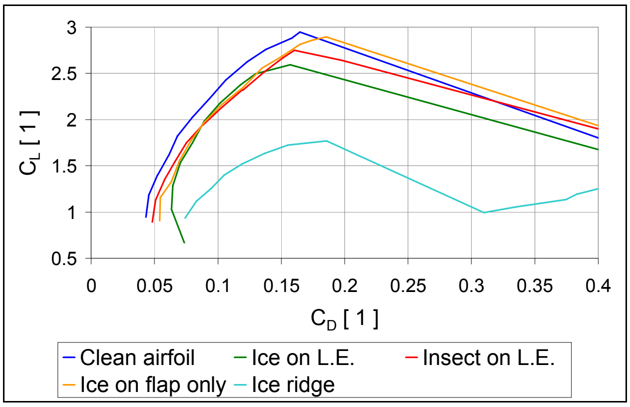

Fig. 5b. Polars for landing configuration

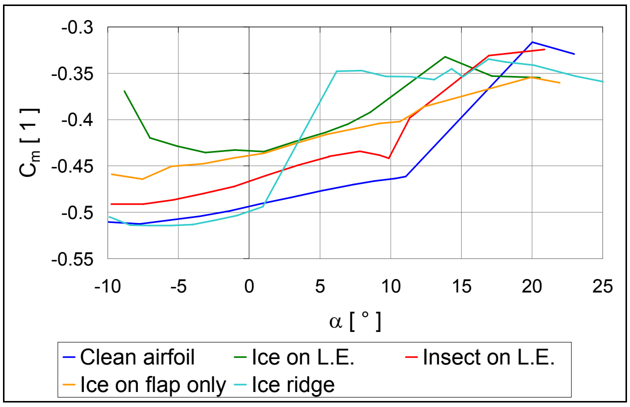

Fig. 5c. Moment curves for landing configuration

The ridge created at the upper surface by the large supercooled droplets has the destroying influence to the aerodynamic performance as in the cruise configuration. The stall occurs again at the angle of attack of 1 degree only, with c_{LMAX} of 1.77.

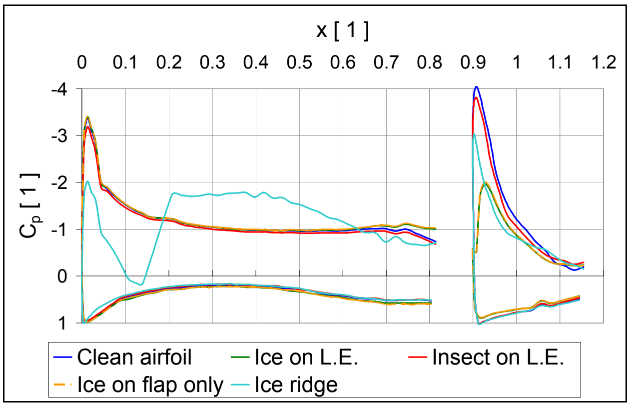

Fig. 6a. Pressure distribution at angle of attack of 0 degrees

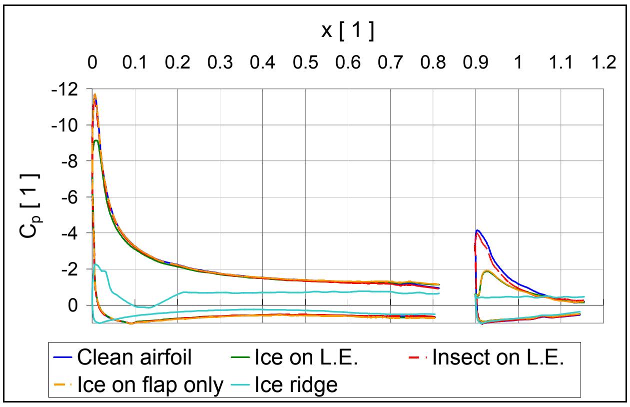

Fig. 6b. Pressure distribution at angle of attack of 9 degrees

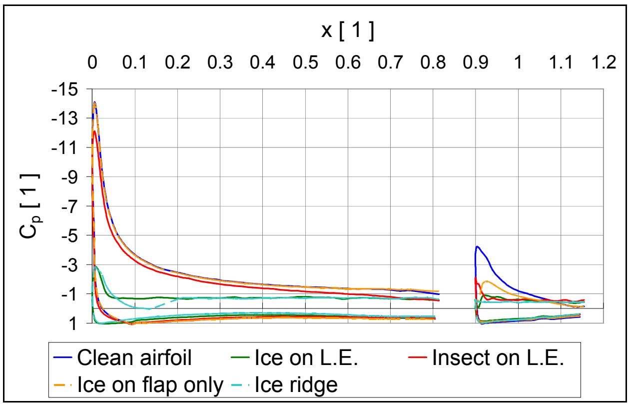

Fig. 6c. Pressure distribution at angle of attack of 11 degrees

The explanation is provided by the pressure distributions (Fig. 6a to 6c). The insect contamination, though being geometrically negligible in comparison with ice accretion, induces premature stall of flap at angle of attack of 10 degrees and then the decrease of pressure minimum on the leading edge of main airfoil.

The ice accretion on the flap only causes the destruction of the primary pressure distribution on the flap, but the pressure distribution on the main airfoil remains practically unchanged.
As expected, the ice accretions both on the main airfoil and the flap create very unfavorable case. The pressure distributions are strongly deformed both on the main airfoil and the flap already at low angles of attack, and the total stall on the both parts occurs very early.
The ridge accretion at 15 % of chord has destroying consequences. At angle of attack of 1 degree, the suction peak does not exist in effect and its indication is followed by c_p of zero magnitude. Successively, the stall occurs with suction values in he order of c_p = -0.8. It was observed that the pressure distribution on the flap was also strongly adversely influenced.

6.3 Take-off

The similar results as for the landing configuration were observed but the phenomena were less significantly pronounced (Fig. 7a to 8c).

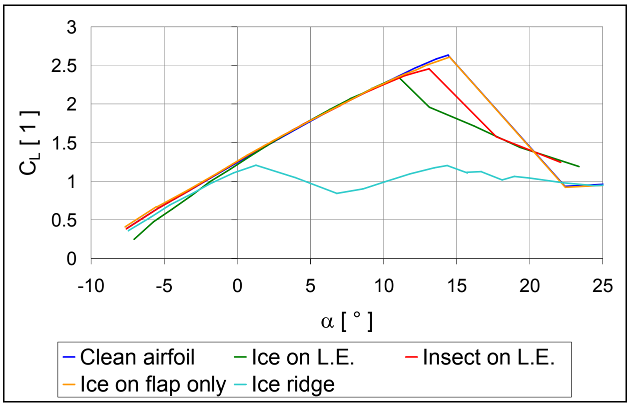

Fig. 7a. Lift curves for take-off configuration

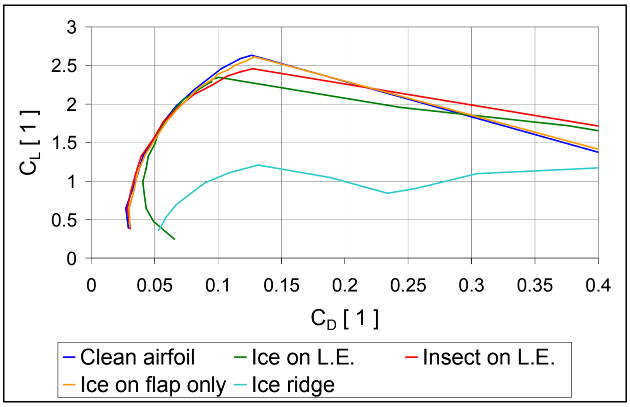

Fig. 7b. Polars for take-off configuration

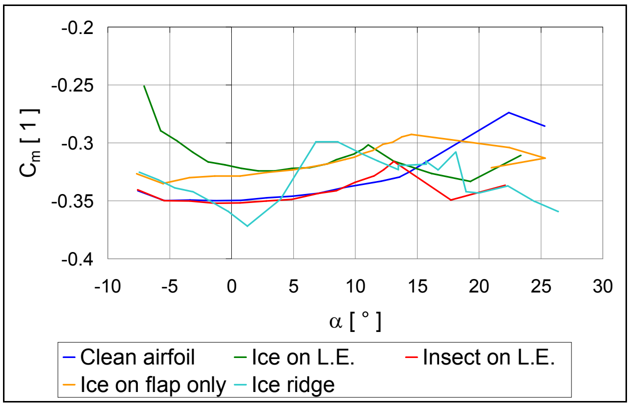

Fig. 7c. Moment curves for take-off configuration

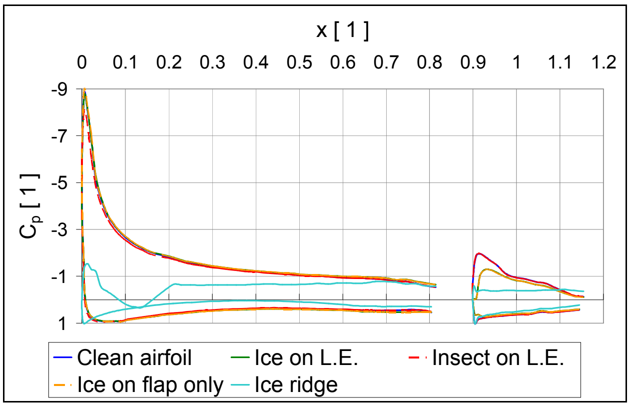

Fig. 8a. Pressure distribution at angle of attack of 9 degrees

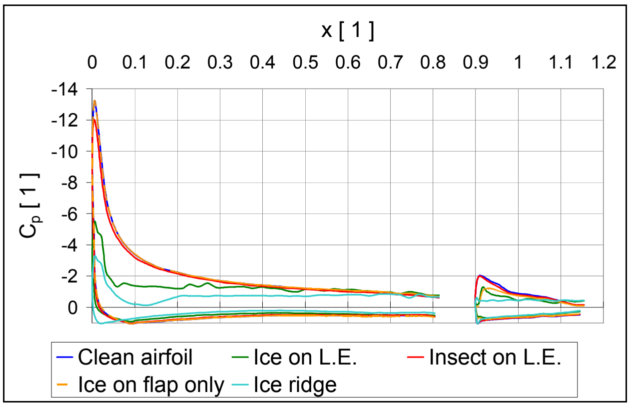

Fig. 8b. Pressure distribution at angle of attack of 13 degrees

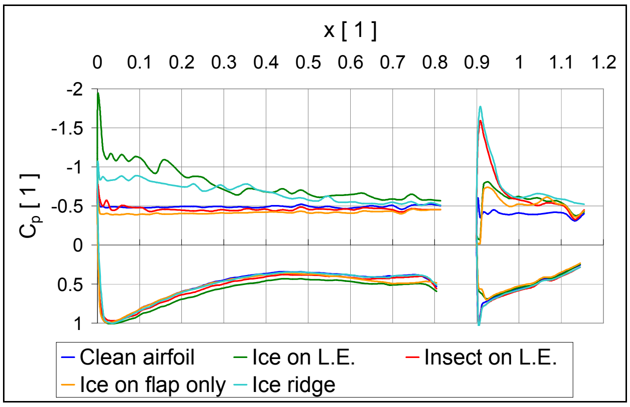

Fig. 8c. Pressure distribution at angle of attack of 23 degrees

7 Conclusions

The well-known danger of performance degradation caused by the different ice accretions was confirmed once again, this once for an advanced low-speed airfoil section. The ice accretion on the main airfoil whether on its leading edge or on the its upper surface strongly compromises the airfoil performance. The ridge created by the supercooled large droplets on the upper surface entirely destroys the aerodynamic characteristics of the airfoil. The ice accretion only on the flap affects the circumfluence round the flap significantly but the influence on the airfoil main part is of small significance, so the global influence except the drag is relatively moderate.

The sensitivity to insect contamination on the leading edge can be relatively high. It is important conclusion for the potential use of the airfoil as there is no practical possibility how to keep the leading edges clean during the standard summer flight operations. The losses from the point of view of maximum lift as well as drag are clearly pronounced.

Acknowledgements

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References

[1] -. Effect of airfoil geometry on performance with simulated ice accretions. Volume 1: Experimental investigation, FAA Report DOT/FAA/AR-03/64, Volume 2: Numerical investigation, FAA Report DOT/FAA/AR-03/65, 2003.

[2] Kim H S, Bragg M B. Effects of leading-edge ice accretion geometry on airfoil performance. AIAA Paper AIAA-99-3150.

[3] -. Effect of large-droplet ice accretion on airfoil and wing aerodynamics and control. FAA Report DOT/FAA/AR-00/14, 2000.

[4] Bragg M B. Aerodynamics of supercooled-large-droplet ice accretions and the effect on aircraft control. FAA Report DOT/FAA/AR-96/81, 1996.

[5] Bragg MB. Aircraft aerodynamic effects due to large droplet ice accretions. AIAA Paper 96-0932, 1996

[6] Holl M, Patek Z, Smrcek L. Wind tunnel testing of performance degradation of ice contaminated airfoils, *ICAS 2000 Proceedings*, Harrogate, ICAS-2000-3.1.1. pp 311.1 – 311.7, 2000.

[7] Hoření B. Výpočet námrazy na profilu křídla s klapkou, *Ústav pro hydrodynamiku AVČR*, Praha, 2006