EXPERIMENTAL AND CFD STUDY OF KRUEGER FLAPS

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Abstract

An experimental and computational study of an airfoil with different geometric shapes of the slot between the Krueger flap and the main element was performed. The aim was to better understand the flow especially in the area between the flap and the main element at several geometrically distinctive cases – without a slot, with miniature slot created by manufacture and assembly tolerances, with well-designed slot and with aerodynamically poorly performing inadequately designed slot. The flow field in the area of the flap strongly depends on the geometry of the slot and on the angle of attack. Even a miniature slot can result in pronounced influence on the airfoil characteristics. Meeting basic rules for usual wider slot design can be insufficient for design of an aerodynamically efficient slot.

1 Introduction

A Krueger flap [1] is a high-lift device that is deployed from the lower side of a wing around the leading edge. A retracted Krueger flap is stored in the lower side of the wing, and hence it does not create surface discontinuities in the proximity of the leading edge that cause early transition to turbulence on the upper surface. In addition to it, a Krueger flap can shield the leading edge during take-off and landing against insect contamination, which, at cruise, can also cause early transition to turbulence [2].

A conventional Krueger flap as proposed by Krueger [1] is designed without any slot between its trailing edge and the main element. A slot has, according to Krueger's results, negative aerodynamic effect. But in a real wing structure, a perfect sealing arrangement between the flap and the main element is not easy to achieve. Usually, a miniature gap is created as a result of kinematic design, tolerances in manufacture, assembly and adjustment.

The flap has been progressively developed in its geometric form and now any device stored in retracted position beneath the leading edge of the wing is frequently called a Krueger flap, including the devices with pronounced gap between the deployed flap trailing edge and the main element. This arrangement can be considered as a Krueger flap from the structural point of view, but it operates aerodynamically as a high-lift device usually known as a slat. The geometric shape of the slot between the flap (i.e. the slat) and the main element is an essential design factor in aerodynamic functioning of a Krueger flap or a slat, as is a well-known fact [3] [4] [5] [6].

The main task of the Krueger flap as a leading edge device is focused on the region of higher angles of attack, especially on postponement of the stall and a corresponding increase of the maximum lift coefficient. But it can happen that it is deployed out of the design range of the angles of attack for many reasons.

The aim of the paper is to study influence of different slots between the flap and the main element in a wide range of the angles of attack.

2 Airfoil

A low-speed laminar airfoil of maximum thickness of 15 percent was used for the study. The Krueger flap on its leading edge could be adjusted at different angular positions and at different horizontal and vertical positions as well. A sketch of the studied geometric configurations is presented in Fig. 1.

Four geometries of the slot were studied:

- a closed gap (a conventional Krueger flap in its original form without any flow passing through the area of its trailing edge)
- an extremely narrow (miniature) slot (representing a Krueger flap with a theoretically closed gap but with imperfections causing a miniature slot
- an optimized well-shaped slot (well-designed slat)
- a non-optimized slot (poorly performing slat)

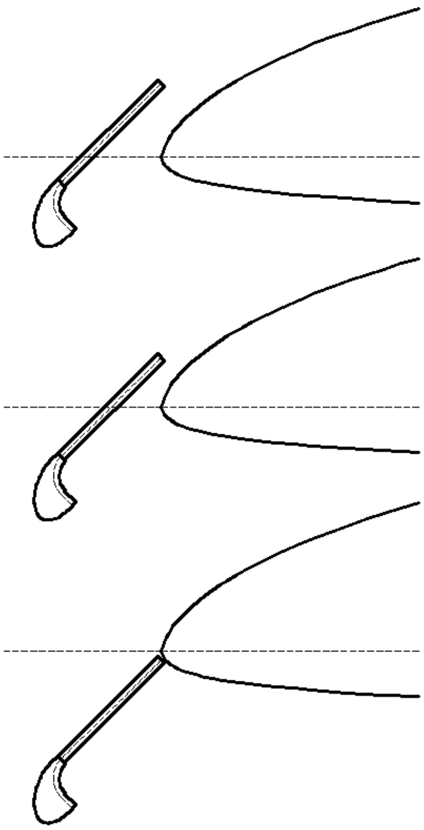

Fig. 1 Geometric configuration of Krueger flaps. Gaps (from top to bottom) 2x/c, 1x/c 0.04x/c.

3 Wind tunnel testing and CFD computations

The study was performed using combined approach of the low-speed wind tunnel testing and the CFD computations.

The pressure distributions on the main element and the PIV measurements in the slot behind the Krueger flap were performed experimentally. The model consisted of a rectangular wing of 0.6 m chord and of 1.2 m span with circular endplates. The low-speed wind tunnel 3mLSWT of VZLU Czech Aerospace Centre was used for the testing.

The pressure and velocity distributions on the Krueger flap, on the main element and in the whole flowfield were computed by means of CFD; EDGE software was used [7]. The flow was modelled by means of RANS equations closed by EARSM turbulence model [8]. Unsteady formulation was used only at points where it was necessary.

4 Results

The wind tunnel testing and the CFD computations were performed for the airfoil Reynolds number (based on the chord) of $1.5\cdot10^6$.

Comparison of experimental and computational results can be found in Figures 3 and 9. In general, results obtained by means of the CFD show lower drag and higher maximum lift coefficient. The probable explanation is that the experimental results are not perfectly corrected for the effects caused by a non-standard experimental setup (adjustments of the end plates of the model for the PIV system, etc.).

4.1 Miniature slot

The results of the miniature slot seem to partly match the Krueger's results; the main difference is that the width of the gap in the report [1] is much wider that is rather surprising. The both experimental and CFD results indicate non-negligible influence even of the very narrow gap, as is the tested case of a gap of 0.04 % of the airfoil chord. The influence pronounces mainly on the pressure distribution of the upper surface of the main element and thus on the total lift coefficient of the airfoil; the decrease of the maximum lift coefficient in the order of 0.1 and the corresponding decrease of the angle of attack of the maximum lift coefficient in the order of 4 degrees are registered both in the experimental and in the computational results.

The reason for the decrease of the lift coefficient consists in lower pressure depression on the upper surface of the whole airfoil, even the very narrow gap connecting the lower surface with the upper one suffices to create this effect. The pressure distribution C_p for the angle of attack α of 20 deg is plotted in Fig. 2.

Regardless of the fact that the slot is very narrow, the air flows through it and a wake is created behind the trailing edge of the flap. The velocity through the extremely narrow exit gap is not negligible as it reaches 60 to 85 percent of the velocity of the undisturbed flow (Fig.4 and Fig. 5 for angle of attack of 10 and 20 deg respectively). Even very low momentum flow (see Table 1) is sufficient to create relatively important influence on the airfoil upper surface.

Table 1 - Jet momentum coefficients Cμ

α [°]	g = 0.04 x/c	g = 2 x/c	g = 1 x/c
20	0.036	6.610	3.610
15	0.022	5.529	2.652
10	0.010	4.381	2.070

$$C\mu = 2gV^2/(cV_\infty) \qquad (1)$$

The jet momentum coefficient is defined by Eqn.1, where g is the gap between the flap and the main element, V is the mean velocity in the gap, c is the airfoil chord and V_∞ is the velocity magnitude of the undisturbed flow.

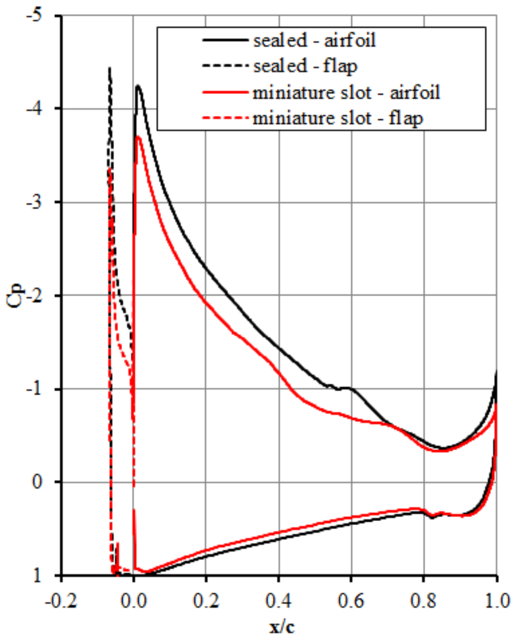

Fig. 2 Pressure distribution (CFD), α = 20 °

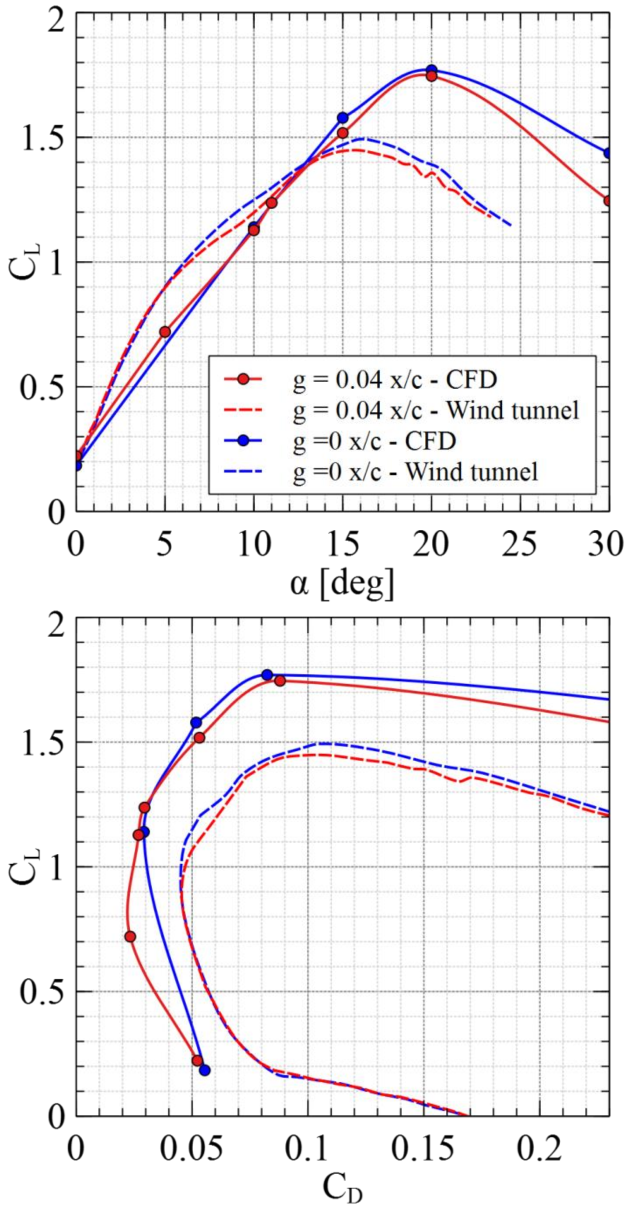

Fig. 3 Aerodynamic characteristics of Krueger flap sealed and with the miniature slot.

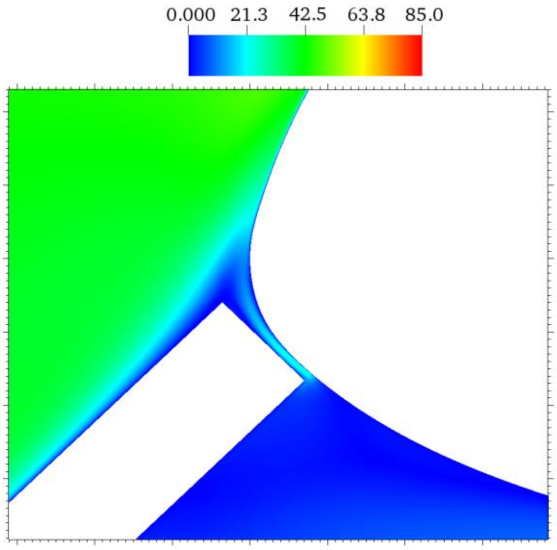

Fig. 4 Velocity contours ($m \cdot s^{-1}$). Detail of Krueger flap (CFD) with miniature slot, α = 10°

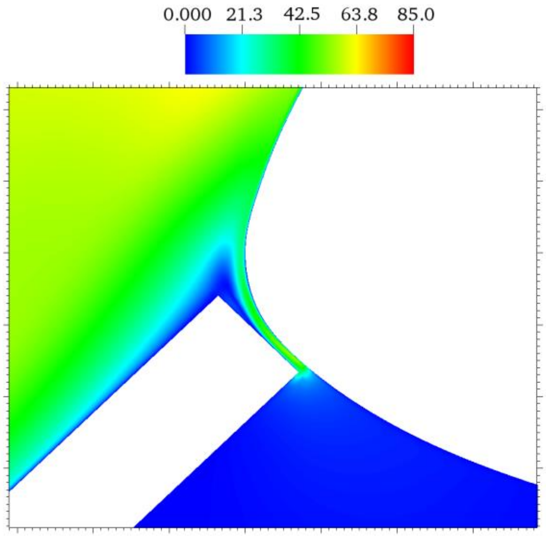

Fig. 5 Velocity contours ($m \cdot s^{-1}$). Detail of Krueger flap (CFD) with miniature slot, α = 20°

4.2 Wide slot

To create the wide slots, the angle of the flap was not changed but the flap was moved upwards with respect to the main element, so it was positioned rather as a slat with a distinctive wide slot.

If the geometry of the slot between the flap and the main element is not designed aerodynamically favourable, the slot can be counterproductive as was shown in the mentioned Krueger's example. Two problematic regions can arise.

The entry into the slot can be totally obstructed by the vast area of the detached flow behind the deployed flap. It could be a case mainly at lower angles of attack, as is presented by PIV measurements of the velocity vectors in Fig. 6.

The second unfavourable area can arise in the form of a detached flow on the upper side of the leading edge of the main element in the rear part of the slot. The PIV and CFD visualizations of the vorticity field in the slot are in Fig. and 8 for a regime of a distinctive drag increment in the region below C_L = 1 (Fig. 9). The vorticity distribution indicates a strong vortex in the entry to the slot behind the lower part of the flap and a detachment of the flow on the upper part of the leading edge of the main element.

Meeting the basic rules of thumb of the design of the slot is not a sufficient condition for an efficient solution as one of the tested examples (the case 2/x, i.e. the exit gap of 2 percent of the airfoil chord) demonstrates. The slot has a wide entry, its width diminishes constantly up to the exit gap and this gap is relatively width (Fig. 10). The basic rules are met but this is not evidently sufficient as is proved by large detachment of the flow on the leading edge of the main element (Fig. 7 bottom) and by lift and polar curves (Fig. 9). Even high momentum flow from the gap is not sufficient to support formation of favourable conditions in the boundary layer of the main element. The reason consists in very different pressure conditions in the gap, especially the development of the pressure gradient on the upper part of the leading edge of the main element (Fig. 11). Contrary to it, the case 1 x/c with an exit gap of 1 percent of the chord performs rather well, despite of the lower momentum flow.

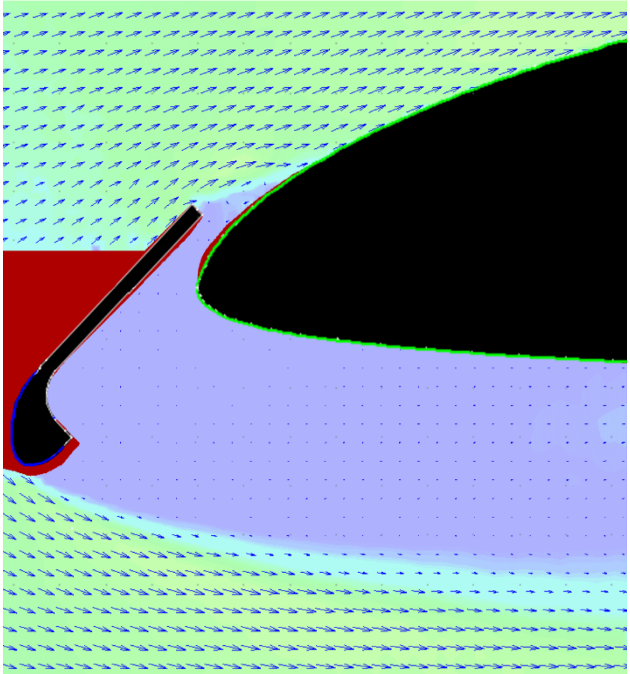

Fig. 6 PIV results, configuration with wide slot g = 1 x/c, α = 0°

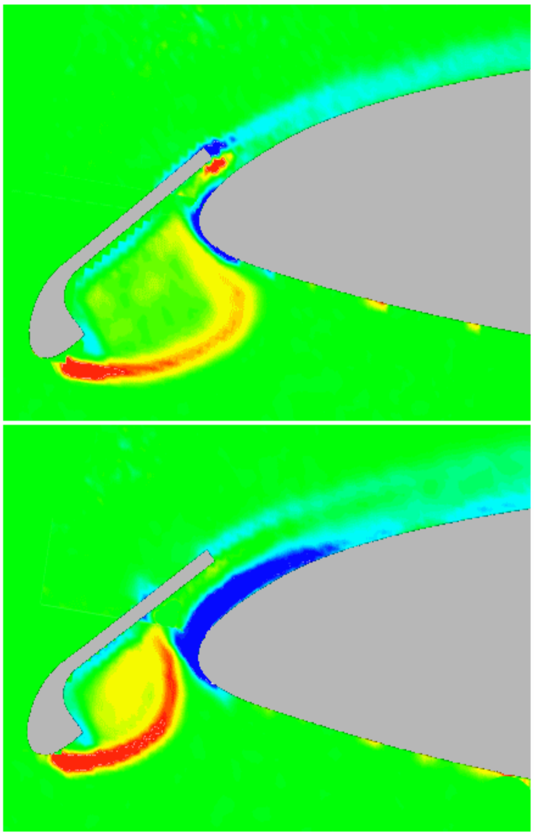

Fig. 7 (PIV) Contours of vorticity (blue - clockwise, red - counterclockwise). Slot 1 x/c - top, 2x/c – bottom

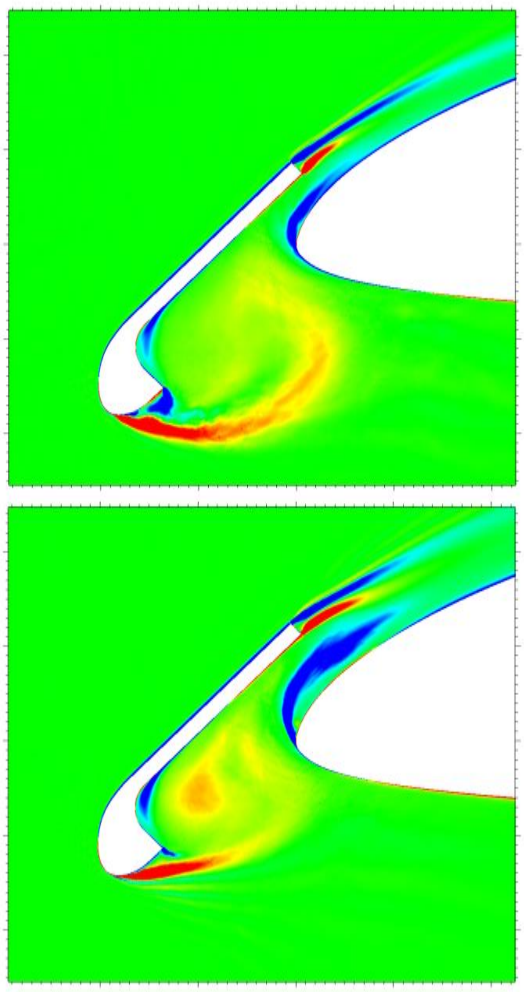

Fig. 8 (CFD) Contours of vorticity (blue - clockwise, red - counterclockwise). Slot 1 x/c - top, 2x/c - bottom

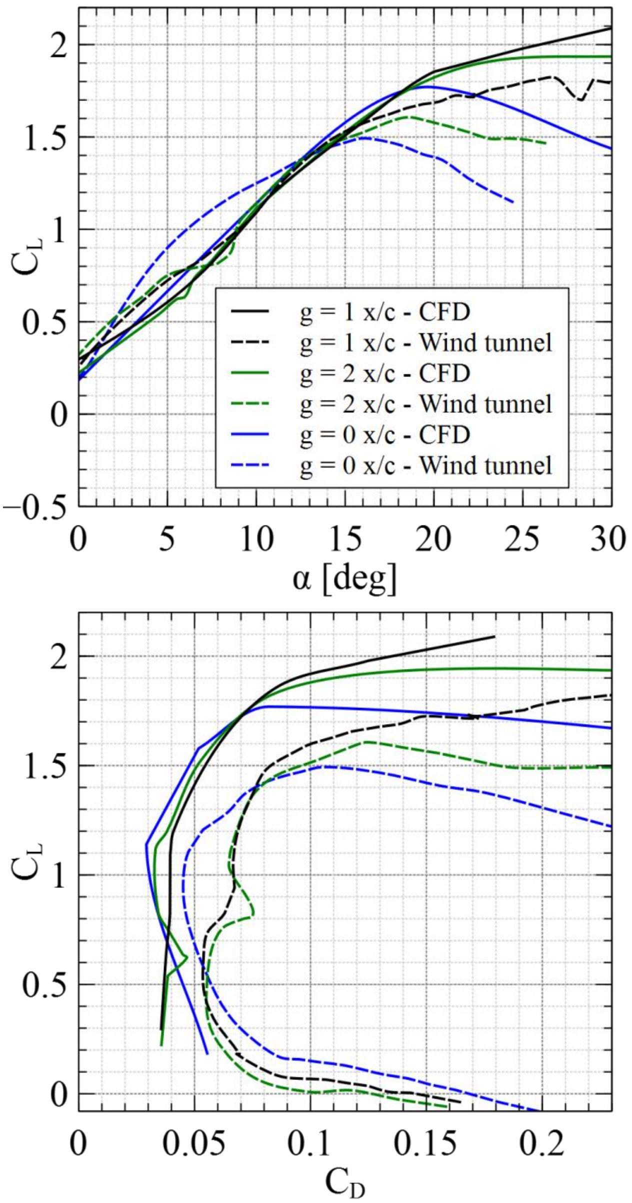

Fig. 9 Aerodynamic characteristics of the Krueger flap with wide slot.

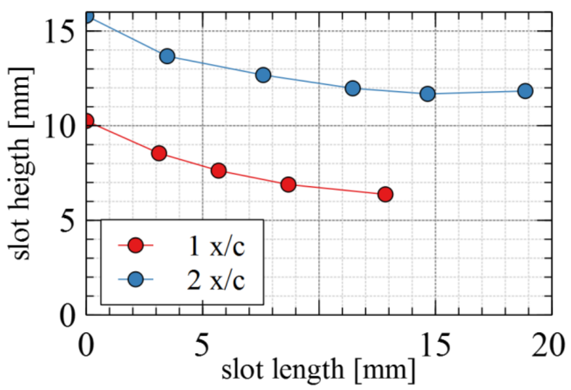

Fig. 10 Evolution of dimensions of wide slots

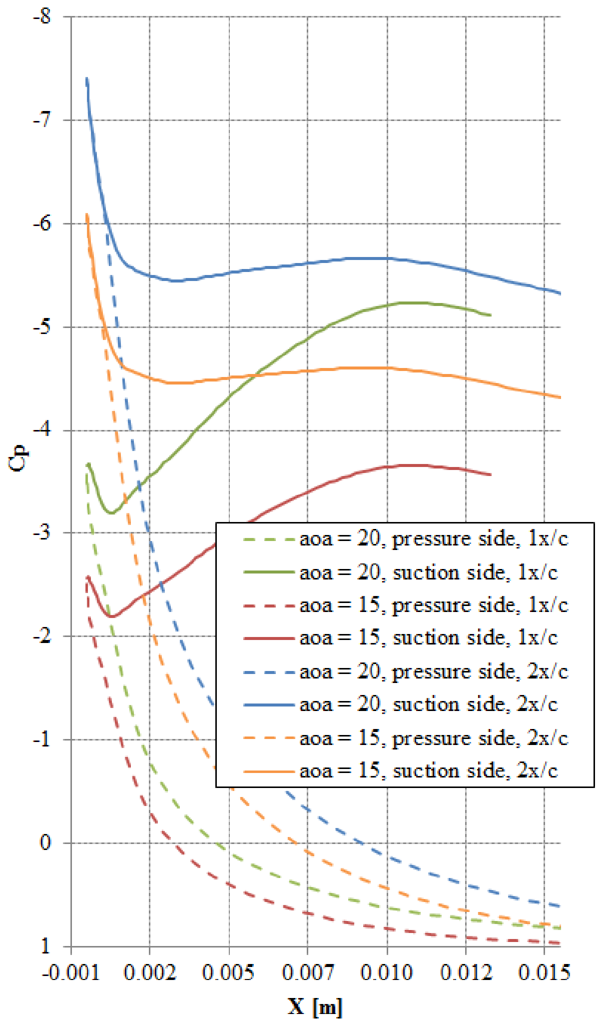

Fig. 11 - Detail of pressure coefficient (CFD) around airfoil leading edge.

5 Conclusions

The effect of a miniature gap between a trailing edge of a Krueger flap and a main element can be relatively important. Such a narrow gap can be easily created or closed as a consequence of usual tolerances during the manufacture or the assembly and the adjustment of the flap. It seems that influence of even small imperfections of the slot shape should be assessed very thoroughly.

Generally, it is once more confirmed by the experimental measurements and the CFD computations that a Krueger flap or a slat should be very carefully designed. Meeting the basic rough rules of the geometrical shaping can be unsatisfactory. If the slot is not designed correctly, the deployment of the flap can result in an increase of the drag coefficient without any reasonable increase of the lift coefficient. The attention has to be paid also to the angles of attack of off-design conditions where the deployment of the flap could result only in an increase of the drag coefficient.

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