On the Most Common Misunderstandings of High-Lift Flows

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Motivation for this talk

- We are facing 100 years of high-lift systems
  - Slotted wing patent application by G. Lachmann (1917/1918)
  - Slat patent by F. Handley Page (1921)
  - Flap patent by Harlan D. Fowler (1927)

- Well known (and cited) summaries on high-lift system aerodynamics
  - W. Pleines, Wing Brake Flaps. *Aircraft Engineering* **7**(9) (1935)
  - A.R. Weyl, High-Lift Devices and Tailless Aeroplanes, Aircraft Engineering, **17**(19) (1945)
  - A.M.O. Smith, High Lift Aerodynamics. Journal of Aircraft **12**(6) (1975)

- Nevertheless, some basic principles are still misunderstood in the wider community and still present in text books and recent publications

A.R. Weyl, High-Lift Devices and Tailless Aeroplanes, Aircraft Engineering, Oct. 1945

- ***Slots***

  A second method [to delay stall] *is to* ***supply kinetic energy to the boundary layer*** *on the upper surface, making it, at the same time turbulent. This can be done by the provision of appropriately shaped air ducts (slots) leading from high pressure regions of the under surface to low-pressure regions on the upper surface, through which a flow of air is sustained. When this flow of air is* ***by means of convergent walls (nozzle)*** *transformed into one of low pressure and high velocity and then added to the boundary layer,* ***it ,"re-vitalizes" the stale boundary layer****, enabling it to follow the contour of the wing surface without separating from it. The powerful downwash which is created by the strong circulation over the forward slat acts in the same way. Slots thus delay the stall; in this way, considerable values of maximum lift are obtained. But slots do not improve the slope of the lift curve,* dC_L/da.

S.F. Hörner & H. V. Borst, *Fluid Dynamic Lift*, 1985

- ***Principle***. *Boundary-layer control by means of slot (such as in slotted trailing -edge flaps) is based on the* ***concept of injecting momentum into a „tired“ boundary layer***. […] *Still another important property of slots is* [...] *that is in* ***a converging slot (as in a nozzle)*** *an equalization of total pressure takes place* […]. *As a consequence* […] *such slots are a suitable means of feeding momentum into the boundary layer at the upper side of flaps or airfoils*

Remark: The original book from Hörner dates back to 1967. The sections on slotted airfoils have not been edited in the current edition.

„Slots supply kinetic energy to the boundary layer“

- energy conservation along stream tube: Bernoulli‘s equation

$$p_t = p + \tfrac{1}{2}\rho\left|\mathbf{v}\right|^2 = const.$$

- without viscous losses the local kinetic energy is

$$\tfrac{1}{2}\rho\left|\mathbf{v}\right|^2 = p_\infty + \tfrac{1}{2}\rho_\infty U_\infty^2 - p$$

- the kinetic energy of the slot flow is (at maximum) exactly the same as the outer flow at the boundary layer edge

Lift potential of „fresh boundary layer“

- Separation criteria by Stratford
  - shortening the length increases allowable adverse pressure gradient
  - for the same pressure rise, shortening the length increases the adverse pressure gradient
  - the remaining benefit on separation is the reduction of x_0

$$\bar{c}_p = 1 - \left(\frac{u}{u_{\max}} \right)^2$$

$$\bar{c}_p \sqrt{x \frac{d\bar{c}_p}{dx}} = \left(10^{-6} Re_0\right)^{1/10} S$$

$$Re_0 = \frac{U_\infty x_0}{\nu}; \quad x_0 : \text{start of pressure rise}$$

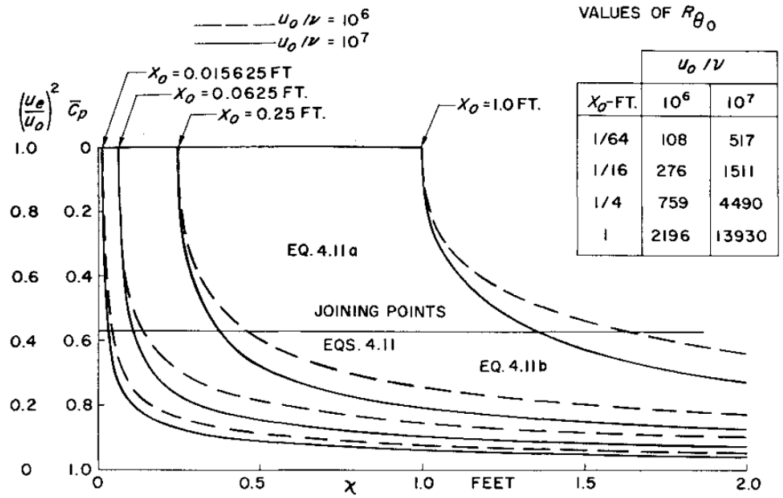


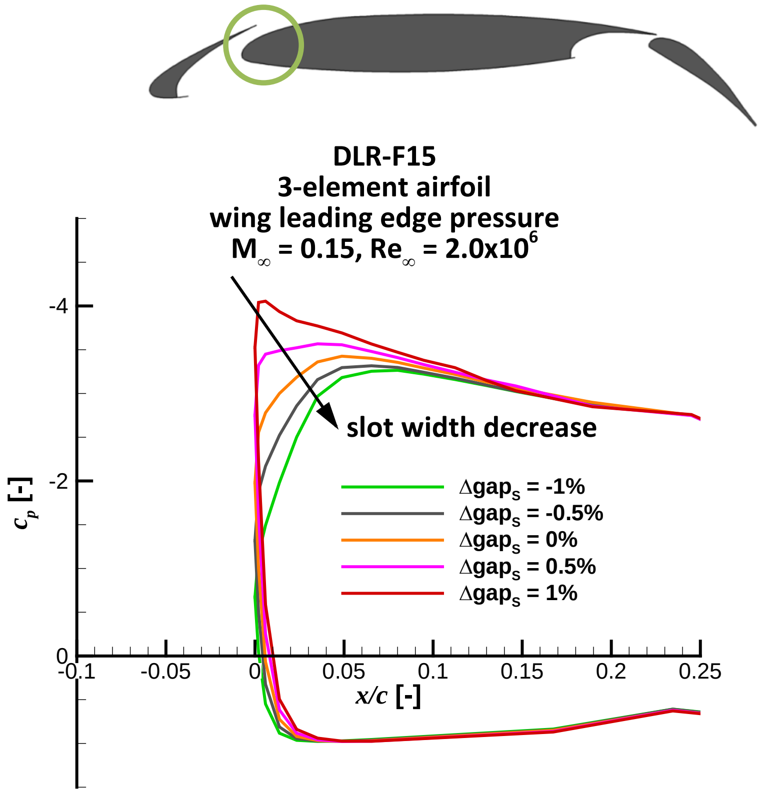
Fig. 21 Stratford limiting flows at two values of unit Reynolds number.

Fig.: © AMO Smith, High Lift Aerodynamics. *Journal of Aircraft* **12**(6) (1975) 501-530

Stratford, B. S., "The Prediction of Separation of the Turbulent Boundary Layer," *Journal of Fluid Mechanics,* Vol. 5, 1959, pp. 1-16

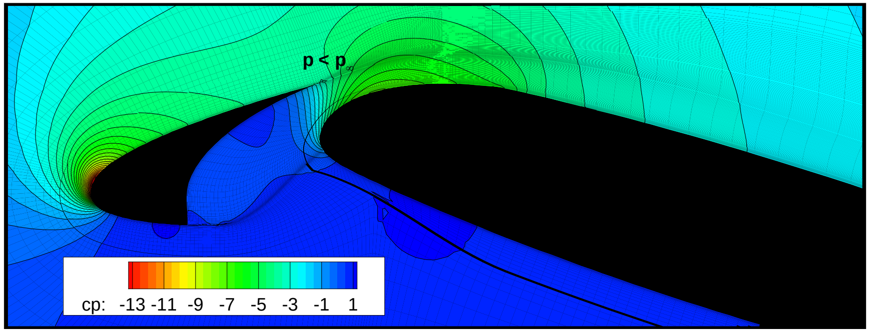
[Slots work] by means of convergent walls (nozzle)

- consequence (of this idea):
  - narrowing the gap increases the local flow velocity at the slot exit
- experimental observation
  - slot velocity decreases with decreased slot width
- explanation
  - other than in pressurized ducts, there is no defined mass flow to go through the slot



What really happens

- slot effects (Smith, 1975)



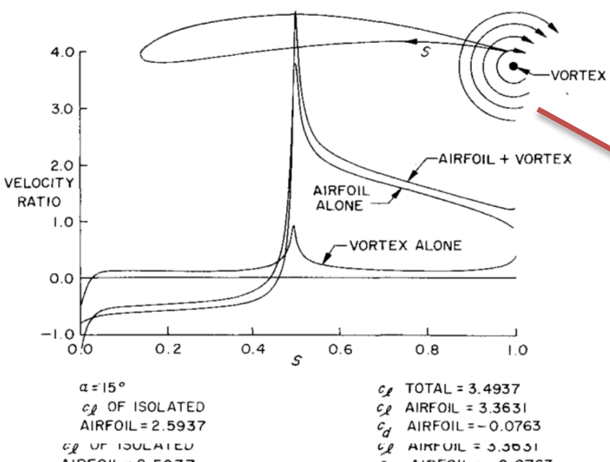


Fig.: © AMO Smith, High Lift Aerodynamics. *Journal of Aircraft* **12**(6) (1975) 501-530

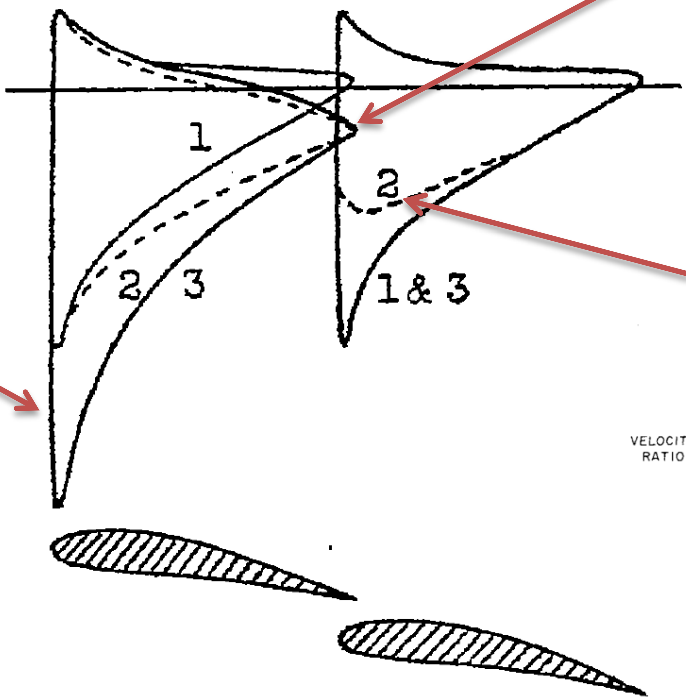


Fig.: A Betz, Theory of the Slotted Wing. *NACA TN-100* (1922)

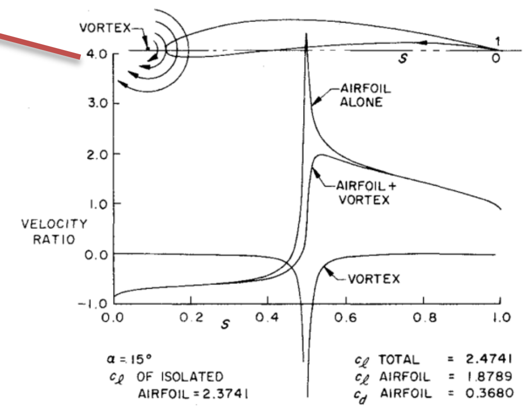


Fig.: © AMO Smith, High Lift Aerodynamics. *Journal of Aircraft* **12**(6) (1975) 501-530

„low-speed (high-lift) flows can be regarded incompressible“

common assumption for incompressible flows:

$$M_\infty \leq 0.3$$

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„low-speed (high-lift) flows can be regarded incompressible“

- potential theory
    - incompressible flow equation (linear potential equation)

$$\phi_{xx} + \phi_{yy} = 0$$

    - compressible small disturbance equation

$$\left(1 - M_\infty^2\right)\phi_{xx} + \phi_{yy} = 0$$

    - Prandtl-Glauert compressibility correction

$$\frac{c_{p,k}}{c_{p,ik}} = \frac{1}{\sqrt{1 - M_\infty^2}}$$

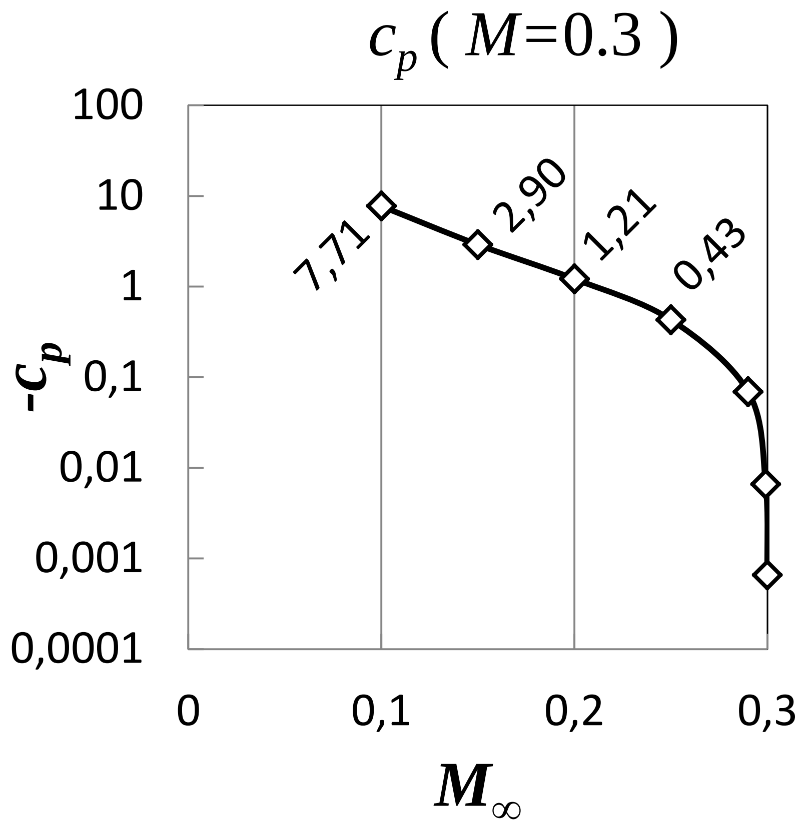
    - incompressible flow assumption

$$\frac{c_{p,k}}{c_{p,ik}} = \frac{1}{\sqrt{1 - 0.3^2}} = 1.0483 \quad \Rightarrow \quad \text{5\% error in } c_p$$

„low-speed (high-lift) flows can be regarded incompressible“

- what‘s a small disturbance?
  - let‘s assume 5% error in pressure coefficient for **local** M>0.3

$$c_p = \frac{\left(1+\frac{\kappa-1}{2}M_\infty^2\right)^{\frac{\kappa}{\kappa-1}} - \left(1+\frac{\kappa-1}{2}M^2\right)^{\frac{\kappa}{\kappa-1}}}{\left(\frac{\kappa}{2}M_\infty^2\right)\left(1+\frac{\kappa-1}{2}M^2\right)^{\frac{\kappa}{\kappa-1}}}$$



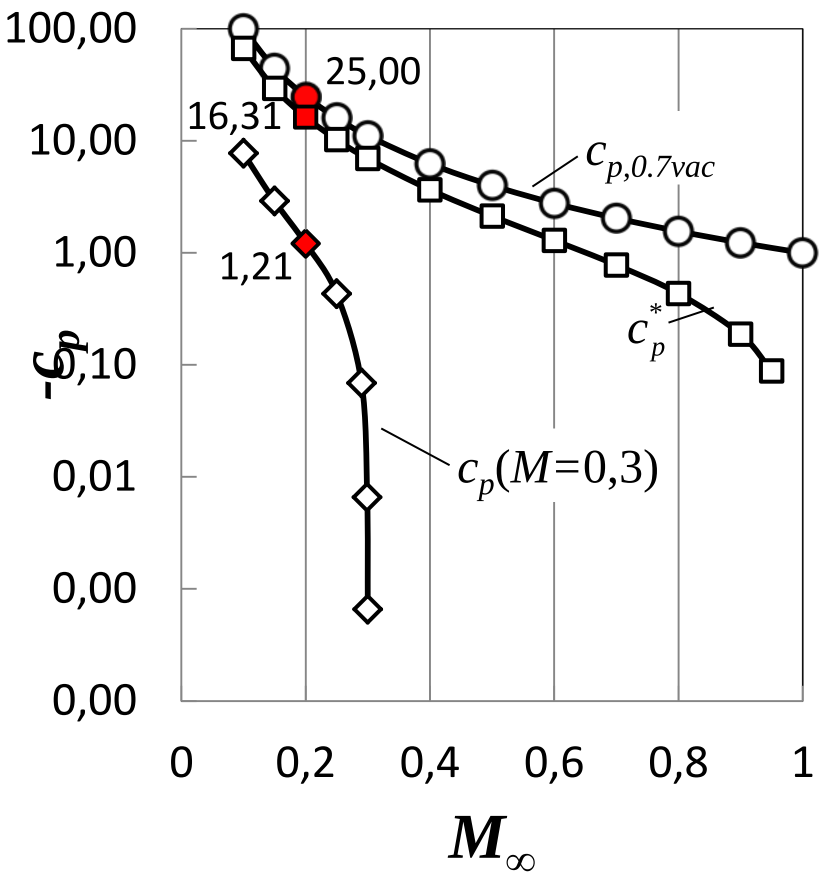
„low-speed (high-lift) flows can be regarded incompressible“

- other characteristic pressure values for compressible flow
  - critical pressure coefficient for **local** M=1

$$c_p^* = \frac{1}{\frac{\kappa}{2} M_\infty^2} \left(1 - \left(\frac{2}{1+\kappa} + \frac{\kappa - 1}{1+\kappa} M_\infty^2 \right)^{\frac{\kappa}{\kappa - 1}} \right)$$

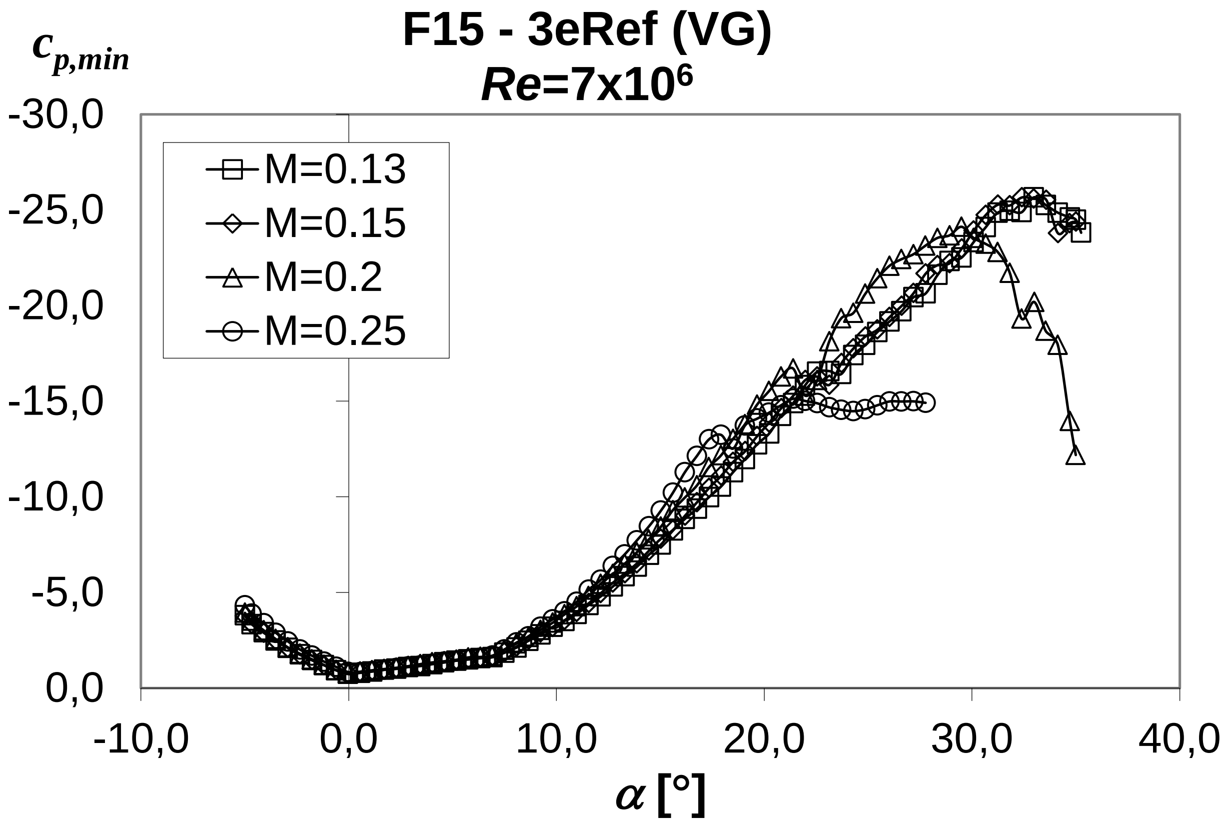
  - 0.7 vacuum rule (Mayer, Research Memo. L8F23, 1948, NACA)

$$c_{p,0.7vac} M_\infty^2 \leq -1$$



„low-speed (high-lift) flows can be regarded incompressible“

- example: slat pressure minimum



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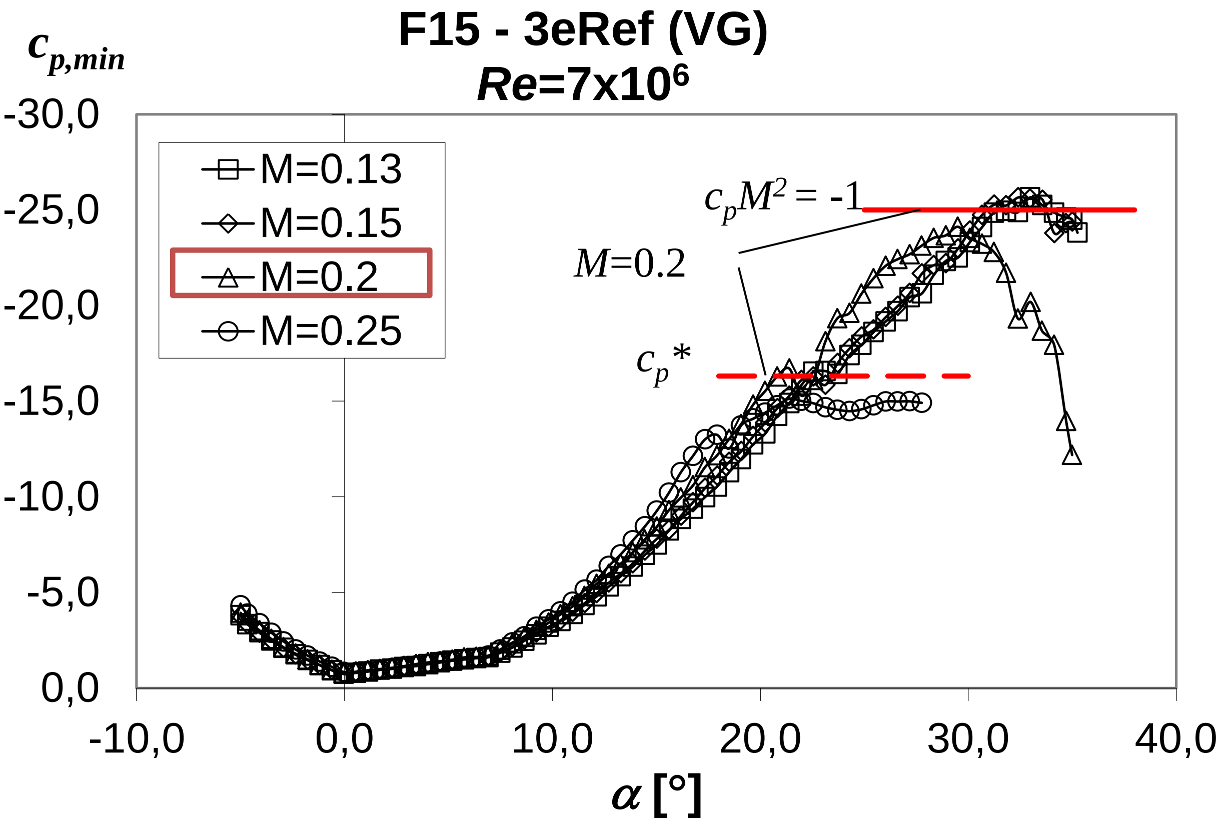

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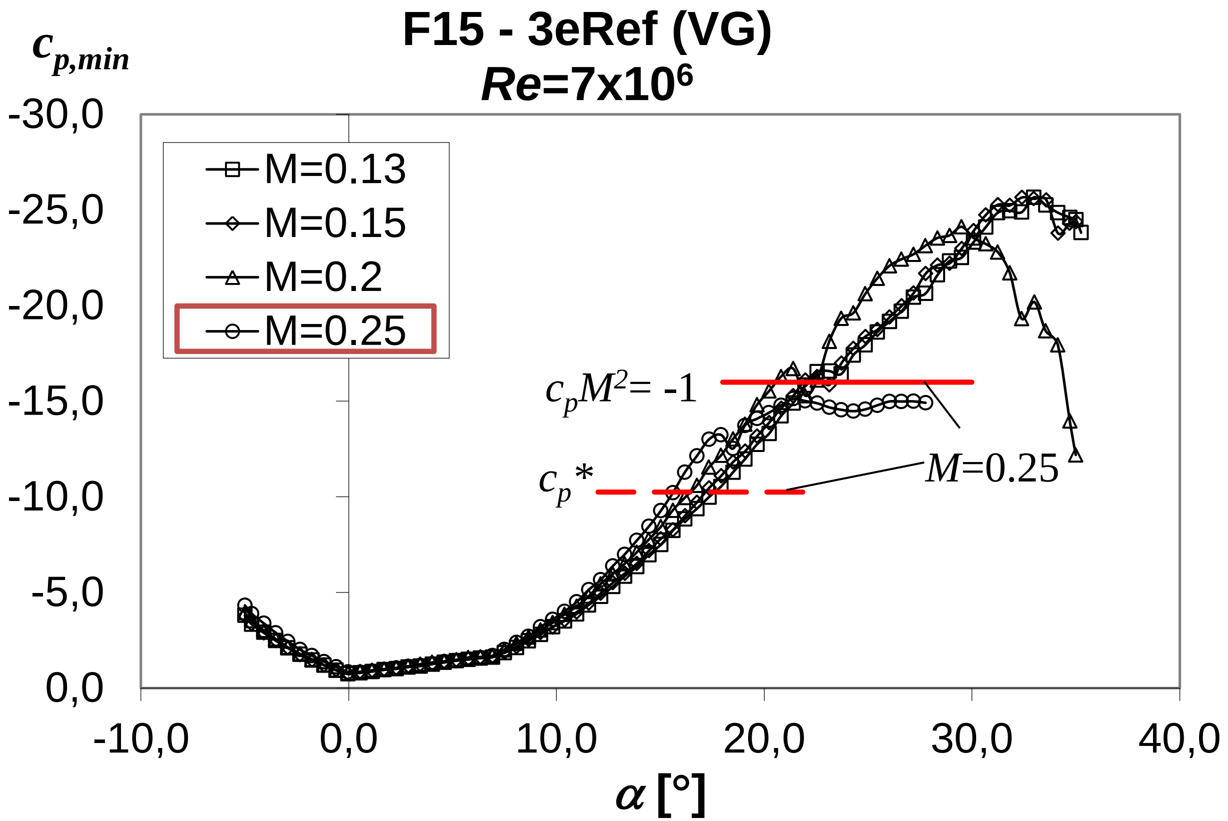
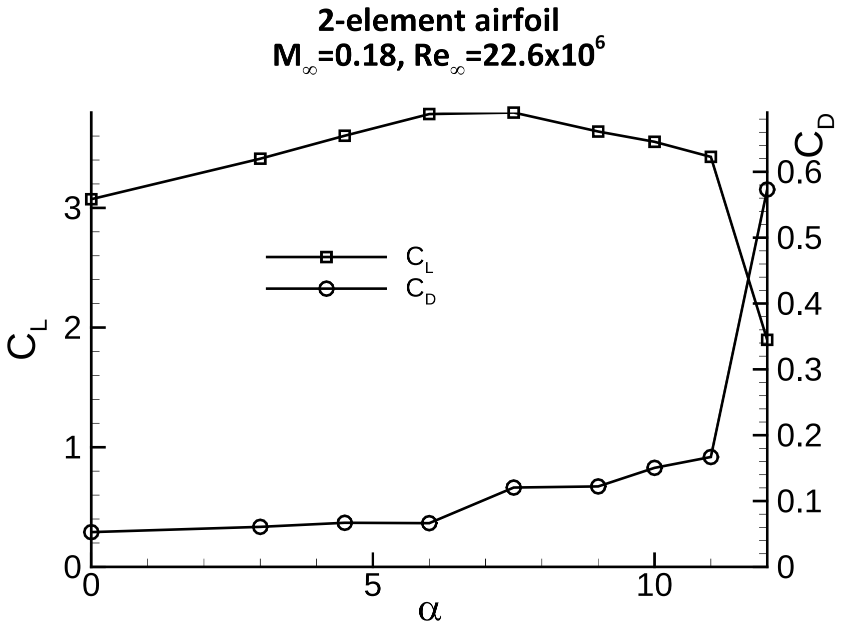
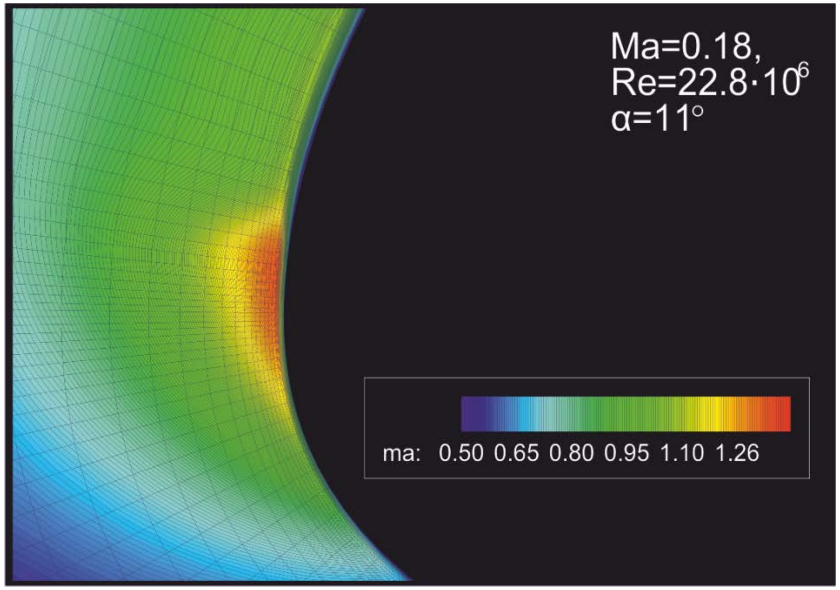


„low-speed (high-lift) flows can be regarded incompressible“

- example: 2-element clean leading edge





Conclusions

- high-lift system aerodynamics often described in text-books in a very simplified way
- the idea of boundary-layer control as the central mechanism survived nearly 100 years of better explanation
- explaining gap flows as „nozzles“ gives the wrong direction for design

- high-lift system flows are a very complex flow structure that may contain very different features
  - compressible flow including shocks
  - viscous flow including boundary layers, free shear layers, separated areas

- the right understanding is necessary to enable highly targeted designs to reduce the complexity, weight, effort

Thank you for listening

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