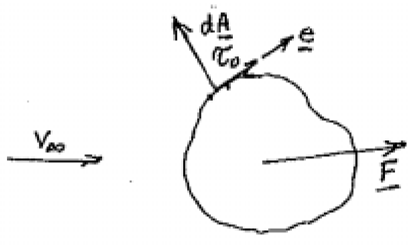
Objective of Building Aerodynamics subject, its structure, tasks of the student:
- determination of wind load aerodynamic forces, moments, static and dynamic effects, pressure- and velocity distribution over the envelope of building, interaction of ambient flow and internal flow (ventilation, air conditioning), pedestrian comfort, dispersion of pollutants,
- organization of the subject: lectures, student projects, laboratory work, progress reports.

1. Aerodynamic forces acting on bodies in flow of real (viscous) fluid.

1.1. At flow inviscid fluid the streamlines follow the surface and no shear stresses and no overall pressure forces arise (D' Alambert paradox).



1.2. In case of real (viscous) fluid both pressure and friction forces play role.

$$\underline{F} = -\int_A p\, d\underline{A} + \int_A \tau_0\, \underline{e} |d\underline{A}|$$

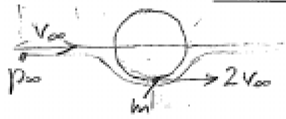
1.3. Pressure- and local friction coefficients.

$$c_p = \frac{p - p_\infty}{\frac{\rho}{2} v_\infty^2} \qquad c'_f = \frac{\tau_0}{\frac{\rho}{2} v_\infty^2}$$

$$\underline{F} = -\int_A p\, d\underline{A} + \int_A \tau_0\, \underline{e}|d\underline{A}| + \int_A p_\infty\, d\underline{A} = \frac{\rho}{2} v_\infty^2 \left[-\int_A c_p\, d\underline{A} + \int_A c'_f\, \underline{e} |d\underline{A}| \right]$$

V_∞ $p_\infty + \frac{\rho}{2} V_\infty^2 = p_t \Rightarrow c_{pt} = \frac{p_t - p_\infty}{\frac{\rho}{2} V_\infty^2} = 1$

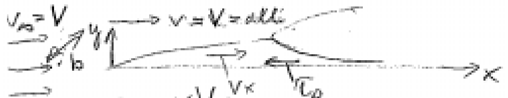
1.4. Estimation of the scale of value of pressure coefficient



$p_\infty + \frac{\rho}{2} V_\infty^2 = p_m + \frac{\rho}{2} (2V_\infty)^2$ $\quad -3 \le c_p \le 1$

$c_{p\,min} = \frac{p_m - p_\infty}{\rho/2\, V_\infty^2} = -3$

1.5. Estimation of the scale of values of local friction coefficient. Characteristics of boundary layer along flat plate at no pressure gradient. Approximate formulas for velocity distribution, BL thickness and local and overall friction coefficient of laminar and turbulent boundary layer.



$Re_x = \frac{xV}{\nu}$

lamináris határréteg

$\frac{V_x}{V} = 1{,}5\frac{y}{\delta} - 0{,}5\left(\frac{y}{\delta}\right)^2$ $\quad \frac{\delta}{x} \approx \frac{5}{\sqrt{Re_x}}$ $\quad c'_f = \frac{\tau_0}{\frac{\rho}{2}V^2} = \frac{0{,}664}{\sqrt{Re}}$

$c'_D = \frac{F_D}{\frac{\rho}{2}V^2 x \cdot b} = \frac{1{,}328}{\sqrt{Re_x}}$

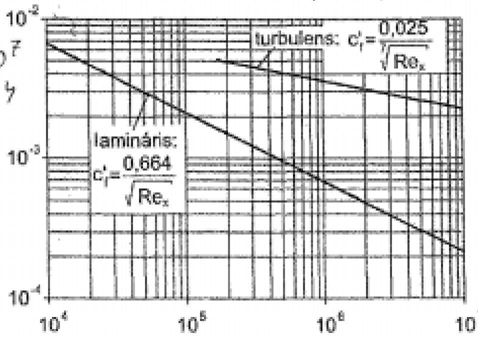
turbulens határréteg

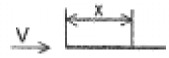
$\frac{V_x}{V} \cong \left(\frac{y}{\delta}\right)^{1/n}$

Re_x	10^5	10^6	10^7
n	6,4	7,8	9,4

$\frac{\delta}{x} = \frac{0{,}14}{\sqrt[7]{Re_x}}$

$c'_f = \frac{0{,}025}{\sqrt[7]{Re_x}}$ $\quad c'_D = \frac{0{,}03}{\sqrt[7]{Re}}$





$Re_x = \frac{Vx}{\nu}$

Example for a given plate: BL thickness, drag force on a wall of a building. .

plate $b = 1\,m$ $x = 0{,}4\,m$ $V = 30\,m/s$ $\nu = 15 \cdot 10^{-6} \frac{m^2}{s}$ $Re_x = \frac{0{,}4 \cdot 30}{15 \cdot 10^{-6}} \doteq 800\,000$ turb.
$\delta_{max} = 0{,}14 \cdot Re_x^{-1/7} \approx 0{,}008\,m$ $c_D' = 0{,}03 \cdot Re_x^{-1/7} = 0{,}0043$ $F_{D\,2sides} = 1{,}86\,N$
Wall $x = 30\,m$ $b = 1\,m$ $V = 30\,m/s$ $Re_x = \frac{30 \cdot 20}{15 \cdot 10^{-6}} = 4 \cdot 10^7$ $c_D' = 0{,}0025$ $F_{D\,1m} = 40{,}5\,N$

1.6. <u>The magnitudes of pressure and friction coefficients</u> differ very much. Usually: $-2.5 < c_p \leq 1$ and $|c_f'| < 0.01$.

1.7. Summary: the <u>friction force coefficients, and so the friction forces are very much smaller than the pressure forces</u>. In general: if the streamlines follow the surface of the body (streamlined bodies) the pressure forces are small (see D' Alambert paradox) so the friction forces dominate. Since these are small, the aerodynamic forces and force coefficients are small.

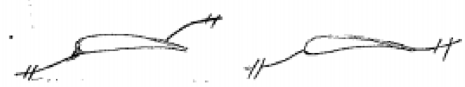
$$c_D = \frac{F_D}{\frac{\rho}{2} v_\infty^2 A} \qquad c_L = \frac{F_L}{\frac{\rho}{2} v_\infty^2 A}$$

Example: the drag force coefficient of a symmetric strut (h/d=5) is very small: $c_D = 0{,}06$, (where h and d are the length and thickness of strut, respectively) at Re > 500000 (related to d). $c'_f = ?$

$c_D = \frac{\frac{\rho}{2} v_\infty^2 \cdot 2 \cdot 1 \cdot h\, c_f'}{\frac{\rho}{2} v_\infty^2\, 1 \cdot d} \rightarrow c_f' = c_D \frac{d}{2h} = 0{,}06 \cdot \frac{1}{2 \cdot 5} = 0{,}006$ $c'_{f\,turb} = \frac{0{,}03}{\sqrt[7]{Re}} = 0{,}0046$

1.8. Boundary layer remains thin in accelerating flow, e.g. over a part of the front of the cylinder the flow field is very similar to the flow developing in a non-viscous fluid.

Take care! In case of airfoil flow field is only partially similar to that of belonging to ideal fluid one: a boundary layer separation shifts the leeward stagnation point to the trailing edge of the airflow. So – in spite of attached flow over the surface of airfoil – large pressure related lift force develops.



1.9. The <u>pressure distribution</u> on a body can easily be assessed by using Euler equation in natural co-ordinate system. At steady, non-viscous flow and neglecting the forces acting on the mass of fluid (e.g. the weight), we obtain:

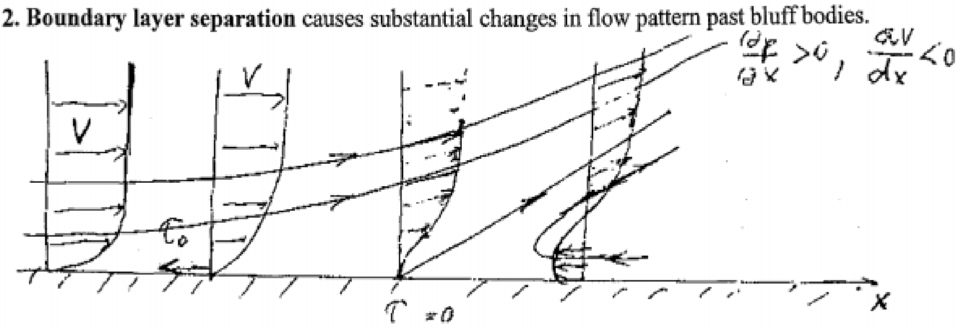
$$\frac{v^2}{r} = \frac{1}{\rho} \frac{\partial p}{\partial n},$$

where r[m] radius of curvature of the streamline, n co-ordinate perpendicular to the streamline. Also Bernoulli equation can be used to assess the pressure distribution.

1.10. The pressure related aerodynamic forces (i.e. the deviation of the real streamlines from that of belonging to flow of ideal flow) are generated to a lesser degree by the emerging of boundary layer, expressed by displacement thickness. Displacement thickness is: $\delta_1 \approx 0{,}1\ \delta$. It depends basically on separation of boundary layers. In this case pressure forces are dominant, so the aerodynamic forces and force coefficients are relatively big.

1.11. <u>Conclusion</u>: the forces acting on bluff bodies are caused mainly by "unbalanced" pressure distribution over the body. The direct effects of wall shear stresses are quite small: the drag of streamlined bodies, where the shear stresses dominate (e.g. wings), is by two orders of magnitude smaller than that of bluff bodies. Where pressure forces are dominant, the aerodynamic forces are relatively big. So the values of aerodynamic force coefficients are large. At bluff bodies the viscosity of fluid exerts its influence not mainly through the forces caused by wall shear stresses but indirectly, by influencing the flow field past bodies (e.g. by boundary layer separation) resulting "unbalanced" pressure distributions.

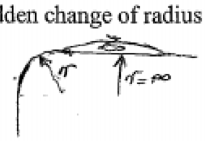
2. Boundary layer separation causes substantial changes in flow pattern past bluff bodies.

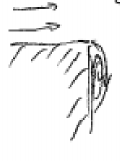


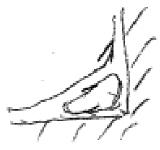
2.1. Two conditions for boundary layer separation are:
- vicinity of the wall (effect of wall shear stresses),
- pressure increase downstream (adverse pressure gradient), related to streamwise decreasing velocity.

2.2. Boundary layer separates if the joint effect of decelerating forces caused by shear stresses near the wall and the adverse pressure gradient exceeds the sum of momentum of velocity distribution at the beginning of the decelerating flow field an the impulse transport from outside flow into the boundary layer.

2.3. Boundary layer separation is promoted by
- large wall shear stresses (roughness) in turbulent boundary layer,
- large gradp caused e.g. by large cone angle of diffuser or small rounding up radius of leading edge. BL. separation frequently occurs at changing the flow direction: in front of a concave and behind a convex edge,
- sudden change of radius of curvature,







- small velocity (low kinetic energy) of the fluid in the vicinity of the wall at the fore-part of BL.

2.4. Boundary layer separation can be prevented or displaced by
- high velocities (kinetic energy) in the vicinity of wall at the fore-part of BL,
- blowing in through a gap a wall jet in the flow direction (energy transfer to the BL),
- suction of BL, removal of small velocity part of BL close to the wall,
- laminar-turbulent transition of the BL or increase of turbulence by using transport of momentum in the BL at a given Re number (because $\mu_{turb} >> \mu_{lam}$ by increase of wall roughness, use of turbulence generators (small wings) and/or by the increase of turbulence of the approaching flow.

2.5. Remark
BL separation is one of the two types of vorticity (rot $\underline{v}$) transport in the potential (irrotational) flow (originally all fluid flow are potential if they are originated from a fluid at rest). Vorticity transport happens

- by conduction: transport equation for vorticity, conduction coefficient is ν kinetic viscosity
  $\underline{v}\,\mathrm{grad}(\mathrm{rot}\,\underline{v})_z = \nu\,\mathrm{div}\,\mathrm{grad}\,(\mathrm{rot}\,\underline{v})_v$

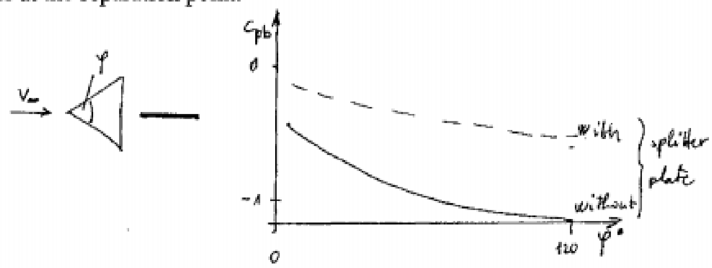
and

- by convection: as a consequence of boundary layer separation on the periphery of the flow the shear layer (boundary layer) enters the internal part of the flow by producing confined, closed separation bubble, or open vortex tube.

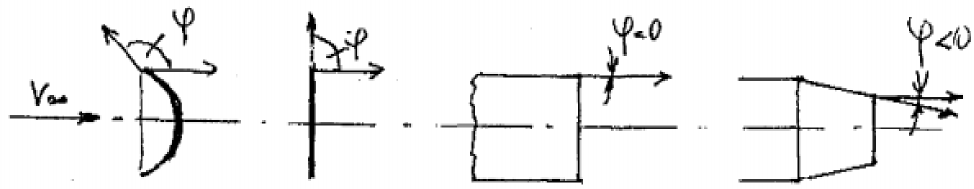
2.6. In both cases the pressure in the separation bubble or in vortex tube is smaller than that in the ambient.

2.7. Development of closed separation bubbles:
boundary layer separation ⇒ formation of shear layer ⇒ large velocity gradient across the shear layer ⇒ intense turbulent mixing ⇒ entrainment (fast moving fluid particles bring the slower particles with them) ⇒ supply of entrainment needs reverse flow ⇒ reverse flow needs pressure below the ambient ⇒ curvature of streamlines ⇒ re-attachment (or closing the bubble by contact of shear layers) ⇒ flow rate balance, feedback.

2.8. Main characteristics of closed separation bubble:
- there is a reverse flow in it (flow direction is opposite to the undisturbed approaching flow),
- the separation bubble is surrounded by solid surface(s) and shear layers,
- the velocities are relatively small: max 20-30% of undisturbed velocity,
- the pressure in the separation bubble is approximately constant (change of the pressure in separation bubble is $\Delta p_{stSB} \sim \rho/2\ (0{,}01 - 0{,}09)v_\infty^2$) and nearly equals the pressure at the separation point (line),
- high turbulence intensity and turbulent mixing (mass transport) but more or less definite flow structures which can be identified and reconstructed,
- the value of the depression (p_{amb}-ps_{SB}) or c_{pSB} pressure coefficient in the separation bubble depends on the angle φ between the undisturbed approaching flow v_∞ and the tangent of the shear layer at the separation point.



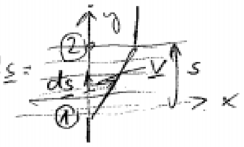
φ decreases ⇒ c_{pb} increases ⇒ base drag c_{Db} decreases



2.9. In closed separation bubble not only the pressure but the Bernoulli sum (total pressure, head) is much smaller than in the approaching (outside) flow that can be explained by the change of Bernoulli sum through a shear layer caused by integral $-\int_1^2 \underline{v} \times \mathrm{rot}\,\underline{v}\, d\underline{s}$.

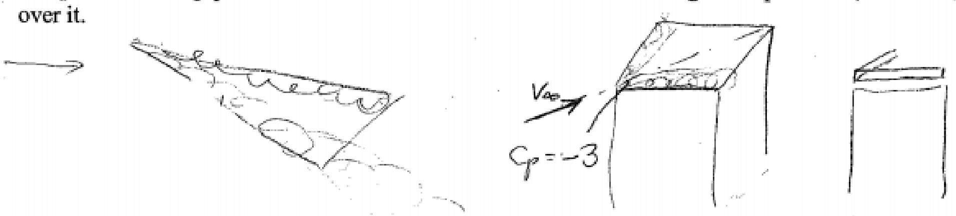
$$\frac{v_2^2 - v_1^2}{2} - \int_1^2 \underline{v} \times \mathrm{rot}\,\underline{v}\, d\underline{s} = -\frac{p_2 - p_1}{\rho} \quad \Big\} \quad p_{2\bar{o}} - p_{1\bar{o}} = \rho \int_1^2 \underline{v} \times \mathrm{rot}\,\underline{v}\, d\underline{s} =$$

$$= \rho \int_1^2 |\underline{v}| \cdot |(\mathrm{rot}\,\underline{v})_z| \cdot dy = \rho \int_0^s v_2 \frac{y}{s} \frac{v_2}{s}\, dy = \rho v_2^2 \frac{1}{2} \left[= \frac{\rho}{2}\left(v_2^2 - v_1^2\right) \right]$$



Closed separation bubbles are a passive flow structures, like a solid body of the same shape.

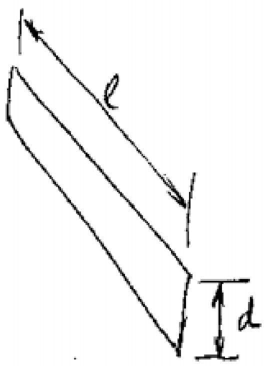
2.10. Open vortex tube arises when there is a relatively small angle between a straight edge and the flow (e.g. delta wing). The tube is open and its diameter increases with the length. The pressure decreases and the velocity decreases considerably when approaching the axis of vortex tube. The open vortex tubes are active structures, they induces velocity and cause low pressure in their vicinity. E.g. close to the edge of quadratic roof of a building there is a large depression if the flow direction is parallel to the diagonal. It can tear up the insulation sheet over the roof. The insulation sheet is fixed to the building by nails the density of which is highest in corners and along sides. Parapet wall with gap elevates the vortex tube over the roof decreasing the depression (wind load) over it.



2.11. The place of the separation is fixed in case of sharp edged bodies. Since the place of separation depends on the pressure distribution over the body surface and vice versa, in case of bodies of curved surface, rounded edges, corners the place of separation moves at start of the flow and find its place of "equilibrium". Because of this interaction the place of separation can move in the time also periodically.

3. 3D bluff bodies

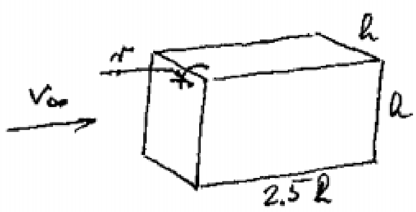
3.1. Stripe of sheet



l/d	c_D	c_{pf}	c_{pb} $\left(c_{pf,b} = \frac{p_{f,b} - p_\infty}{\frac{\rho}{2} v_\infty^2}\right)$
∞	2	0.8	-1.2
18	1.4		
4	1.19		
1	1.1	0.79	-0.31
		small change	substantial change

3.2. Significant change of c_D is caused by decrease of base pressure. For aspect ratios $l/d < 20$ three-dimensional character of flow increases. The flow around sides induced by pressure differences weakens the periodic shedding of strong vortices (similar effect as caused by a splitter plate). In 3D flow field *no regular shedding of strong vortices* can be observed.

3.3. Flow past a brick shaped 3D bluff body.



Carr's measurements on a brick shape body:

leading edges	sharp	rounded
r/h	0	0.3
c_D	0.88	0.2
$c_{pf,mean}$	0.57	- 0.03
$10c'_{f,mean}$	0.001	0.003
$c_{pb,mean}$	- 0,3	- 0,2

$$D = \overline{(p_f - p_\infty)}h^2 + 4hl\tau_0 - \overline{(p_b - p_\infty)}h^2 \quad \Rightarrow c_D = \frac{D}{\frac{\rho}{2}v_\infty^2 h^2} = \overline{c_{pf}} + 4\frac{l}{h}c_f' - c_{pb}$$

3.4. Drag reduction

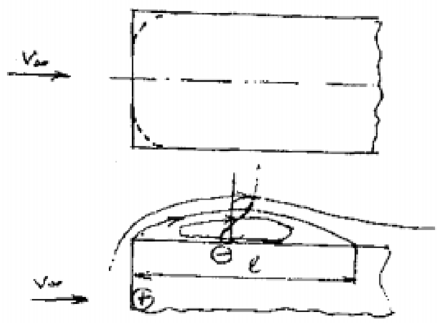
A. forebody drag (2/3 of the overall drag) can be reduced by reducing the average pressure over the front by rounding up the leading edges to r/h = 0,3.

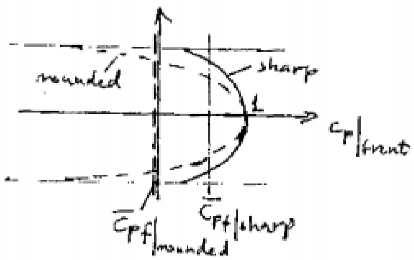
B. the shear stress is small, so side wall drag can be neglected but, if the size of the building parallel to the wind is extremely high in comparison to the crosswind size,

C. the base drag can be reduced by tapering the bluff body (rounding up is also a way of tapering).

3.5. Reducing forebody drag

The pressure distribution on the front face of a quadratic brick shaped bluff body with sharp and rounded leading edges shows that the rounding of leading edges accelerates the flow and results in large suction on the periphery of the front face.

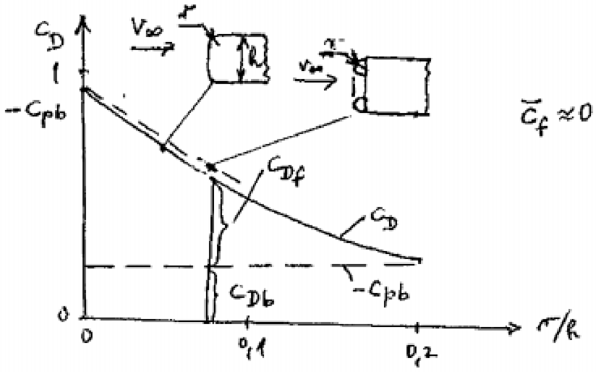




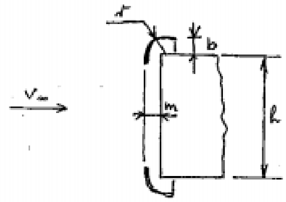
If the leading edge is sharp or the rounding radius is small, the adverse pressure gradient is too high. Therefore, the boundary layer separates and a separation bubble develops beside the side walls. The length of the separation bubble l is a good indicator of the forebody drag. (A linear relation has been found between c_D and l/h.) The flow turnaround the leading edge results in any case in a low pressure region. The forebody drag can be reduced by shifting this low pressure region at least partly over the front face.

3.6. Decreasing the adverse pressure gradient i.e. increasing the rounding can stop the boundary layer separation on the periphery edge. Rounding radius r depends on Reynolds number. From criteria $2r\, v_\infty/\nu \geq Re_{kr} \approx 200.000$ $r_{sufficient} \geq 1,5/v_\infty$,

3.7. The drag of the brick shape bluff body can be reduced also by "add-on-devices", e.g. by a "lip" characterized by the rounding radius r. c_D and the base drag ($c_{Db} = -\, c_{pb}$) at $Re_h = 3\cdot10^5$

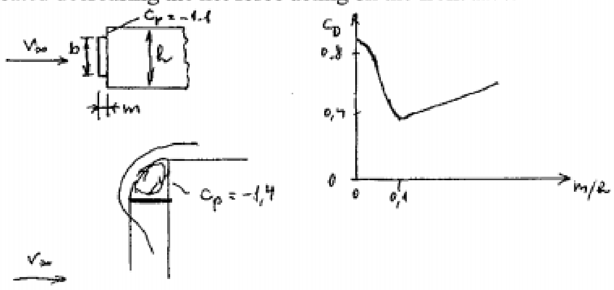


An other add-on-device is the turning vane around the leading edge:



r/h = 0.125, m/h = 0.1, b/h = 0.05. $c_D = 0.8$ without turning vane, $c_D = 0.35$ with turning vane. If the turning wane is disconnected from the body and it is held from outside $c_D = 0.81$. That means that the drag of bluff body is reduced by the forces acting on the vane, directed against the approaching flow.

3.8. The forebody drag can also be reduced by artificially creating a boundary layer separation on the periphery of the front face by using a "step" or a "fence". Near the separation bubble, a low pressure area is created decreasing the net force acting on the front face.

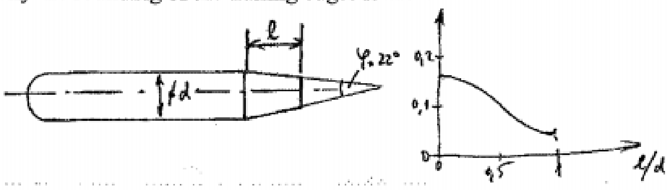


3.9. The base the base drag can be reduced by tapering the bluff body. Rounding up is also a way of tapering: rounding of trailing edge r/h=0 ⇒ 0.3 results in drag reduction:

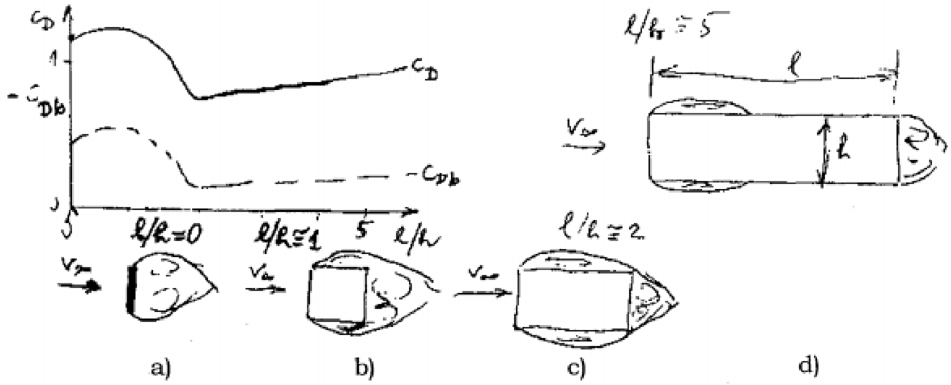
if leading edge is sharp r/h = 0 $\Delta c_D = -0.025$

if the leading edge is rounded r/h = 0.3 $\Delta c_D = -0.089$

For rounded leading edge the flow past side walls of the bluff body is "sound" (no separation bubble) that is why the rounding of the trailing edges is more efficient.



3.10. Brick shape bluff bodies of different lengths with quadratic cross section and sharp leading and trailing edges:



The drag is high, if the base of the body is in the separation bubble attached to the leading edge of the body (φ is large) cases a) and b). If the base is in the separation bubble originated from leading edge is attached to trailing edge, the base drag and so the overall drag is much smaller (φ is negative, separation bubble is similar to that at boat tailing). In case d) the base two separation bubbles are generated one on leading and the other at trailing edge. Because φ is higher than at case c) the base drag and the overall drag is higher, too.

4. In building aerodynamics buildings are bluff bodies exposed to wind. The results of bluff body aerodynamics can be applied as an approach by utilizing the "method of reflection". Let's suppose that we know the flow field past a cube where the velocity vector of approaching flow is perpendicular to a symmetry axis of the cube. Since the ground can be regarded as symmetry plane of the flow past a building twice as high as the original one, so the flow field around the upper half of the cube can be regarded as flow field past a building of quadratic top view the height of which is half of its length and width.