Flow Separation and Reattachment

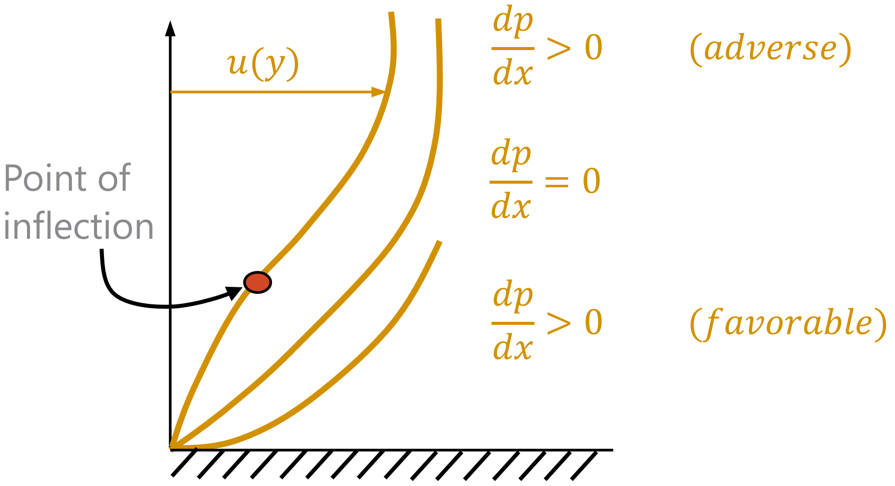
Real External Flows – Lesson 4

Boundary Layer Separation

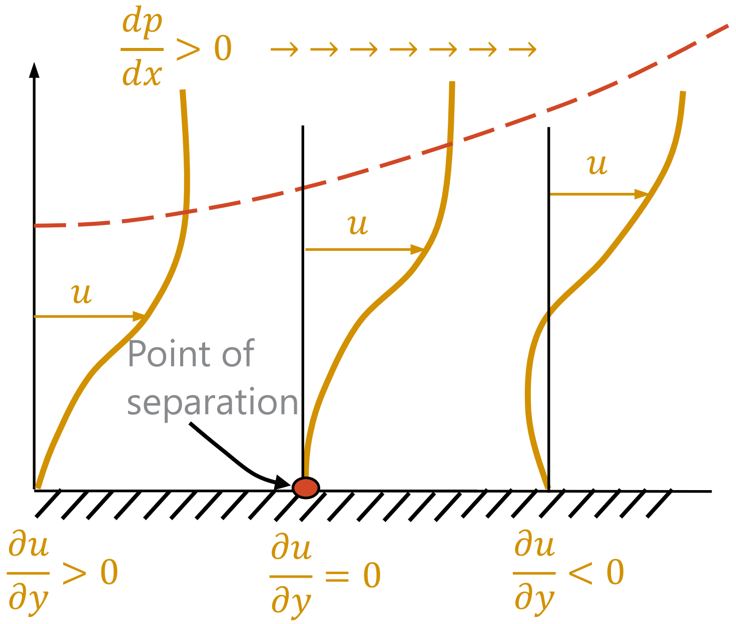
- In general, wall-bounded flows are subject to pressure variations due to surface curvature or an external forcing.
- When the freestream pressure increases in the direction of flow, it is known as an adverse pressure gradient.
- Adverse pressure gradients cause the flow to slow down. When the velocity gradient at the wall approaches zero, the flow will lift off the surface, diverting the streamlines away from the wall. This process is known as separation.
- When a boundary layer becomes separated, the boundary layer equations are no longer valid. However, we can predict the point of separation by monitoring the velocity gradient (or shear stress) at the wall in our solution and noting where it becomes close to zero.

Effects of Pressure Gradient

- The pressure field in the fluid flow past an object (other than a flat plate) is nonuniform. When the pressure gradient is nonzero, the velocity profile is affected as shown below.



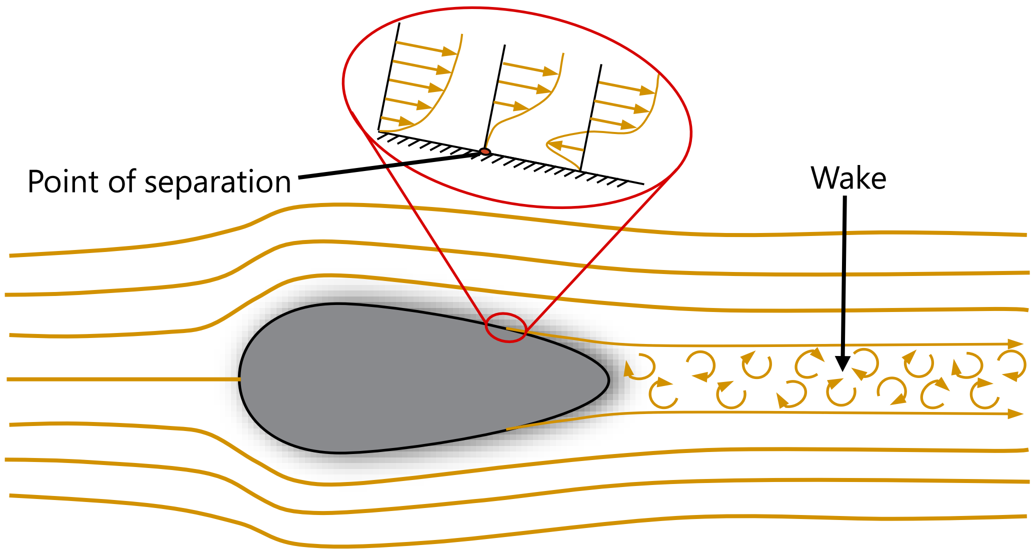
Types of Profile for Different Pressure Gradients

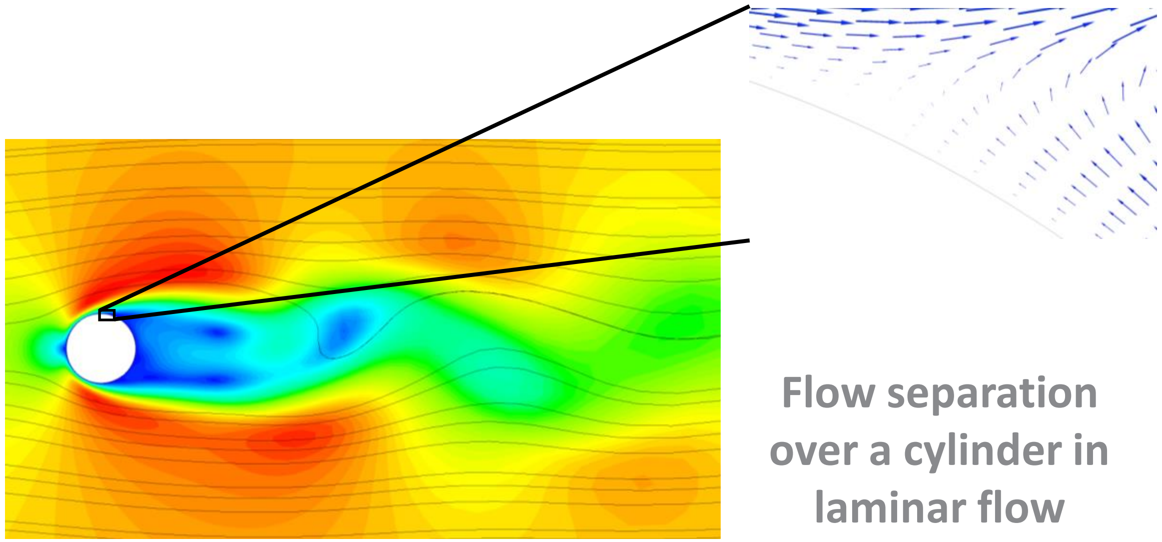


Types of Profile for Persistent Adverse Pressure Gradient

Separation of Boundary Layers

- Separation of boundary layers in general occurs when the velocity of the boundary layer "struggling" against an adverse pressure gradient becomes nearly zero, following the flow by reversing its direction.
  - The separation point is defined as a location between forward and inverse flow where the wall shear stress is zero.
  - The thickness of the boundary layer abruptly increases at the separation point, and the layer is forced off the surface by the reversed flow near the wall.
  - Detached flow takes the form of vortical structures, which can be laminar or turbulent depending on the flow regimes.

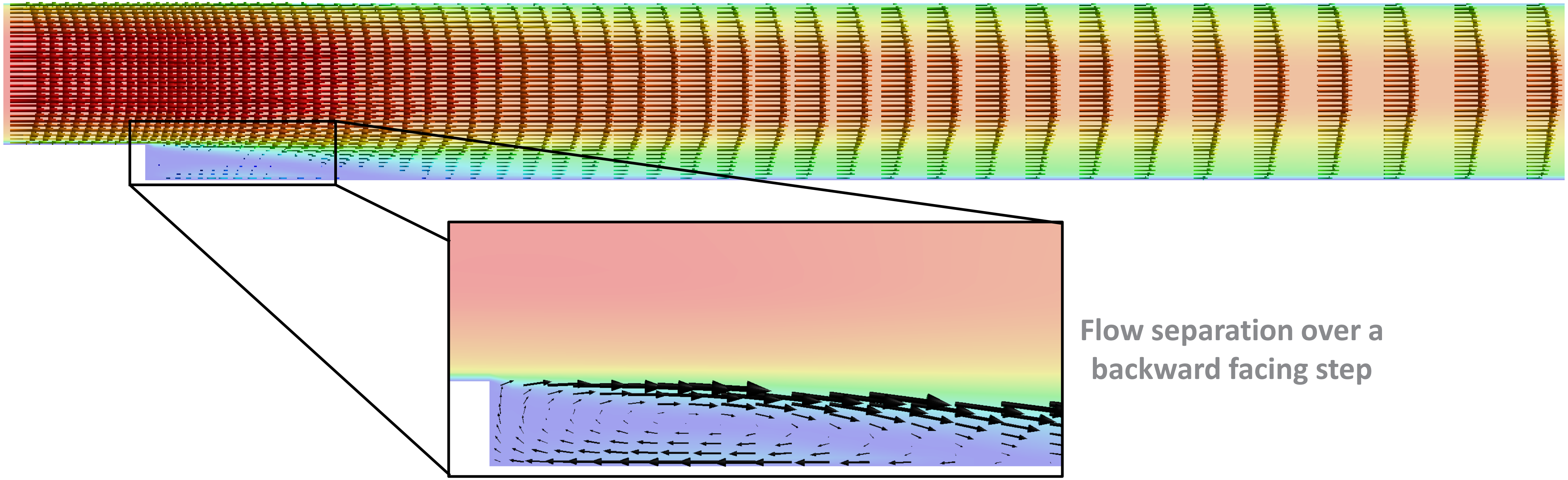




Flow separation over a cylinder in laminar flow

Separation at Sharp Corners

- At sharp corners and turns the flow naturally separates, as can be easily understood from the conservation of momentum.
- At the corner, the boundary layer maintains its momentum in the direction of the flow, and simply cannot stay attached in the absence of an external pressure gradient forcing it to turn around the corner.



Flow separation over a backward facing step

Prediction of Laminar Boundary Layer Separation

- Despite the pervasiveness of boundary layer separation and the importance of its consequences for the flow characteristic, there is no concise, comprehensive analytical description of this phenomenon.

- Some analytical estimates can be made to predict the position of the laminar separation location, but nothing else.

- In the section on laminar boundary layers, we discussed Thwaites correlation for laminar boundary layers:

$$\tau_w \approx \frac{\mu V_\infty}{\theta}(\lambda + 0.09)^{0.62}, \qquad \lambda = \left(\theta^2/\nu\right)\left(dV_\infty/dx\right)$$

- Separation will occur at a point of zero shear stress, which gives the criterion for λ: $\lambda_{sep} \approx -0.09$

- Then $\theta(x)$ can be calculated. The accuracy of Thwaites estimate of separation is $\pm 10\%$.

Prediction of Laminar Boundary Layer Separation

- As we saw, separation occurs in a region of decreasing boundary layer velocity. Thus, at some point upstream, the velocity must be maximum and the pressure minimum.

- Stratford (1954) derived a more accurate estimate for separation location. He used inner-outer velocity profile matching to show that the pressure coefficient at separation,

$$C_p = \frac{p - p_{min}}{\frac{1}{2}\rho V_{max}^2} = 1 - \frac{u^2}{V_{max}^2}$$

satisfies the following relation:

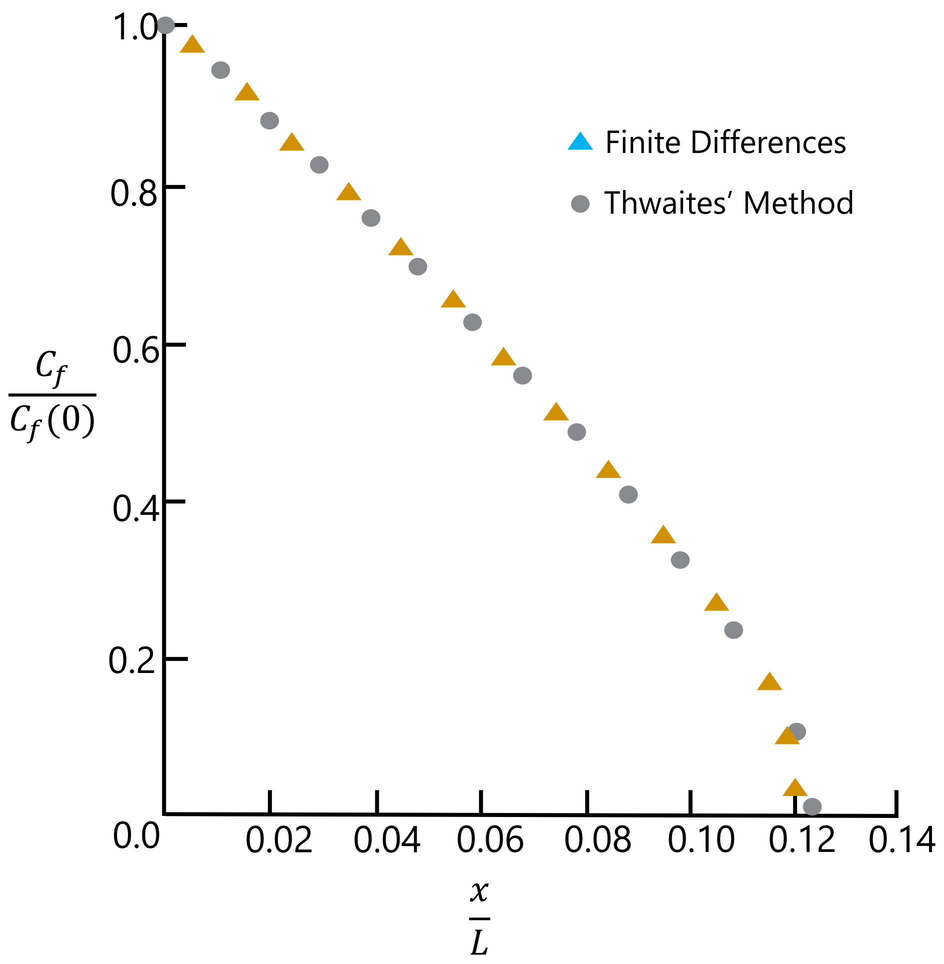
$$(x - x')C_p \left(\frac{dC_p}{dx}\right)^2 = 0.0104$$

Here $(x - x')$ is the effective length of the boundary layer and x' is the “false” origin of the layer

- If V_{max} is at $x = 0$, then $x' = 0$
- If V_{max} is at $x = x_m > 0$, then x' is such that the momentum thickness at x_m equals the value of θ that would grow in a Blasius layer over the distance $(x_m - x')$

Prediction of Laminar Boundary Layer Separation

- Another more precise method of predicting the separation of a laminar boundary layer is to solve the boundary layer equations numerically under prescribed adverse pressure gradient.
- Recall that these equations are parabolic, and they can be marched in space downstream, starting from the prescribed velocity profile until the point of zero shear stress corresponding to the separation location.
- This numerical technique, while requiring some computer programming, is easier to implement than a CFD code solving full Naiver-Stokes equations. The numerical solution of boundary layer equations will also be much faster than a full CFD solution.
- Predictions of separation by this numerical technique are often used as “exact” to assess the accuracy of different correlations.



Comparison of finite-difference and Thwaites method for wall friction in the Howarth linearly decelerating flow

Prediction of Turbulent Boundary Layer Separation

- Stratford[1] extended the laminar boundary layer method to predict separation of turbulent layers:

$$C_p\left((x-x')\frac{dC_p}{dx}\right)^{1/2} = k\left(\frac{Re}{10^6}\right)^{0.1}$$

$$C_p = 1 - \frac{u^2}{V_{max}^2}$$

$$Re = \frac{x'V_{max}}{\nu}$$

$$k = \begin{cases} 0.35, d^2p/dx^2 \leq 0 \text{ (concave recovery)} \\ 0.39, d^2p/dx^2 > 0 \quad \text{(convex recovery)} \end{cases}$$

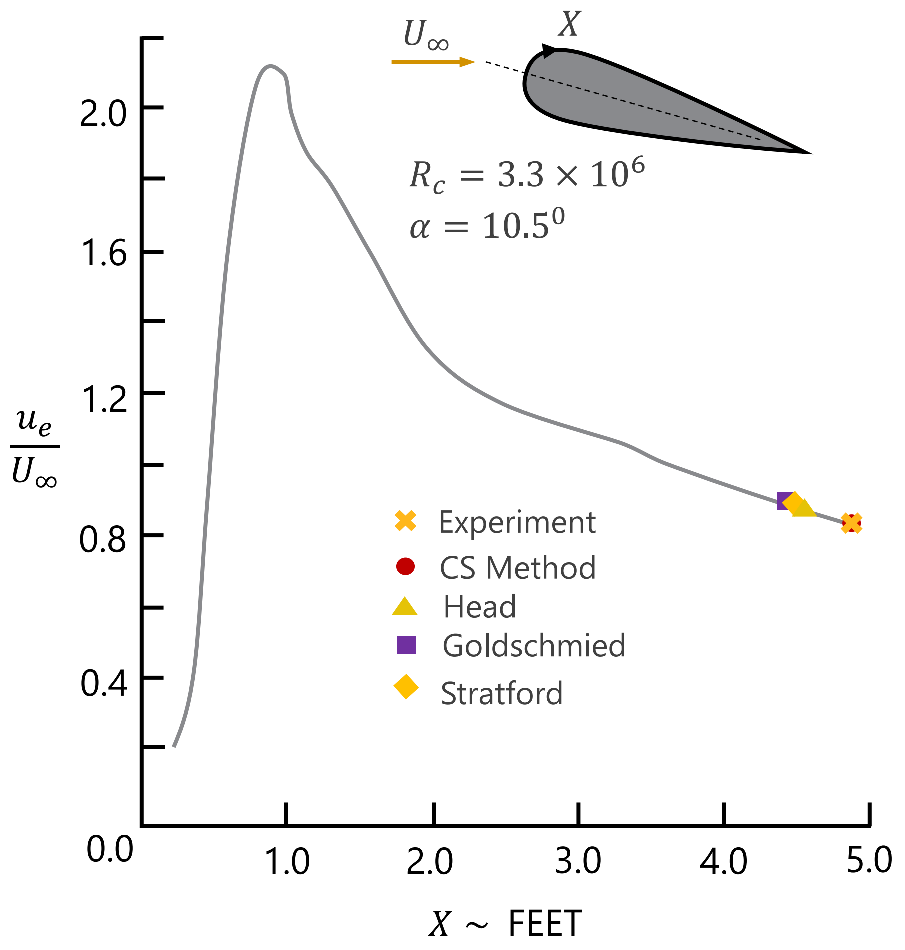
$(x - x')$ is the effective length of the boundary layer and x' is the "false" origin of the layer"

- $k = 0.5$ value was used by other researchers as it gives less conservative prediction.
- Other prediction methods for turbulent boundary layer separation are discussed in detail by Cebeci et al[2]

[1]Stratford, B. S. (1959) “"The Prediction of Separation of the Turbulent Boundary Layer”, Journal of Fluid Mechanics, Vol. 5, pp. 1-16.

[2]Cebeci, T., Monsinskis, G. J., and Smith, A. M. O. (1972) “Calculation of Separation Points in Incompressible Turbulent Flows,” J. Aircraft, vol. 9, No. 9, pp. 618n-624.

Prediction of Turbulent Boundary Layer Separation (cont.)



Separation and Vortex Shedding

- Boundary layer separation can, under a certain range of Reynolds numbers, generate a repeating pattern of vortices. This trail of vorticies is called the Karman vortex street.
- Vortex shedding in the Karman street locks into a self-sustained periodic pattern at a singular frequency (expressed in terms of non-dimensional Strouhal number) as:

$$St = 0.198\left(1 - \frac{19.7}{Re_D}\right)$$

$40 < Re_d < 150$

- Karman vortex shedding can be observed in nature and in man-made devices.
- Periodic vortex shedding results in periodic fluid forces on the surface of the object.

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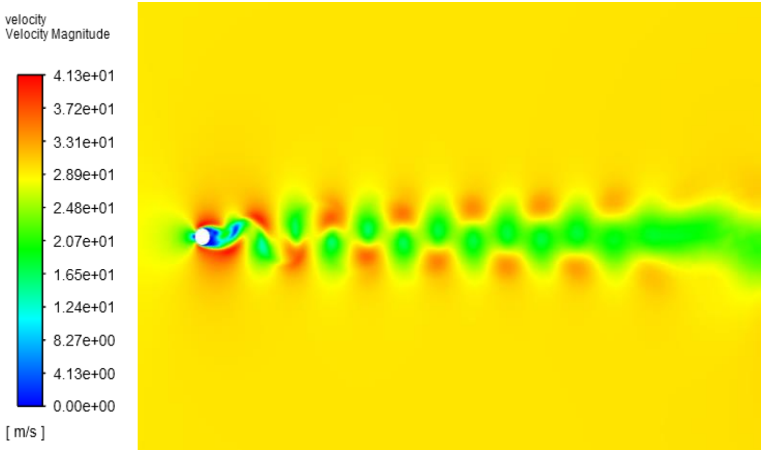
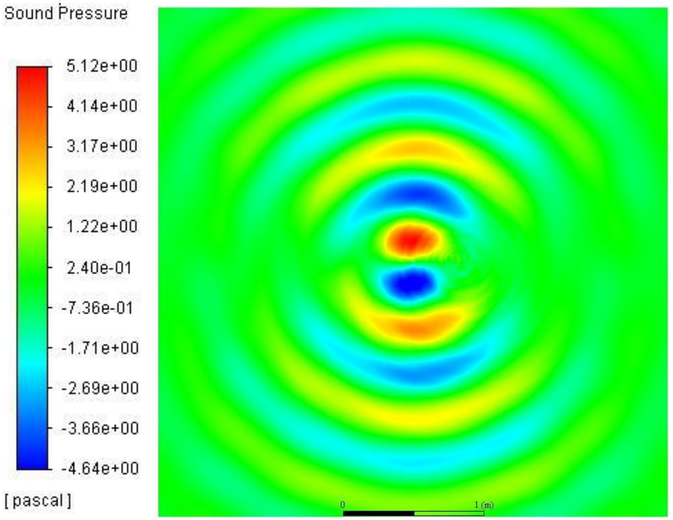
Separation and Vortex Shedding (cont.)

- At higher Reynolds numbers periodic vortex street transitions into a turbulent wake, but identifiable periodicity in fluctuations of separating boundary layers remains, and an identifiable tonal frequency can be identified up to $Re{\sim}10^5$.

- Forces induced on object's surface by periodic separation fluctuations have two distinct side effects as they:
  - generate acoustic (sound) waves in a compressible fluid (think of noise emitted by a rapidly spun thin rope)
  - can become culprits of resonant effects in the structure of the object when their frequency coincides with a natural frequency of the structure.



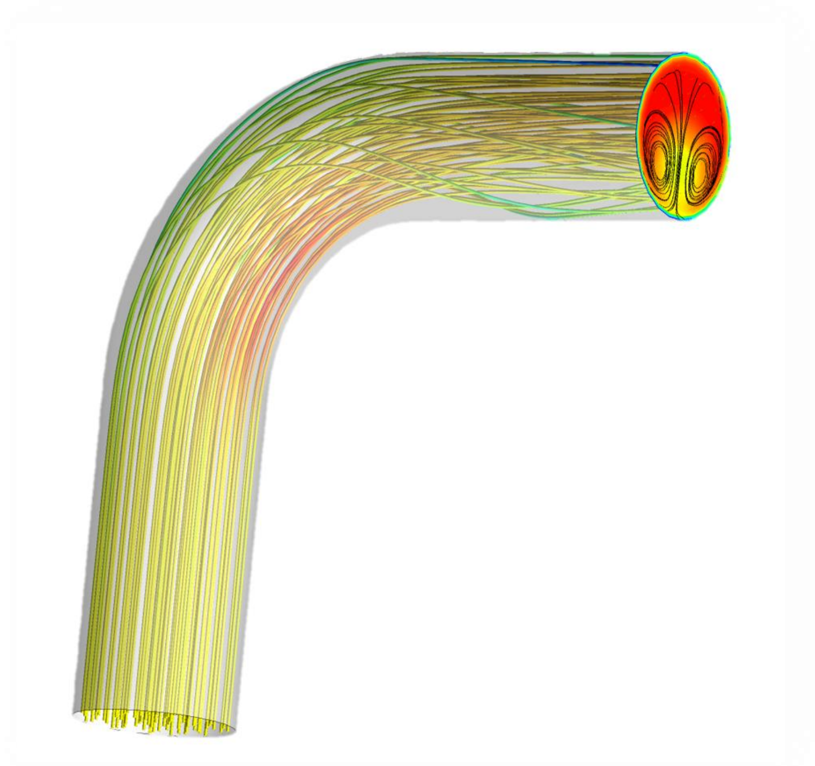
Velocity contours corresponding to flow past a cylinder



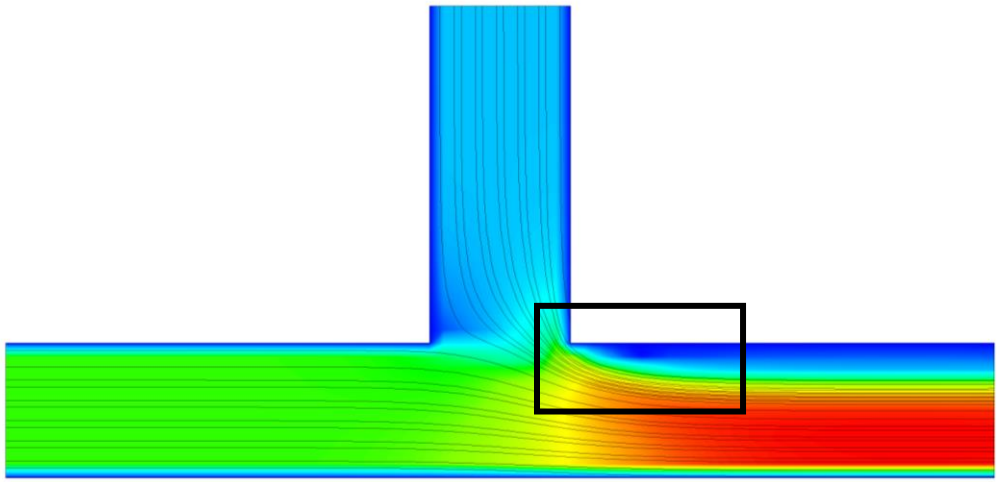
Corresponding acoustic (sound) waves generated in the domain

Separation in Internal Flows

- Separation in internal flows is driven largely by the same physical process as in external flows.
- As the wall-bounded flow is subjected to adverse pressure gradient, e. g., to a turn of elbow pipe or expansion, flow separation can occur.



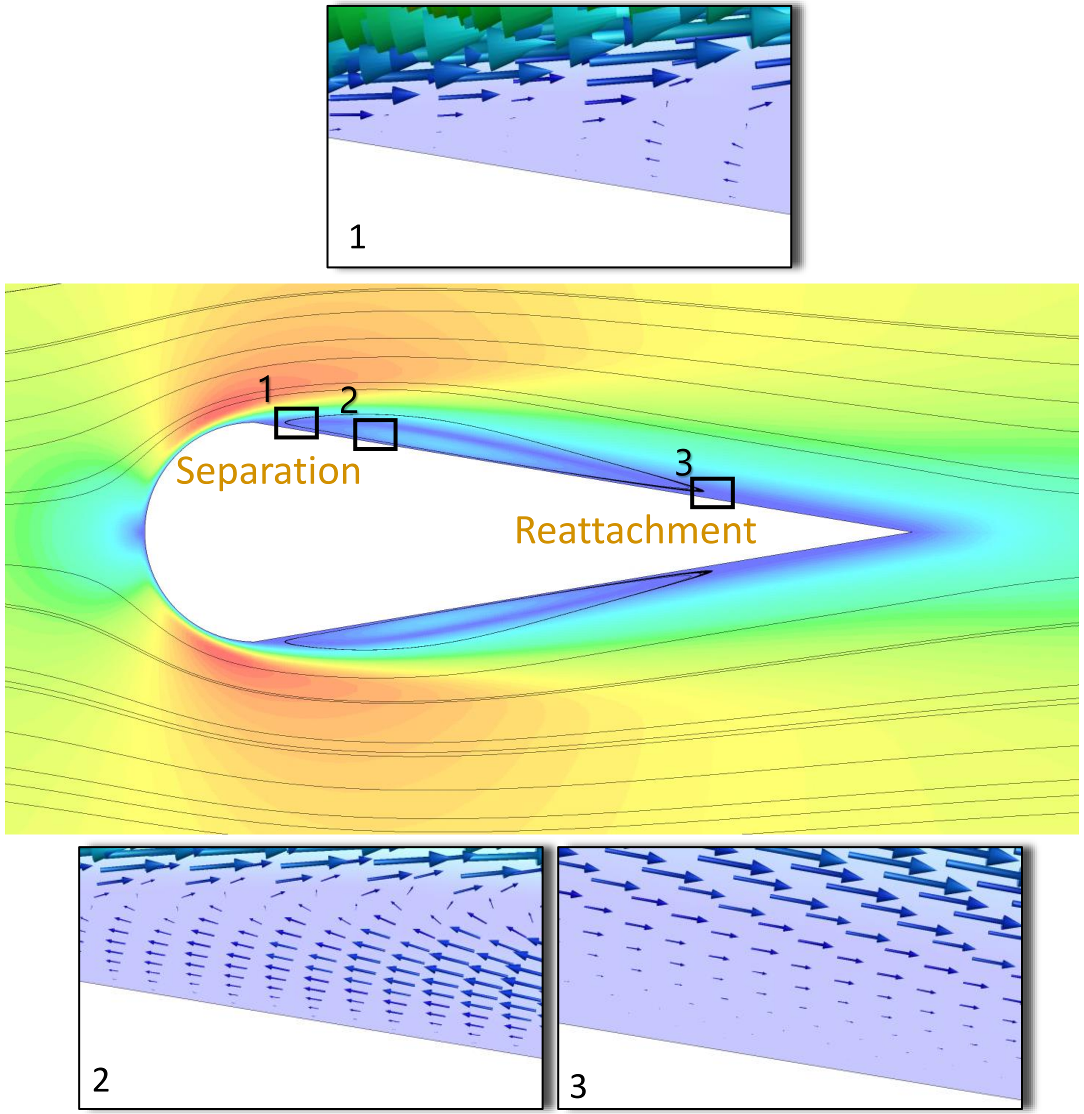
Flow Separation in a 90º Elbow



Flow Separation in T-junction

Reattachment of Separated Flow

- In some situations separated flow can reattach itself to the surface.
- Very little theory exists to describe the reattachment phenomenon. In broad terms it can be explained as follows:
  - Separation is induced by adverse pressure gradients. If a favorable pressure gradient is recovered past the separation point, then the flow can, in principal reattach itself.
    - A favorable gradient alone may not always be enough for reattachment.
  - If a separated laminar flow transitions to turbulent, then it has a better chance of reattachment as turbulent flows are less susceptible to separation under adverse gradients than laminar flows due to the orders of magnitude better wall-normal momentum transport.



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Summary

- We examined the phenomenon of flow separation in this lesson.
- We covered selected theoretical methodologies for predicting separation of laminar and turbulent boundary layers.
- We also briefly discussed reattachment of separated flows.

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