Diffusion of vorticity & Boundary layers

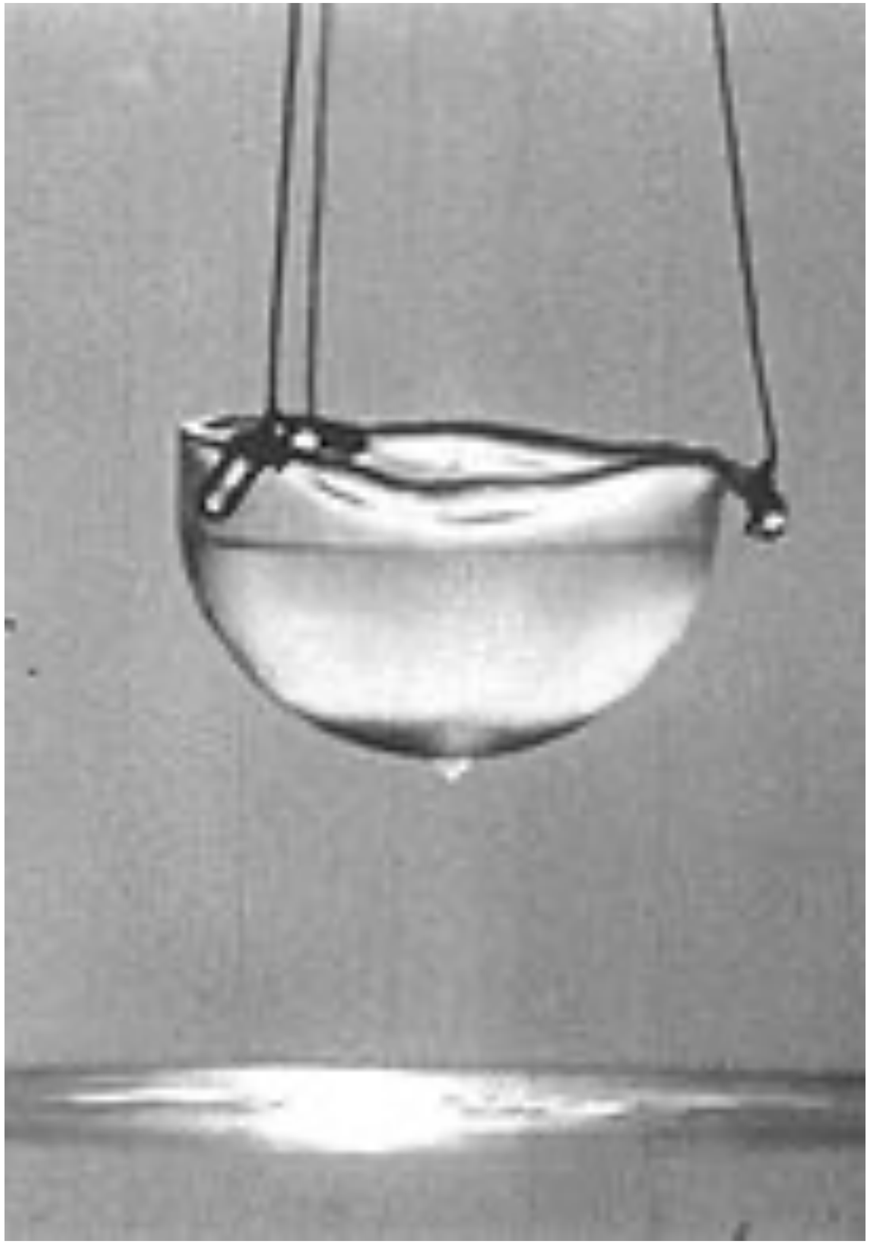
Overview

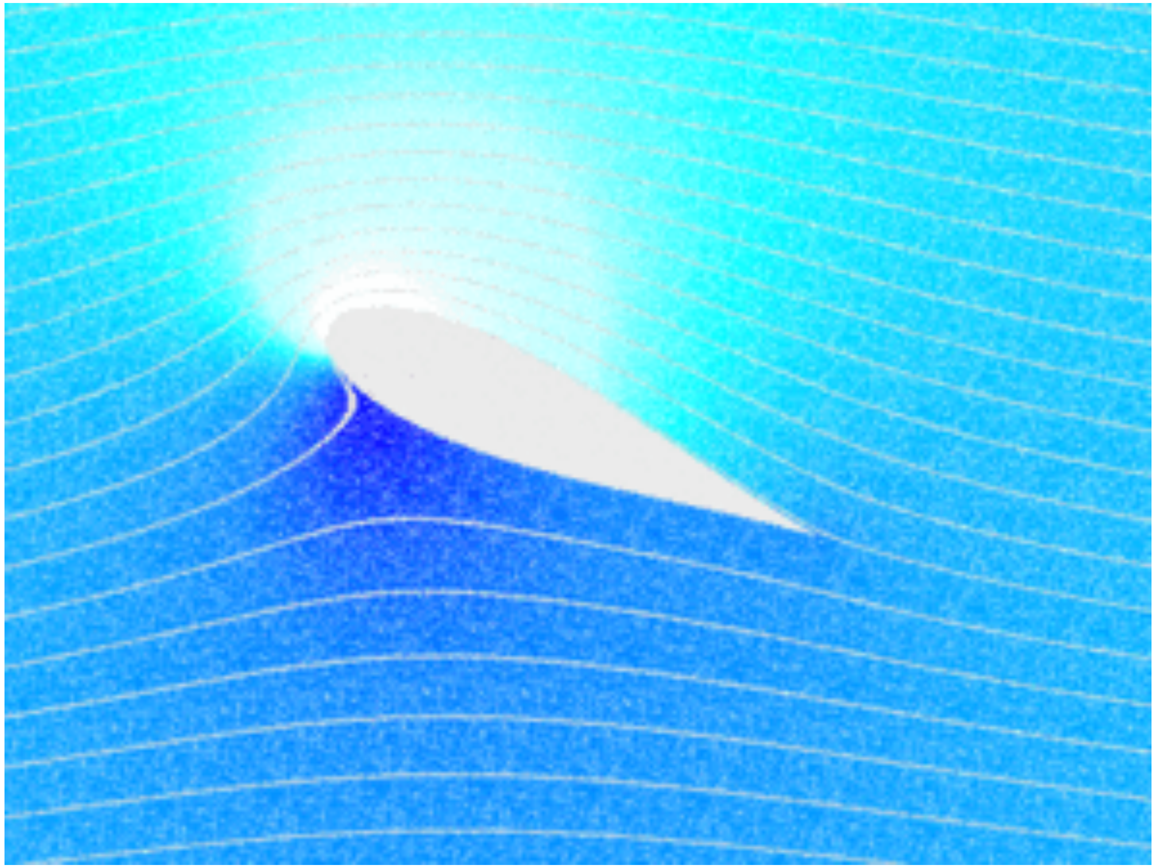
- There are at least two flow situations in which the viscous term in the Navier–Stokes equation can be neglected.
- The first occurs in high Reynolds number regions of flow where net viscous forces are known to be negligible compared to inertial and/or pressure forces; we call these inviscid regions of flow.
- The second situation occurs when the vorticity is negligibly small; we call these irrotational or potential regions of flow.
- In either case, removal of the viscous terms from the Navier–Stokes equation yields the Euler equation.
- There are some serious deficiencies associated with application of the Euler equation to practical flow problems.
- High on the list of deficiencies is the inability to specify the no-slip condition at solid walls.
- Viscosity drives the diffusion of vorticity.
- Boundary layer theory provides a (semi-)analitycal description of the effects of viscosity close to solid walls and of the diffusion of vorticity into the biulk fluid.

Inviscid flow

- Superfluid He^4 has zero viscosity and it flows without any resistance.
- Persistent currents in the absence of drive.
- Since the viscosity is nearly zero, the Reynolds number approaches infinity.

- Superfluids can flow out of containers by climbing the walls.
- Supercurrents may be driven by superficial forces.



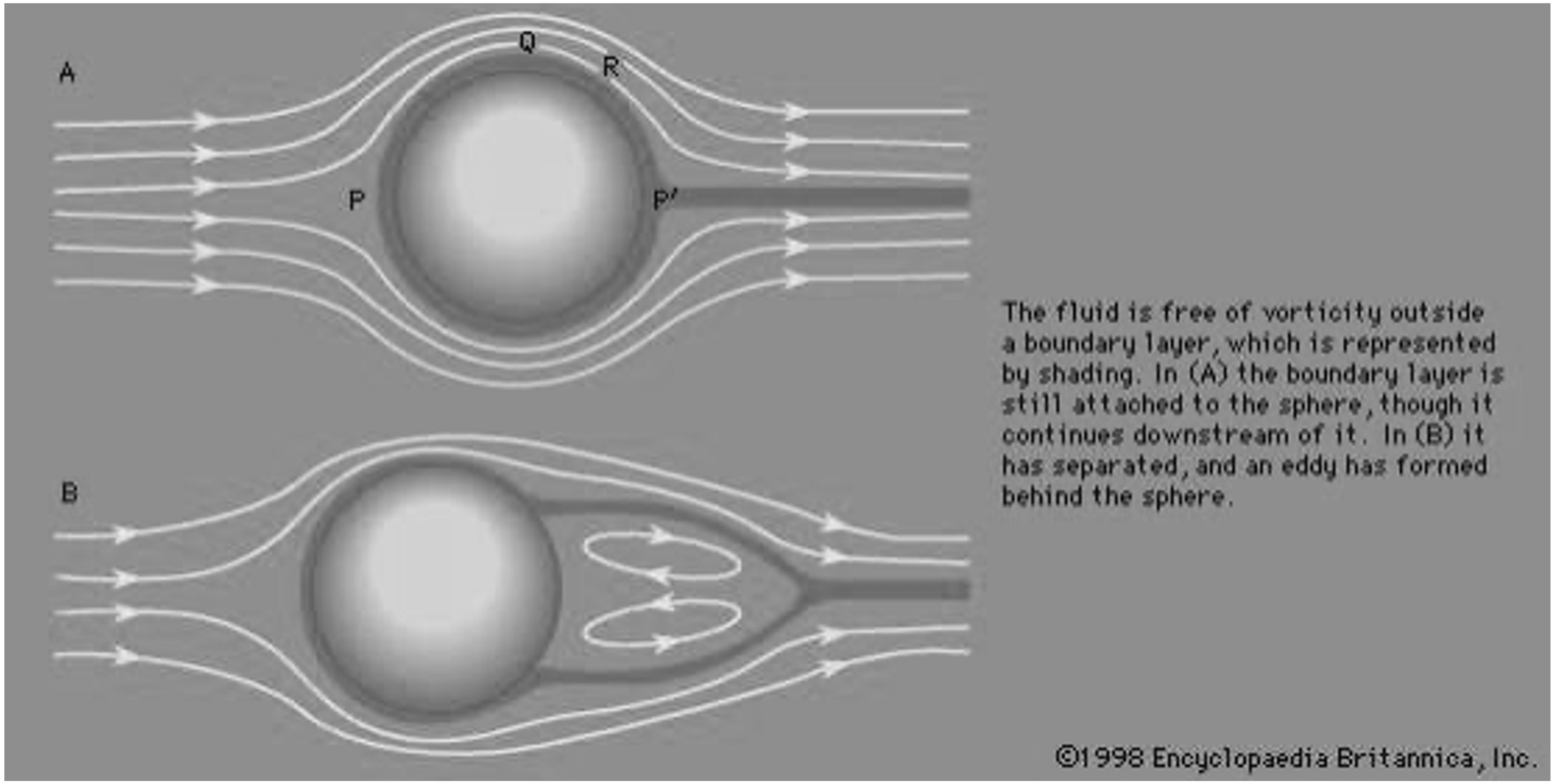


Irrotational flow

- Irrotational flow around a wing.
- The solution may be obtained from potential flow theory.
- This particular solution is obtained as the sum of three elementary solutions: free stream, line source and line vortex.
- Lift force proportional to the circulation and free stream velocity.
- Drag force zero.

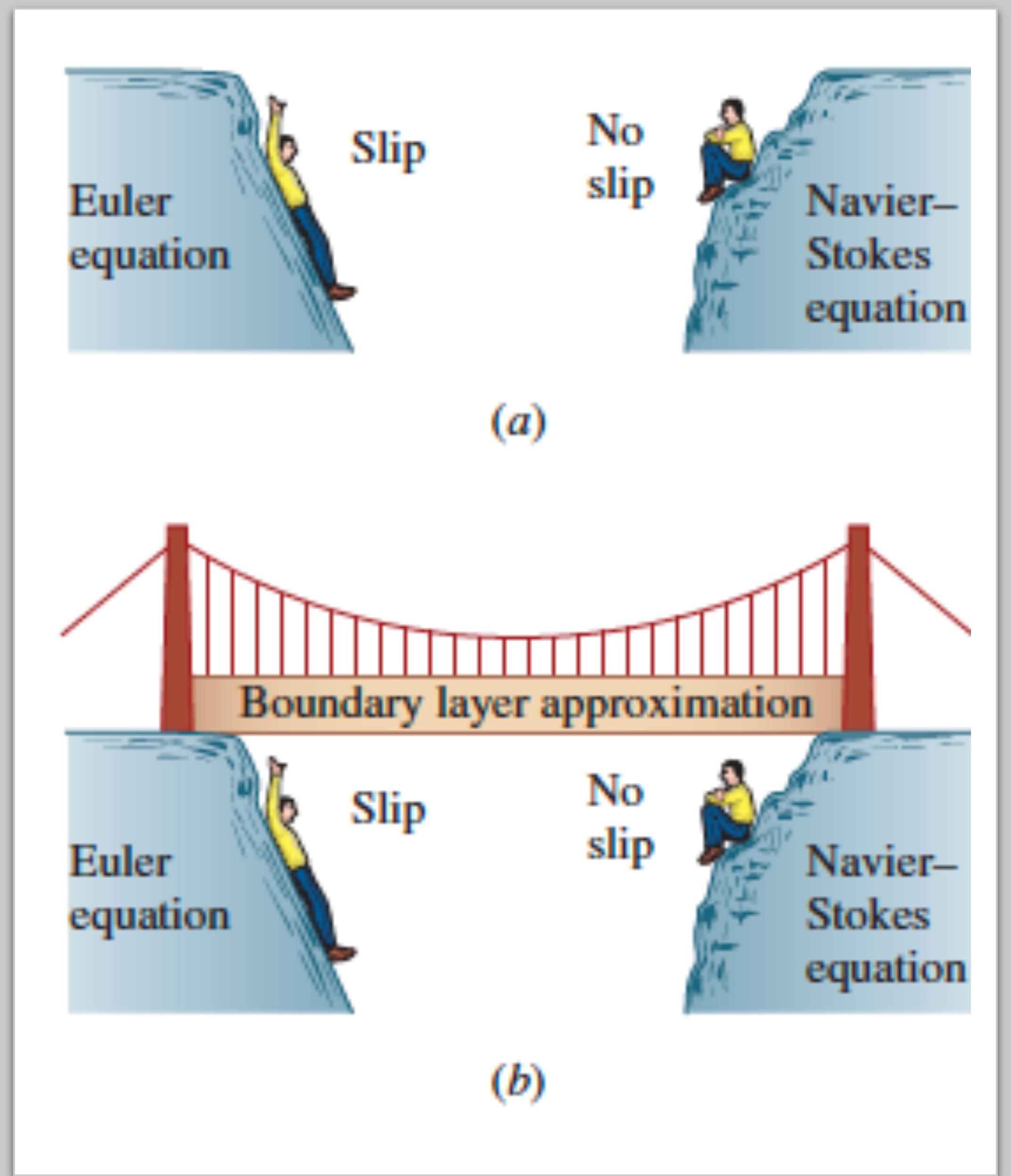
- By the mid-1800s, the Navier–Stokes equation was known, but couldn't be solved except for flows of very simple geometries.
- Meanwhile, mathematicians were able to obtain beautiful analytical solutions of the Euler equation and of the potential flow equations for flows of complex geometry, but their results were often physically meaningless.
- A major breakthrough in fluid mechanics occurred in 1904 when Ludwig Prandtl (1875–1953) introduced the boundary layer approximation.
- Prandtl's idea was to divide the flow into two regions: an outer flow region that is inviscid and/or irrotational, and an inner flow region called a boundary layer—a very thin region of flow near a solid wall where viscous forces and rotationality cannot be ignored.
- In the outer flow region, the continuity and Euler equations apply to obtain the outer flow velocity field, and the Bernoulli equation to obtain the pressure field. Alternatively, if the outer flow region is irrotational, we may use potential flow techniques.

Finite Re number flow past a sphere



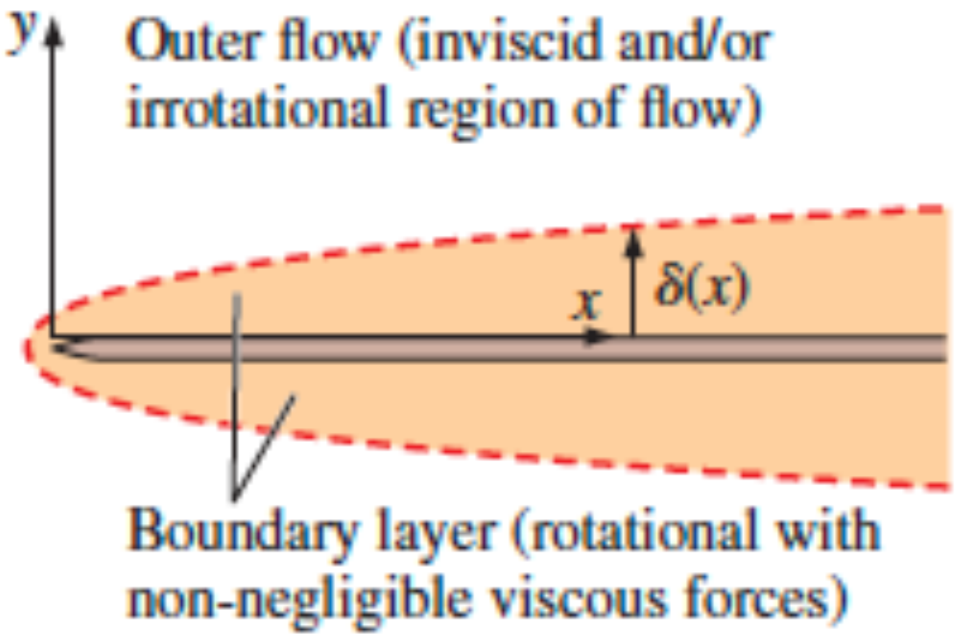
The boundary layer

The boundary layer approximation bridges the gap between the Euler equation and the Navier–Stokes equation, and between the slip condition and the no-slip condition at solid walls.

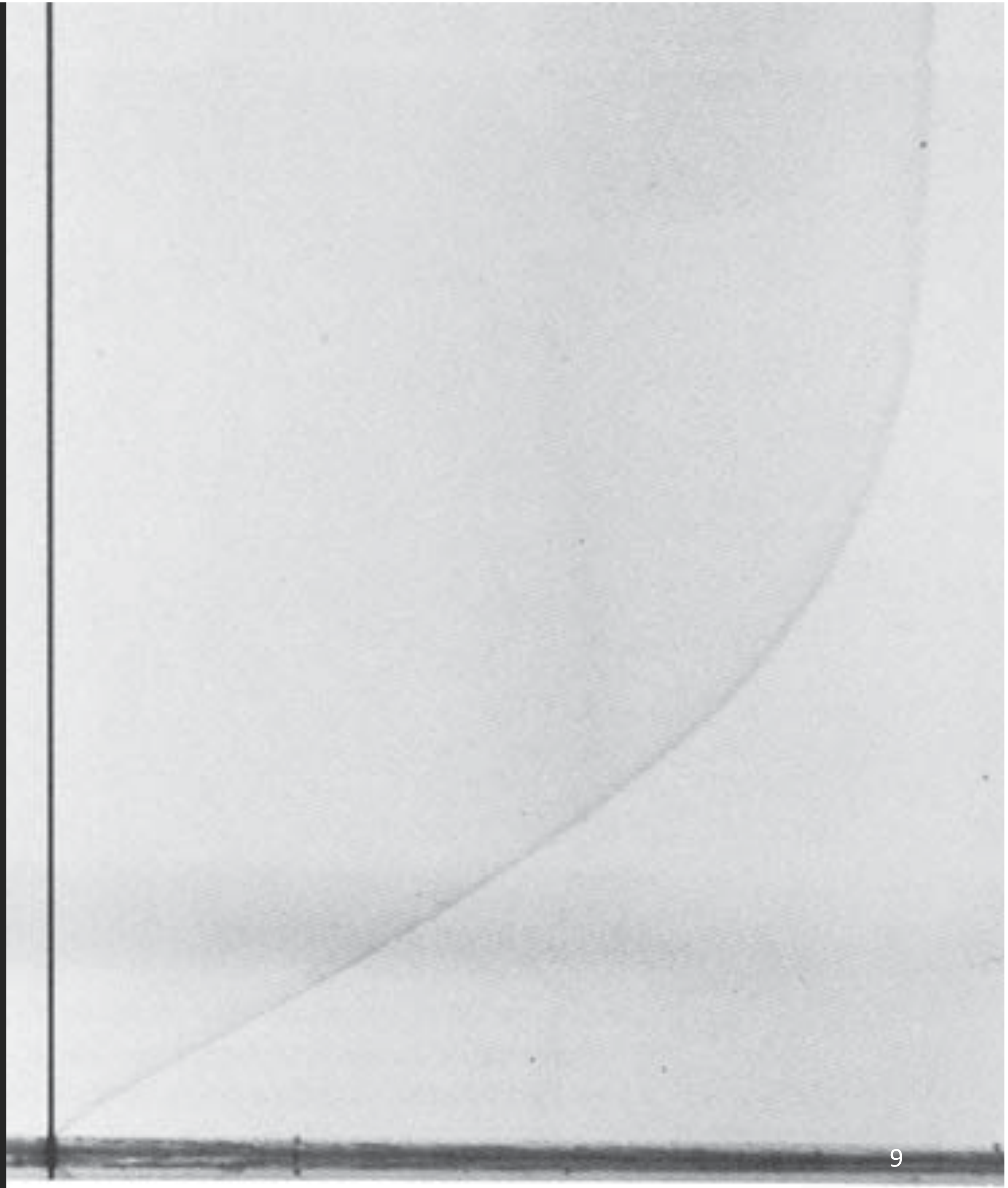


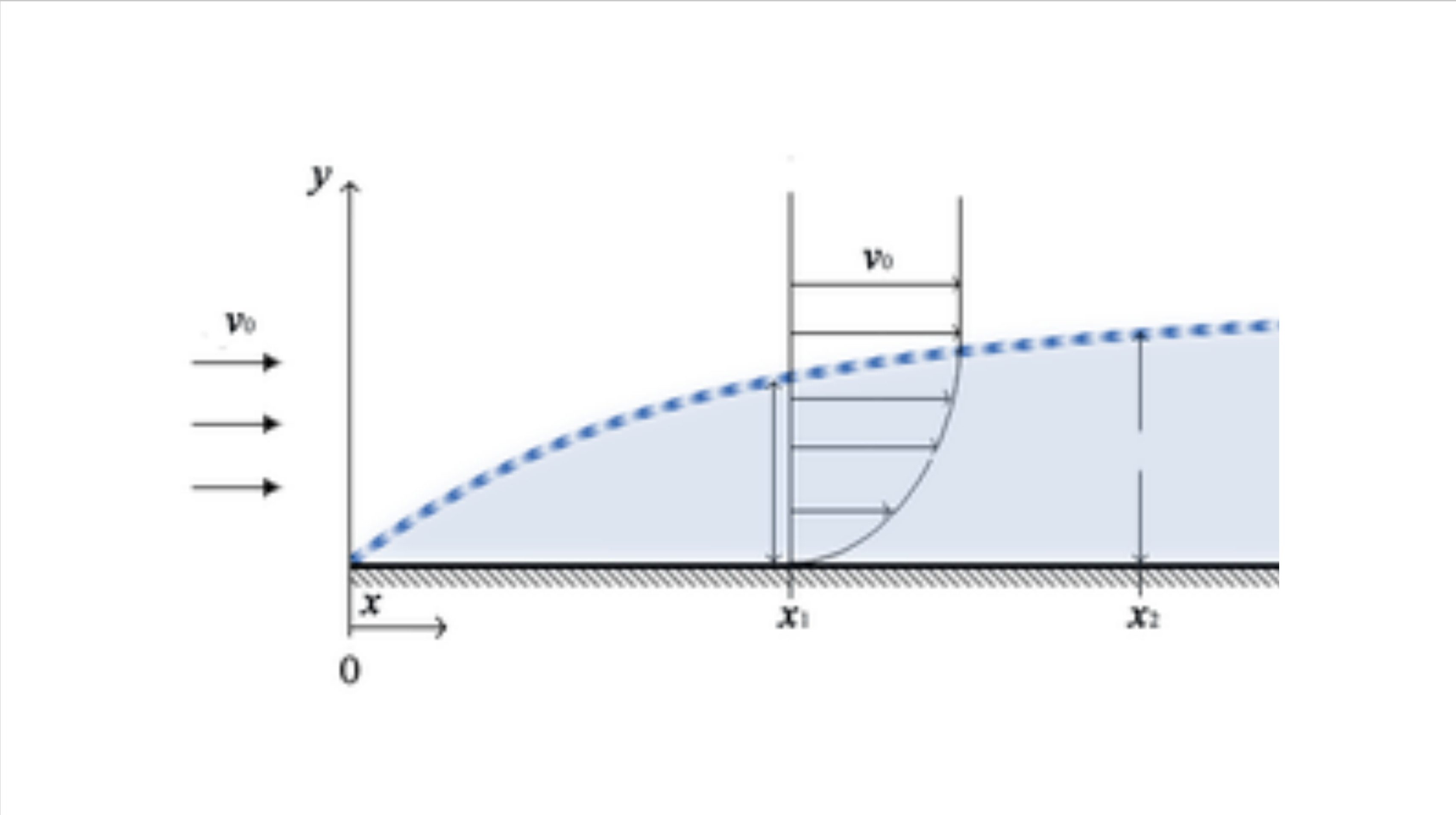
The idea

Solve for the outer flow region first, and then fit in a thin boundary layer in regions where vorticity and viscous forces cannot be neglected.



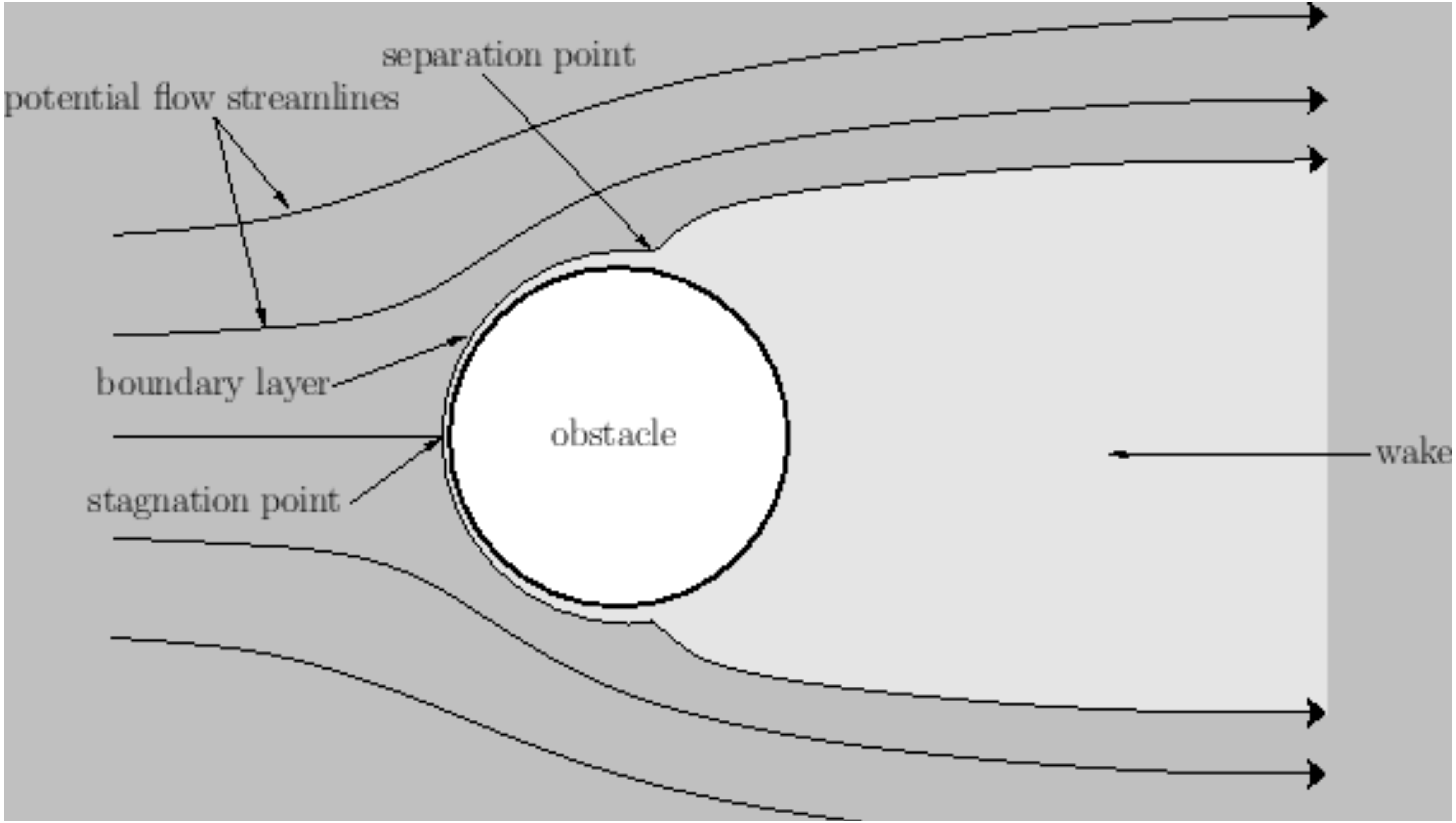
Photograph of velocity profile of a uniform stream over a flat plate



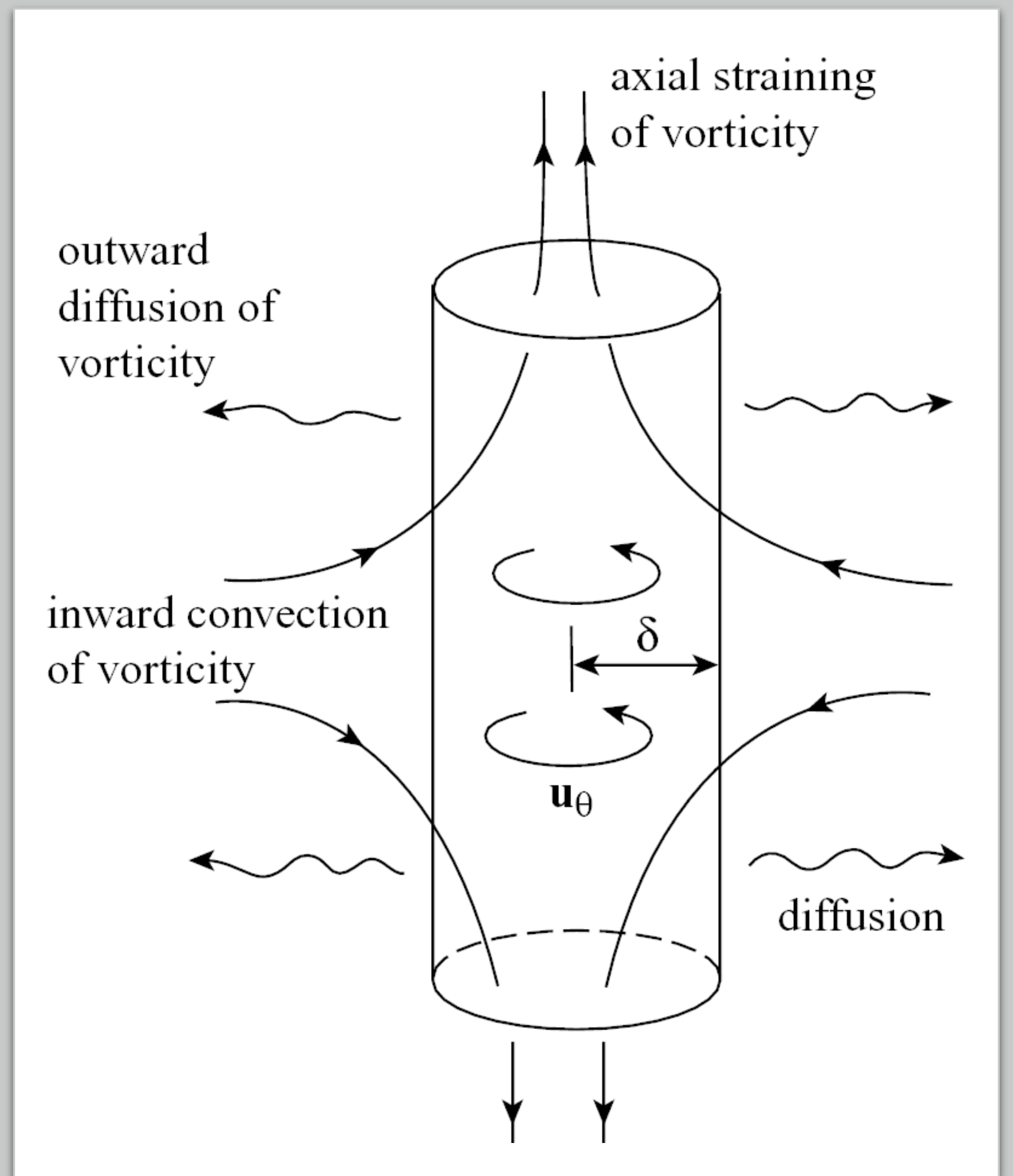


Negligible viscosity or irrotational flow cannot be assumed near solid boundaries, such as the case of the airplane wing.

Boundary layers (MFM 602-610)



Viscosity drives the diffusion of vorticity



Vorticity and lines of vorticity

- Since $\vec{\Omega} = \nabla \times \vec{V}$ its divergence is zero, i.e. $\nabla \cdot \vec{\Omega} = 0$.

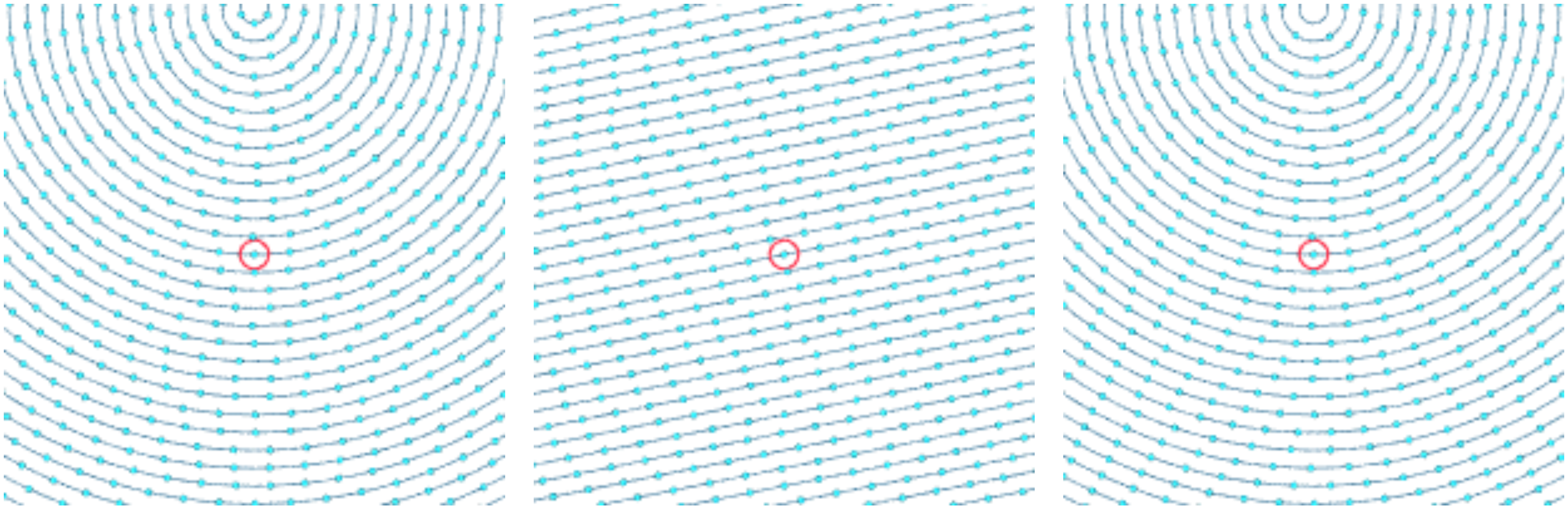
- The vorticity is a solenoidal field with lines of vorticity (like streamlines) parallel to its direction and density proportional to its magnitude.

- Dynamics of the lines of vorticity differs in the Euler and Navier-Stokes equations.

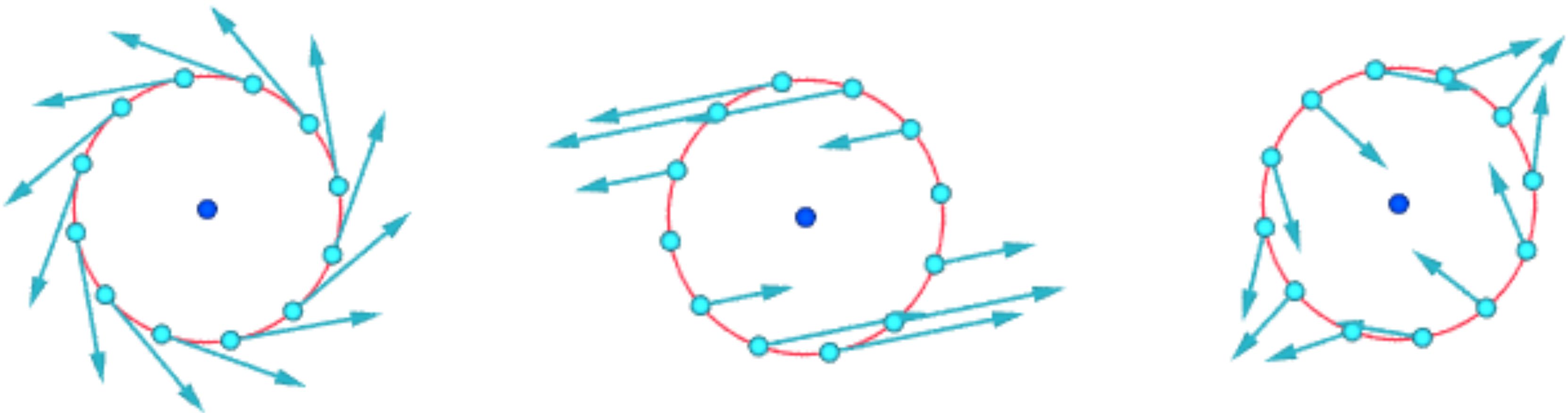
Rigid-body-like vortex
$v \propto r$

Parallel flow with shear

Irrotational vortex
$v \propto 1/r$



Relative velocities (magnified) around the highlighted point



Vorticity ≠ 0

Vorticity ≠ 0

Vorticity = 0

Euler fluid

In any Euler fluid, lines of vorticity may be regarded as embedded in the fluid and obliged to move with it, and they are conserved in number.

Apply the curl to the Euler equation

$$-\frac{1}{\rho}\nabla p^* = \frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u}.$$

This operation leads, when ρ is uniform and $\nabla\cdot\boldsymbol{u} = 0$, to

$$0 = \frac{\partial \boldsymbol{\Omega}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{\Omega} - (\boldsymbol{\Omega}\cdot\nabla)\boldsymbol{u}$$

and hence to

$$\frac{\mathrm{D}\boldsymbol{\Omega}}{\mathrm{D}t} = (\boldsymbol{\Omega}\cdot\nabla)\boldsymbol{u}.$$

To see what this result means, let us write out its components, choosing the x_3 direction to coincide locally with the direction of $\boldsymbol{\Omega}$, in which case $\Omega_1 = \Omega_2 = 0$. We have

$$\frac{\mathrm{D}\Omega_1}{\mathrm{D}t} = \Omega_3\frac{\partial u_1}{\partial x_3}, \tag{7.1}$$

a similar equation to describe $\mathrm{D}\Omega_2/\mathrm{D}t$, and

$$\frac{\mathrm{D}\Omega_3}{\mathrm{D}t} = \Omega_3\frac{\partial u_3}{\partial x_3}. \tag{7.2}$$

Lines of vorticity are embedded and conserved in an Euler fluid

Now the quantity $\partial u_1/\partial x_3$ which appears in (7.1) is the angular velocity with which a short line embedded in the fluid, initially lying along the x_3 axis and therefore coinciding in direction with $\boldsymbol{\Omega}$, is rotating about the x_2 axis; (7.1) tells us that within the element of fluid which contains this line the vorticity vector precesses about x_2 at the same rate. Since it also precesses about x_1 at the same rate as the embedded line, the embedded line and the local line of vorticity must remain coincident at all times. As for (7.2), this tells us that where the fluid is being elongated in the direction of $\boldsymbol{\Omega}$ the magnitude of $\boldsymbol{\Omega}$ increases.

Equation (7.2) shows that within any cylindrical element of fluid whose axis coincides with the direction of $\boldsymbol{\Omega}$, whether it forms part of the core of a vortex line or not, the product of Ω and the cross-sectional area of the element is constant. Both equations are clearly consistent with the notion that lines of vorticity are embedded and conserved.

Navier-Stokes: Viscosity drives the diffusion of vorticity

To find what difference viscosity makes, we need to repeat the above analysis using the Navier–Stokes equation as our starting point, rather than the Euler equation. The viscous term on the left-hand side of (6.25) is $-\eta\boldsymbol{\nabla} \wedge \boldsymbol{\Omega}$, and the curl of this, since $\boldsymbol{\nabla} \cdot \boldsymbol{\Omega} = 0$, is $\eta\nabla^2\boldsymbol{\Omega}$. Hence we now have

$$\frac{\mathrm{D}\boldsymbol{\Omega}}{\mathrm{D}t} = (\boldsymbol{\Omega} \cdot \boldsymbol{\nabla})\boldsymbol{u} + \frac{\eta}{\rho} \nabla^2\boldsymbol{\Omega}. \tag{7.3}$$

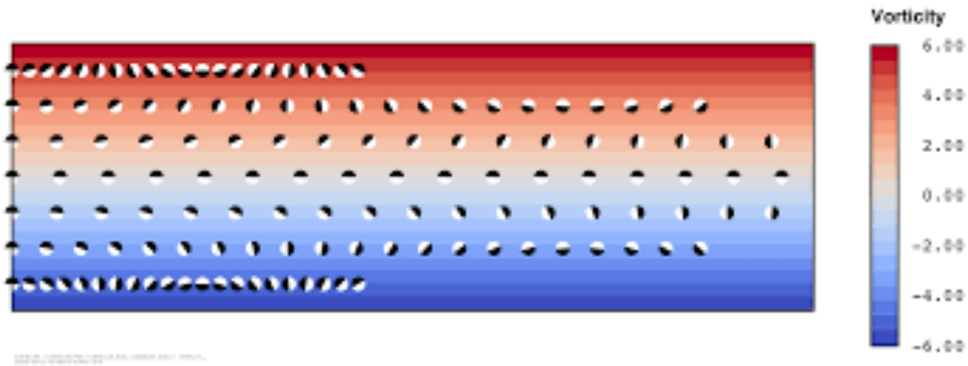
Apart from the $(\boldsymbol{\Omega} \cdot \boldsymbol{\nabla})\boldsymbol{u}$ term, the effects of which are as described above, this is just a three-dimensional diffusion equation for each of the components of $\boldsymbol{\Omega}$; to be more precise, it becomes a three-dimensional equation in the co-moving frame for which $\mathrm{D}\boldsymbol{\Omega}/\mathrm{D}t$ and $\partial\boldsymbol{\Omega}/\partial t$ are the same. Thus vorticity is not permanently embedded if the fluid has viscosity; where $\nabla^2\boldsymbol{\Omega}$ is non-zero it spreads by diffusion, and its *diffusivity* is the kinematic viscosity, $\nu = \eta/\rho$. Since the process described by the diffusion equation always conserves the thing which is diffusing, whether it be dye or heat or whatever, the fact that vorticity is liable to diffuse does not affect our conclusion that lines of vorticity are conserved.

Example: Poiseuille flow

If, however, the vorticity is positive in region A and negative in an adjoining region B, diffusion from A to B and *vice versa* is bound to result in some degree of cancellation. The lines of vorticity in such situations tend to form closed loops which disappear by collapsing to a point. For example, consider the simple case of a fluid undergoing Poiseuille flow along a straight cylindrical pipe whose axis is the x_3 axis. In the plane $x_2 = 0$, say, Ω_1 and Ω_3 both vanish, while

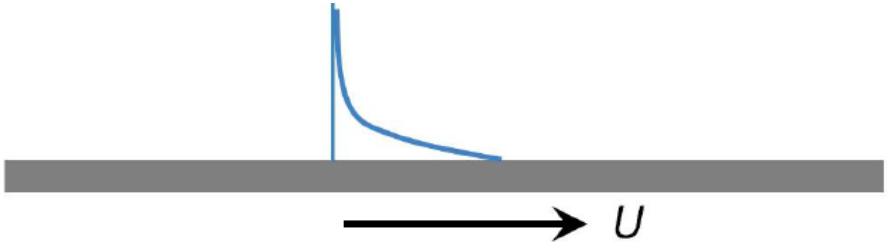
$$\Omega_2 = -\frac{\partial u_3}{\partial x_1} = -\frac{x_1}{2\eta}\nabla_3 p$$

Thus $\boldsymbol{\Omega}$ changes sign on the axis in the plane $x_2 = 0$, and it also does so in the plane $x_1 = 0$ where Ω_1 is the non-vanishing component; evidently the lines of vorticity are closed circular loops coaxial with the pipe. Now the direction in which the lines of vorticity diffuse is determined by the sign of $\partial\Omega/\partial r$. Because this is positive we should picture the loops as diffusing inwards, to smaller values of radius r, and ultimately collapsing on the axis. We should therefore picture the surface of the fluid, where it is in contact with the solid wall of the pipe, as a vorticity source at which new loops are continuously created to replace those which collapse.



Sudden motion of an infinite flat plane (revisited)

Flow above a solid wall at y = 0. Initially, the fuid is at rest. At time t = 0, the boundary starts to move with velocity U in the x direction.



The velocity field is

$$\mathbf{u} = (u(y,t), 0, 0).$$

and the Navier-Stokes equation

$$\rho \frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\nabla p + \mu \nabla^2 \mathbf{u},$$

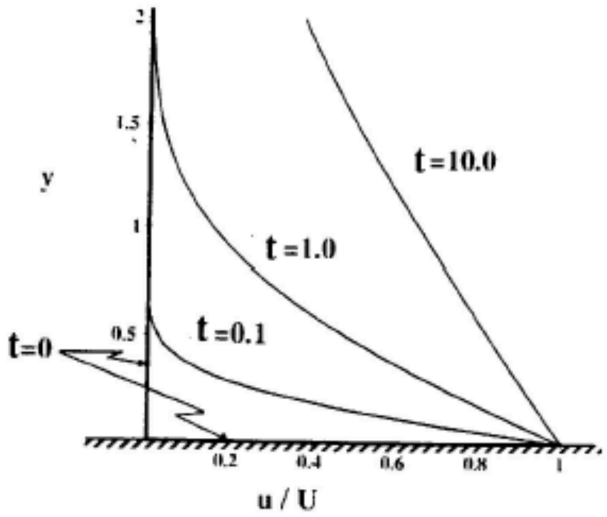
reduces to

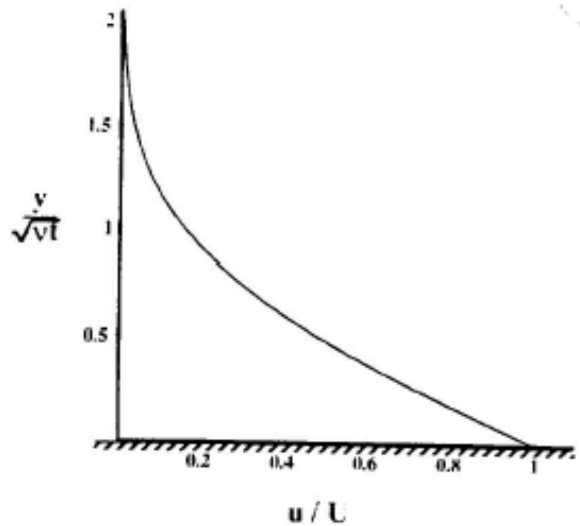
$$\rho \frac{\partial u}{\partial t} = \mu \frac{\partial^2 u}{\partial y^2},$$

- Boundary conditions: u = U on y = 0 and U → 0 as y → ∞.
- We also impose the initial condition: u = 0 at t = 0.
- The velocity u(x, t) thus satisfies the 1-D diffusion equation with diffusivity $\upsilon = \frac{\mu}{\varrho}$, where υ is the kinematic viscosity.
- The similarity solution is

$$u(y,t) = U\left[1 - \operatorname{erf}\left(\frac{y}{2\sqrt{\nu t}}\right)\right].$$

The velocity $u(y,t)$ will be approximately zero wherever $y/2\sqrt{\nu t}$ is large. In addition, for a fixed value of y, the velocity will remain less than $0.01U$ until a time t such that $y \approx 4\sqrt{\nu t}$. Hence, at time t, the fluid is only moving within a narrow region of thickness $4\sqrt{\nu t}$. This narrow region is called the *viscous boundary layer*. Note that the boundary layer thickness is independent of U.





SOLUTION OF THE 1D DIFFUSION EQUATION

We seek a *similarity solution*:

$$u(y,t) = f(\eta), \text{ where } \eta = yt^a,$$

for some constant a. Using the chain rule:

$$\frac{\partial}{\partial y} = t^a \frac{d}{d\eta},$$
$$\frac{\partial}{\partial t} = ayt^{a-1}\frac{d}{d\eta},$$

so that equation (4.1) becomes:

$$ayt^{a-1}\frac{df}{d\eta} = \nu t^{2a}\frac{d^2 f}{d\eta^2},$$

and therefore:

$$\frac{d^2 f}{d\eta^2} - \frac{ayt^{-a-1}}{\nu}\frac{df}{d\eta} = 0.$$

For the similarity solution to exist, this equation must only contain y and t in the combination $\eta = yt^a$ and therefore $-a-1 = a$. We get: $a = -\frac{1}{2}$. Solutions thus exists for the similarity variable $\eta = y/\sqrt{t}$ and satisfy:

$$\frac{d^2 f}{d\eta^2} + \frac{\eta}{2\nu}\frac{df}{d\eta} = 0.$$

Substituting $v = df/d\eta$ we have:

$$\frac{dv}{d\eta} = -\frac{\eta}{2\nu}v,$$

which has general solution:

$$v = \frac{df}{d\eta} = A\exp\left(-\frac{\eta^2}{4\nu}\right).$$

Integrating again, we obtain:

$$f = A\int_0^\eta \exp\left(-\frac{\eta^2}{4\nu}\right)d\eta + B.$$

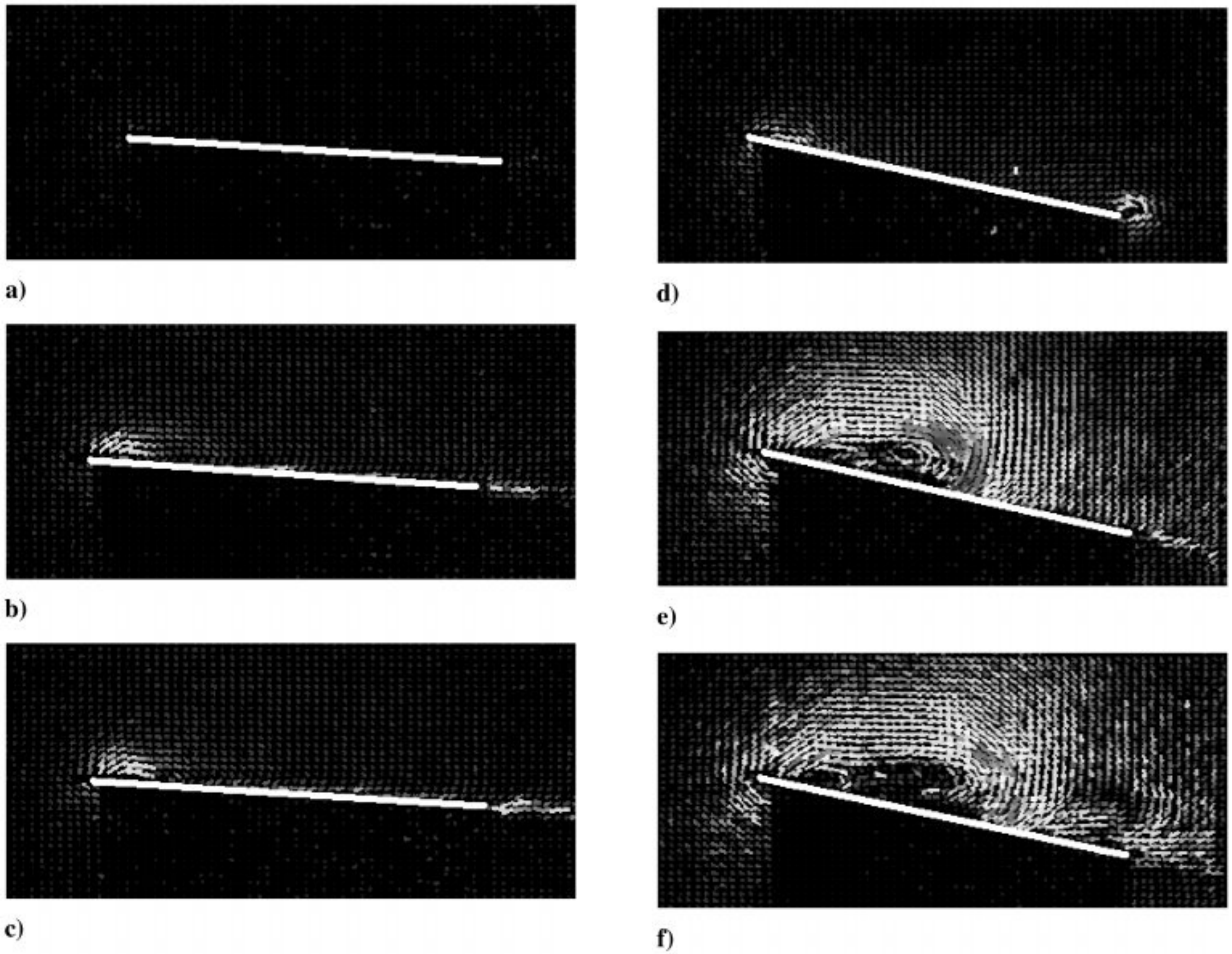
The above integral can be expressed in terms of the error function:

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp\left(-x^2\right)dx.$$

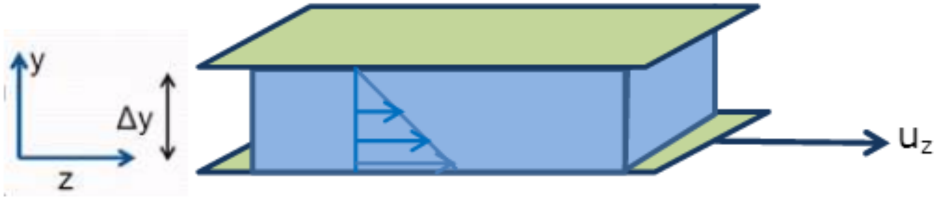
Substituting $x = \eta/2\sqrt{\nu}$, we have:

$$f = A\sqrt{\nu\pi}\,\mathrm{erf}\left(\frac{\eta}{2\sqrt{\nu}}\right) + B.$$

Impulsively started flat plate (MFM 612-614)



Start up of shear flow (parallel plates)



Let us now modify the previous problem by considering the start-up of a shear flow between two parallel plates located at $y = 0$ and $y = h$. Once again, we begin to move the lower plate with velocity U at $t = 0$. The problem is the same as that above except that the boundary condition at infinity is replaced by one at $y = h$. The velocity now satisfies:

$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2}, \tag{4.3}$$

together with the boundary conditions: $u(0, t) = U$ and $u(h, t) = 0$, and the initial condition $u(y, 0) = 0$.

First, we observe that the steady solution $u_s = U\,(1 - y/h)$ satisfies the equation at any $t \neq 0$ and the boundary conditions. We then write:

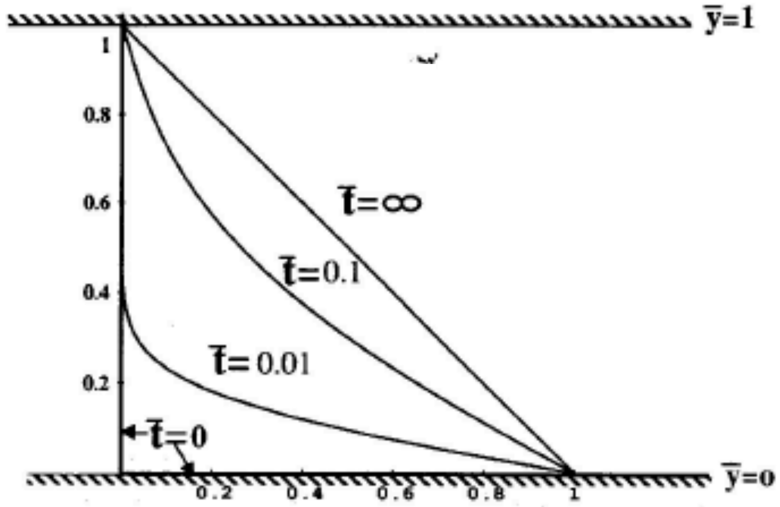
$$u(y, t) = u_s + v(y, t),$$

and seek a separable solution of the form:

$$v(y, t) = T(t)Y(y).$$

Hence, the solution is:

$$u(y,t) = U\left(1 - \frac{y}{h}\right) - \frac{2U}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\exp\left(-\frac{\nu n^2\pi^2}{h^2}t\right)\sin\left(\frac{n\pi y}{h}\right).$$



This flow resembles that of the unbounded plate until the boundary layer grows to the width of the channel. The solution then approaches the steady state u_s. Note that the slowest decaying exponential in the sum corresponds to $n = 1$. As a result, the flow reaches u_s on a time of order $h^2/(\nu\pi^2)$. For water in a 1cm channel, this time is about 10s and scales inversely with ν so that in a fluid of lower viscosity it becomes longer.

SOLUTION OF START UP OF SHEAR FLOW

This gives:

$$YT' = \nu TY'',$$

so that:

$$\frac{Y''}{Y} = \frac{1}{\nu}\frac{T'}{T} = k,$$

where k is the constant of integration. Since u_s takes care of the moving boundary, we want to find solutions satisfying $Y(0) = Y(h) = 0$. We thus choose solutions of the form:

$$Y(y) = \sin\left(\frac{n\pi y}{h}\right),$$

so that:

$$\frac{Y''}{Y} = -\frac{n^2\pi^2}{h^2}.$$

It follows:

$$\frac{T'}{T} = -\frac{\nu n^2\pi^2}{h^2},$$

and so we have separable solutions of the form:

$$v_n = \exp\left(-\frac{\nu n^2\pi^2}{h^2}t\right)\sin\left(\frac{n\pi y}{h}\right).$$

The general solution for u satisfying the boundary conditions is:

$$u(y,t) = U\left(1-\frac{y}{h}\right) + \sum_{n=1}^{\infty} a_n \exp\left(-\frac{\nu n^2\pi^2}{h^2}t\right)\sin\left(\frac{n\pi y}{h}\right).$$

The initial condition at $t = 0$ requires:

$$\sum_{n=1}^{\infty} a_n \sin\left(\frac{n\pi y}{h}\right) = -U\left(1-\frac{y}{h}\right),$$

for $0 < y < h$. We can determine the a_n using Fourier series properties:

$$a_n = \frac{2U}{h}\int_0^h \left(\frac{y}{h}-1\right)\sin\left(\frac{n\pi y}{h}\right)dy = -\frac{2U}{n\pi},$$

Hence, the solution is:

$$u(y,t) = U\left(1-\frac{y}{h}\right) - \frac{2U}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\exp\left(-\frac{\nu n^2\pi^2}{h^2}t\right)\sin\left(\frac{n\pi y}{h}\right).$$

Diffusion of vorticity from the surface to the fluid

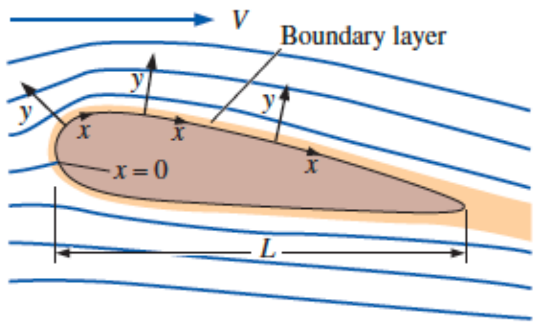
Let us now return to the case of the flow above a boundary that is set in motion at time $t = 0$. Initially, the vorticity is zero everywhere, except at $y = 0$ where the fluid velocity jumps from U to 0. At time t, the velocity is given by equation (4.2). The vorticity ω reads:

$$\omega = -\frac{\partial u}{\partial y} = \frac{U}{\sqrt{\pi \nu t}} \exp\left(-\frac{y^2}{4\nu t}\right).$$

This is a Gaussian distribution of standard deviation $\sqrt{2\nu t}$. Hence, as times increases, the vorticity gradually spreads away from the boundary over a distance of order $\sqrt{2\nu t}$.

Boundary layer equations

- We consider steady, two-dimensional flow in the xy-plane in Cartesian coordinates. The methodology can be extended to axisymmetric boundary layers or to three-dimensional boundary layers in any coordinate system.
- We neglect gravity since we are not dealing with free surfaces or with buoyancy-driven flows (free convection flows), where gravitational effects dominate.
- We consider laminar boundary layers; turbulent boundary layer equations are beyond the scope of this course.
- For a boundary layer along a solid wall, we adopt a coordinate system in which x is everywhere parallel to the wall and y is everywhere normal to the wall.
- When we solve the boundary layer equations, we do so at one x-location at a time, using this coordinate system locally, and it is locally orthogonal.

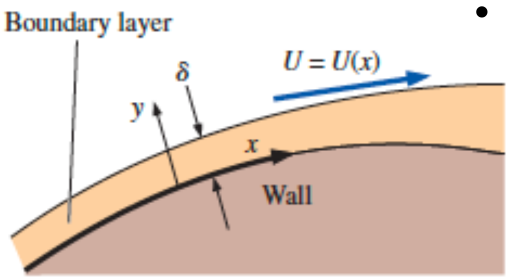


The nondimensionalized Navier–Stokes equation is

$$(\vec{V}^* \cdot \vec{\nabla}^*)\vec{V}^* = -[\mathrm{Eu}]\vec{\nabla}^* P^* + \left[\frac{1}{\mathrm{Re}}\right]\nabla^{*2}\vec{V}^*$$

- The Euler number is of order 1, since pressure differences outside the boundary layer are determined by the Bernoulli equation and $\Delta P \sim \rho V^2$.
- V is a characteristic velocity of the outer flow, typically the free-stream velocity for bodies immersed in a uniform flow.
- The characteristic length is L, some characteristic size of the body. For boundary layers, x is of order of L, and Reynolds number is Re_x, usuallly very high.

Redo the nondimensionalization of the equations based on appropriate scales within the boundary layer.



- Since x ~ L, we use L as the scale for distances in the streamwise direction and for derivatives with respect to x. However, this scale is too large for derivatives with respect to y. We use δ for distances in the direction normal to the streamwise direction and for derivatives with respect to y.

- Similarly, we use U as the characteristic velocity, where U is the magnitude of the velocity component parallel to the wall at a location just above the boundary layer. U is in general a function of x.

- Thus, within the boundary layer at some value of x, the orders of magnitude are

$$u \sim U \qquad P - P_\infty \sim \rho U^2 \qquad \frac{\partial}{\partial x} \sim \frac{1}{L} \qquad \frac{\partial}{\partial y} \sim \frac{1}{\delta}$$

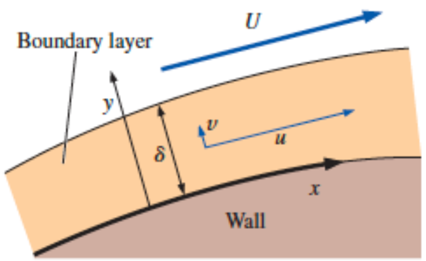
- The order of magnitude of velocity component v is obtained from the continuity equation

$$\underbrace{\frac{\partial u}{\partial x}}_{\sim U/L} + \underbrace{\frac{\partial v}{\partial y}}_{\sim v/\delta} = 0 \quad \rightarrow \quad \frac{U}{L} \sim \frac{v}{\delta}$$

- Since the two terms have to balance each other, they must be of the same order of magnitude. Thus we obtain the order of magnitude of velocity component v,

$$v \sim \frac{U\delta}{L}$$

- Since δ/L << 1 in a boundary layer, we conclude that v << u, and the adimensional variables are



$$x^* = \frac{x}{L} \qquad y^* = \frac{y}{\delta} \qquad u^* = \frac{u}{U} \qquad v^* = \frac{vL}{U\delta} \qquad P^* = \frac{P - P_\infty}{\rho U^2}$$

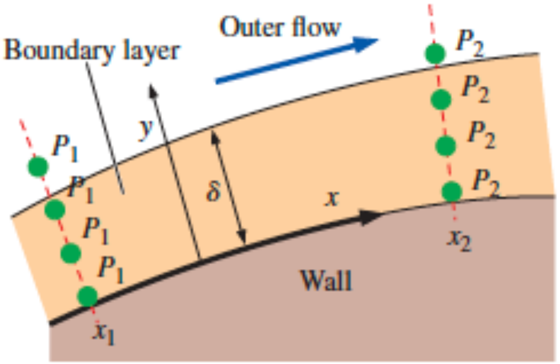
We now consider the x- and y-components of the Navier–Stokes equation. We substitute these nondimensional variables into the y-momentum equation, giving

$$\underbrace{u}_{u^*U}\underbrace{\frac{\partial v}{\partial x}}_{\frac{\partial}{\partial x^*}\frac{v^*U\delta}{L^2}} + \underbrace{v}_{v^*\frac{U\delta}{L}}\underbrace{\frac{\partial v}{\partial y}}_{\frac{\partial}{\partial y^*}\frac{v^*U\delta}{L\delta}} = \underbrace{-\frac{1}{\rho}\frac{\partial P}{\partial y}}_{\frac{1}{\rho}\frac{\partial}{\partial y^*}\frac{P^*\rho U^2}{\delta}} + \underbrace{\nu\frac{\partial^2 v}{\partial x^2}}_{\nu\frac{\partial^2}{\partial x^{*2}}\frac{v^*U\delta}{L^3}} + \underbrace{\nu\frac{\partial^2 v}{\partial y^2}}_{\nu\frac{\partial^2}{\partial y^{*2}}\frac{v^*U\delta}{L\delta^2}}$$

After some algebra

$$u^*\frac{\partial v^*}{\partial x^*} + v^*\frac{\partial v^*}{\partial y^*} = -\left(\frac{L}{\delta}\right)^2\frac{\partial P^*}{\partial y^*} + \left(\frac{\nu}{UL}\right)\frac{\partial^2 v^*}{\partial x^{*2}} + \left(\frac{\nu}{UL}\right)\left(\frac{L}{\delta}\right)^2\frac{\partial^2 v^*}{\partial y^{*2}}$$

The middle term on the r.h.s. is clearly smaller than any other term since $Re_L = UL/\upsilon \gg 1$. For the same reason, the last term on the right is much smaller than the first term on the right. Neglecting these two terms leaves the two terms on the left and the first term on the right. However, since $L \gg \delta$, the pressure gradient is orders of magnitude greater than the advective terms on the left of the equation. Thus, the only term left is the pressure term. Since no other term in the equation can balance that term, we have no choice but to set it to zero. Thus, the nondimensional y-momentum equation is



$$\frac{\partial P^*}{\partial y^*} \cong 0$$

The pressure across a boundary layer (y-direction) is nearly constant.

Since P is not a function of y, we replace ∂P/∂x by dP/dx, where P is the pressure calculated from the outer flow approximation (using either continuity plus Euler, or the potential flow equations plus Bernoulli). The x-component of the Navier–Stokes equation becomes

$$\underbrace{u}_{u^*U}\underbrace{\frac{\partial u}{\partial x}}_{\frac{\partial}{\partial x^*}\frac{u^*U}{L}} + \underbrace{v}_{v^*\frac{U\delta}{L}}\underbrace{\frac{\partial u}{\partial y}}_{\frac{\partial}{\partial y^*}\frac{u^*U}{\delta}} = \underbrace{-\frac{1}{\rho}\frac{dP}{dx}}_{\frac{1}{\rho}\frac{\partial}{\partial x^*}\frac{P^*\rho U^2}{L}} + \underbrace{\nu\frac{\partial^2 u}{\partial x^2}}_{\nu\frac{\partial^2}{\partial x^{*2}}\frac{u^*U}{L^2}} + \underbrace{\nu\frac{\partial^2 u}{\partial y^2}}_{\nu\frac{\partial^2}{\partial y^{*2}}\frac{u^*U}{\delta^2}}$$

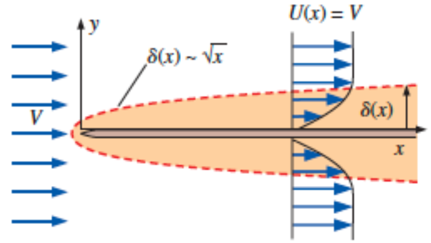
or

$$u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} = -\frac{dP^*}{dx^*} + \left(\frac{\nu}{UL}\right)\frac{\partial^2 u^*}{\partial x^{*2}} + \left(\frac{\nu}{UL}\right)\left(\frac{L}{\delta}\right)^2\frac{\partial^2 u^*}{\partial y^{*2}}$$

The middle term on the right side is orders of magnitude smaller than the terms on the left. What about the last term on the right? If we neglect this term, we throw out all the viscous terms and are back to the Euler equation. Clearly this term must remain. Furthermore, since all the remaining terms are of order unity, the combination of parameters in parentheses in the last term on the right side must also be of order 1,

$$\left(\frac{\nu}{UL}\right)\left(\frac{L}{\delta}\right)^2 \sim 1$$

$$\frac{\delta}{L} \sim \frac{1}{\sqrt{\mathrm{Re}_L}}$$

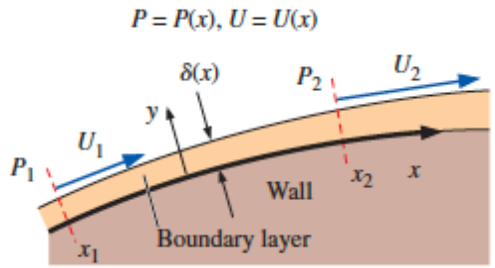


x-momentum boundary layer equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{dP}{dx} + \nu\frac{\partial^2 u}{\partial y^2}$$

Finally, since we know from the y-momentum equation analysis that the pressure across the boundary layer is the same as that outside the boundary layer, we apply the Bernoulli equation to the outer flow region. Differentiating with respect to x we get

$$\frac{P}{\rho} + \frac{1}{2}U^2 = \text{constant} \quad \rightarrow \quad \frac{1}{\rho}\frac{dP}{dx} = -U\frac{dU}{dx}$$



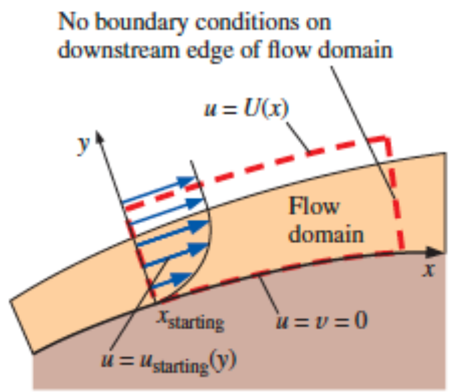
Substitution yields

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U\frac{dU}{dx} + \nu\frac{\partial^2 u}{\partial y^2}$$

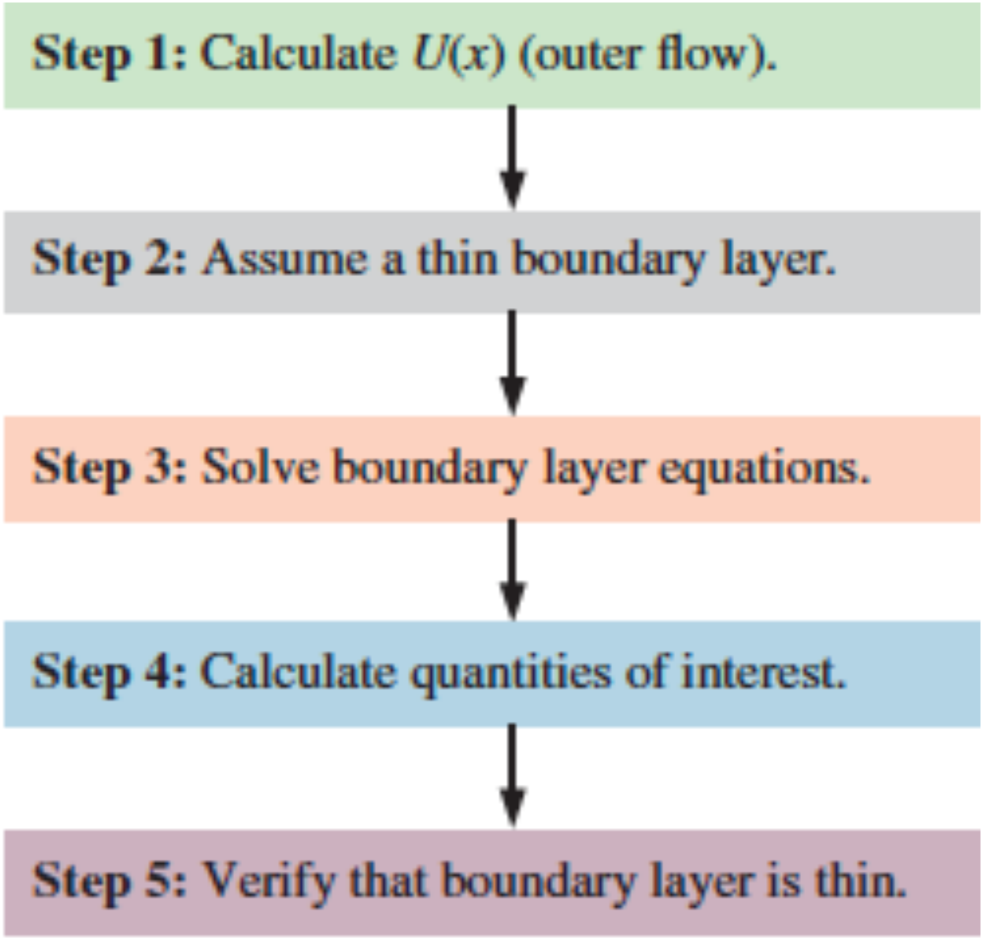
Boundary layer equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U\frac{dU}{dx} + \nu\frac{\partial^2 u}{\partial y^2}$$



- For a typical boundary layer problem along a wall, we specify the no-slip condition at the wall ($u = v = 0$ at $y = 0$), the outer flow condition at the edge of the boundary layer and beyond [$u = U(x)$ as $y \to \infty$], and a starting profile at some upstream location [$u = u_{starting}(y)$ at $x = x_{starting}$, where $x_{starting}$ may or may not be zero]. With these boundary conditions, we simply march downstream in the x-direction, solving the boundary layer equations as we go.



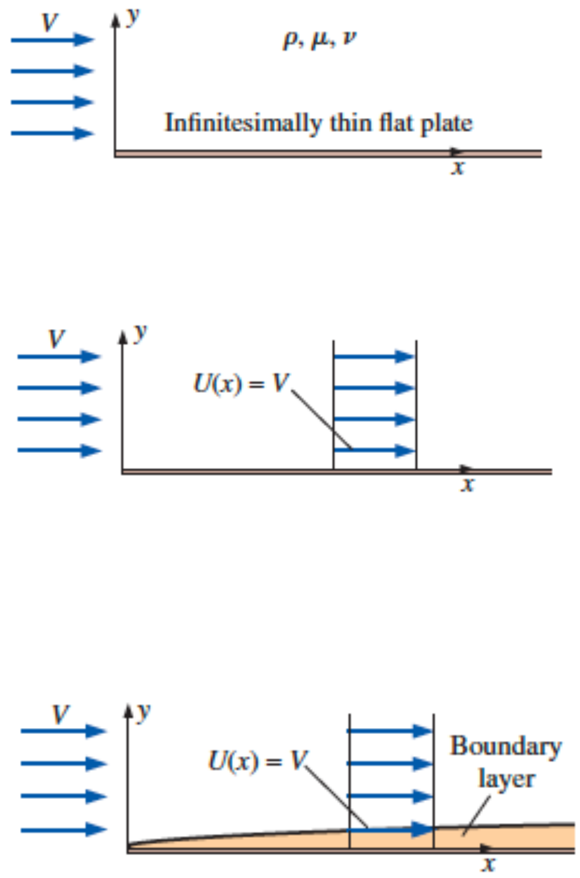
Example: Flat plate

Outer flow: $U(x) = V = \text{constant}$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2}$$

$$u = 0 \text{ at } y = 0 \qquad u = U \text{ as } y \to \infty$$

$$v = 0 \text{ at } y = 0 \qquad u = U \text{ for all } y \text{ at } x = 0$$



No convenient analytical solution is available. However, a series solution was obtained in 1908 by Blasius.

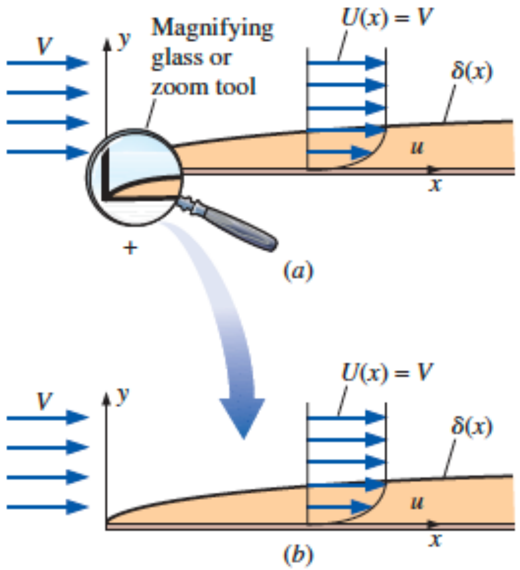
Blasius similarity solution

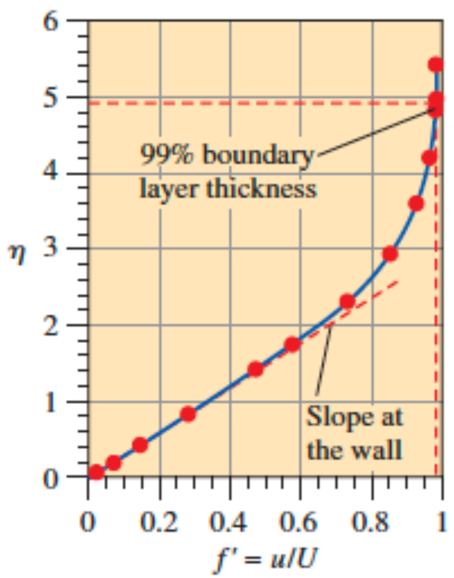
Blasius introduced a **similarity variable** η that combines independent variables x and y into one nondimensional independent variable,

$$\eta = y\sqrt{\frac{U}{\nu x}}$$

and he solved for a nondimensionalized form of the x-component of velocity,

$$f' = \frac{u}{U} = \text{function of } \eta$$

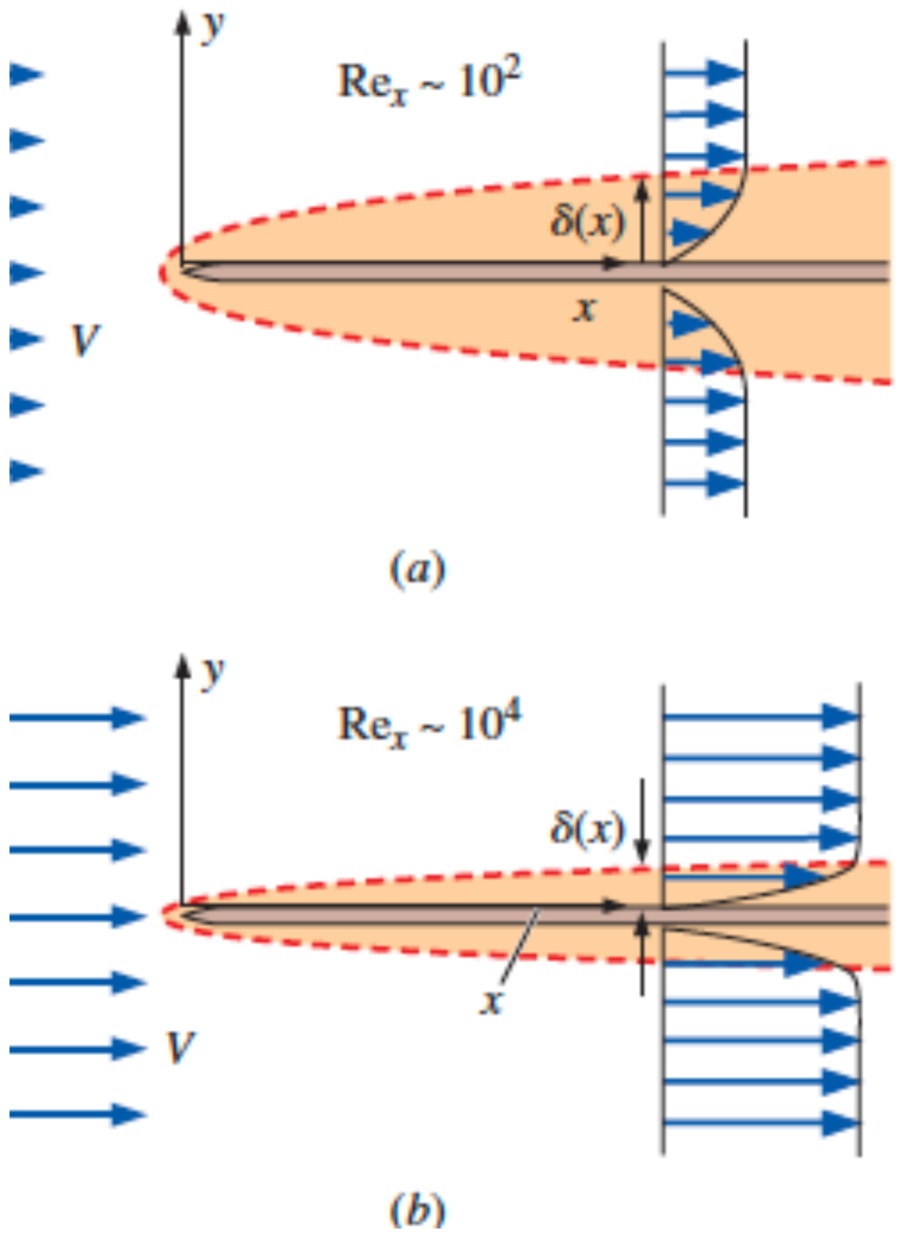




$$\eta = 4.91 = \sqrt{\frac{U}{\nu x}}\delta \rightarrow \frac{\delta}{x} = \frac{4.91}{\sqrt{\mathrm{Re}_x}}$$

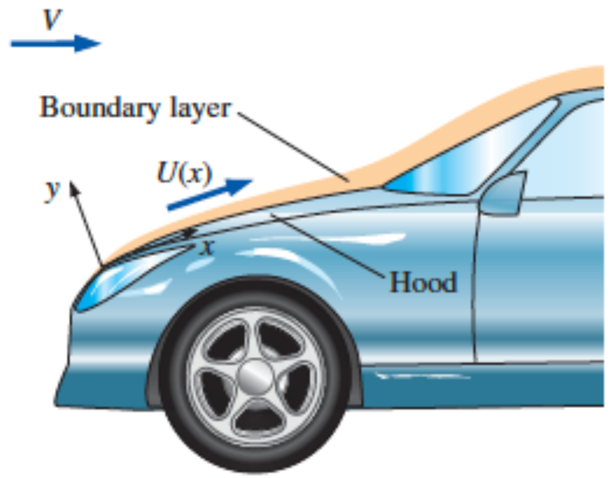
Shear stress in physical variables: $$\tau_w = 0.332\frac{\rho U^2}{\sqrt{\mathrm{Re}_x}}$$

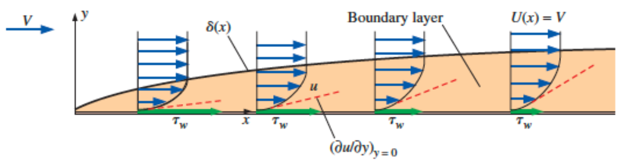
Flow of a uniform stream parallel to a flat plate (drawings not to scale):
(a) $Re_x = 10^2$, (b) $Re_x = 10^4$. The larger the Reynolds number, the thinner the boundary layer along the plate at a given x-location.



- Discussion: The Blasius boundary layer solution is valid only for flow over a flat plate perfectly aligned with the flow.

- However, it is often used as a quick approximation for the boundary layer developing along solid walls that are not necessarily flat nor exactly parallel to the flow, as in a car hood.





Blasius solution

Non-linear third order ODE.

Solved numerically or by a series expansion.

Similarity Variable

$$\eta = \frac{y}{\delta} = \frac{y}{\sqrt{2\nu x / U_0}}$$

Streamfunction

$$f(\eta) = \frac{\psi}{\delta U_0} = \frac{\psi}{\sqrt{2\nu x U_0}}$$

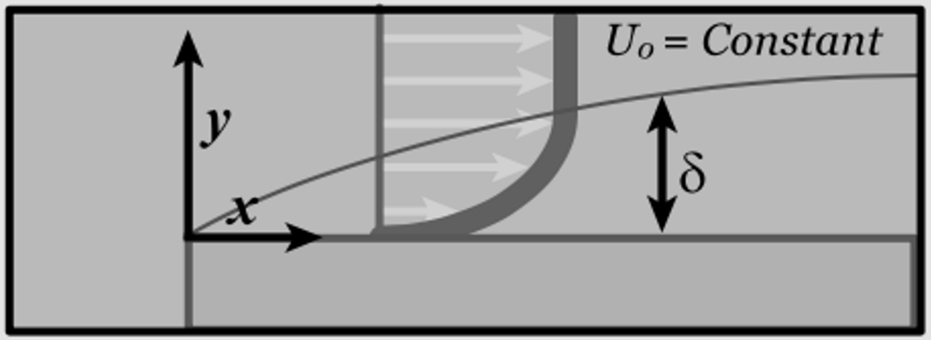
Blasius Equation

$$f''' + ff'' = 0$$

Boundary Conditions

wall: $\eta = 0 \qquad f = f' = 0$

freestream: $\eta \to \infty \qquad f' = 1$



Falkner-Skan solution

Non-linear third order ODE.

Solved numerically

Similarity Variable $\eta = \frac{y}{\delta} = \frac{y}{\sqrt{\frac{2\nu x}{U_0(m+1)}}}$

Streamfunction $f = \frac{\psi}{\delta U_0} = \frac{\psi}{\sqrt{\frac{2\nu x U_0}{m+1}}}$

Falkner-Skan Equation

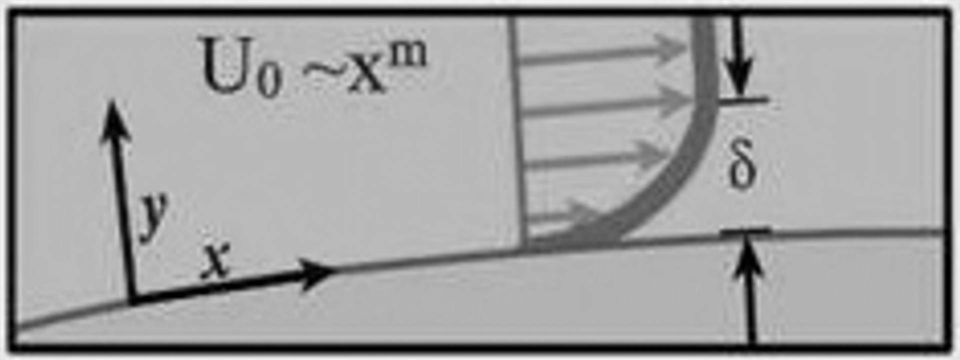
$$f''' + ff'' + \beta(1 - f'^2) = 0$$

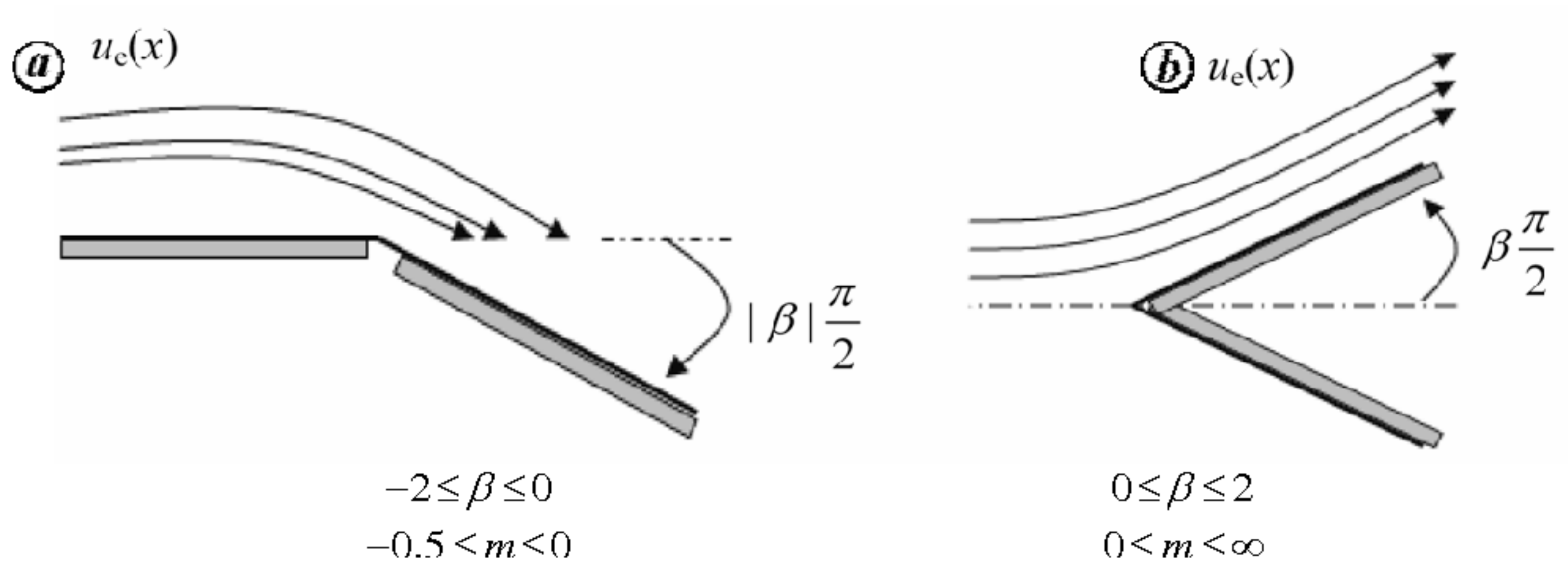
$$\beta = 2m/(m+1)$$

Boundary Conditions

wall: $\eta = 0 \quad f = f' = 0$

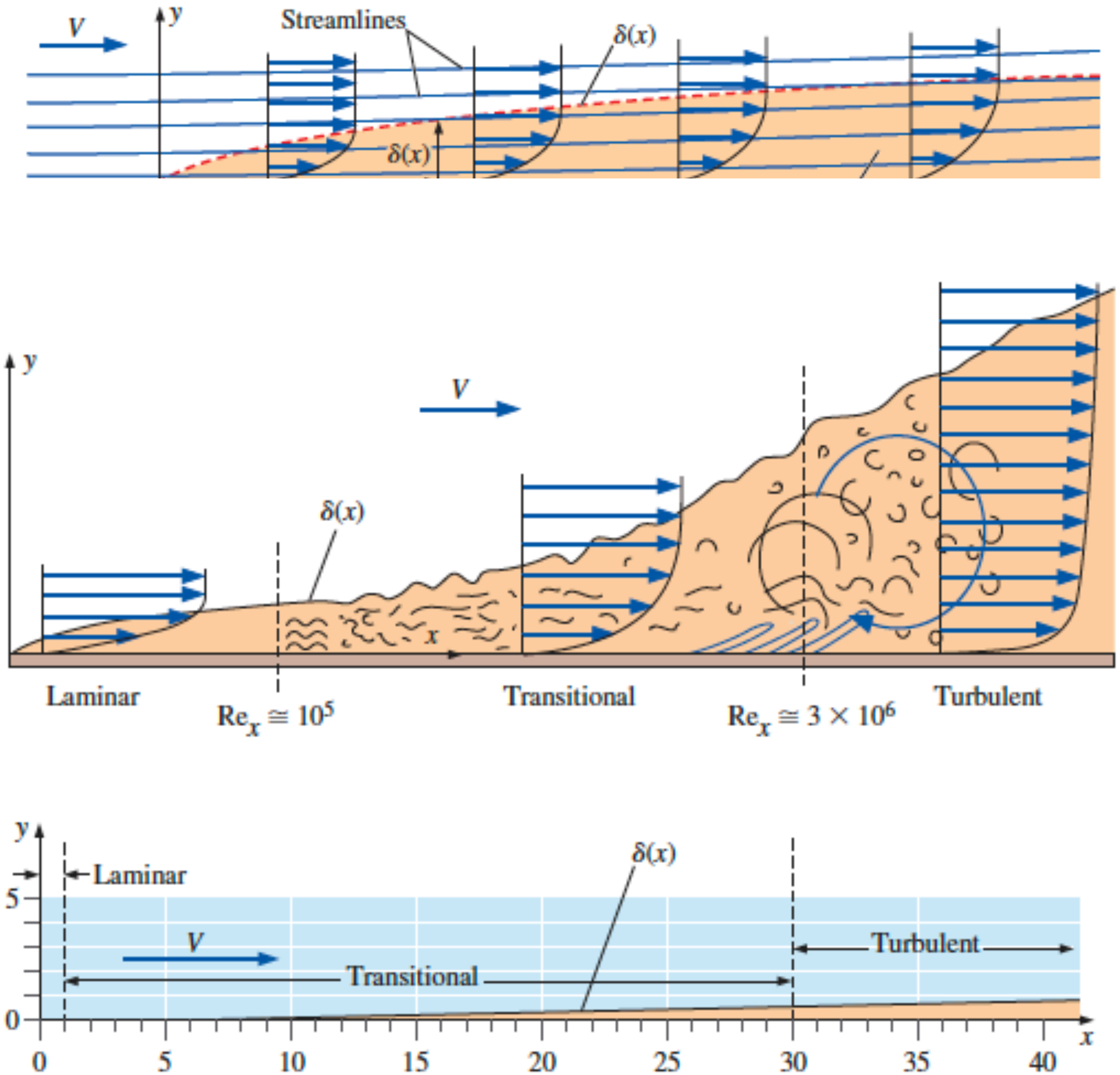
freestream: $\eta \rightarrow \infty \quad f' = 1$



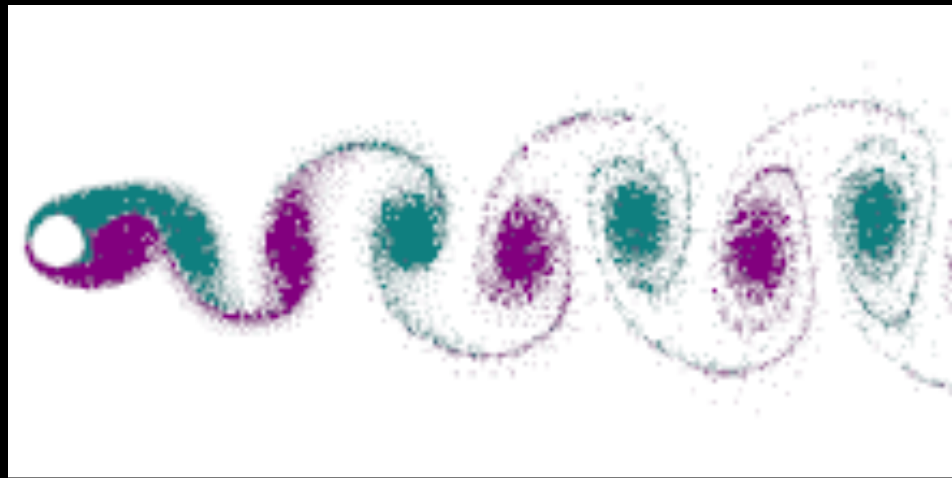


Blasius and Falkner-Skan solutions (MFM 637)

Laminar and turbulent boundary layers



Backflow, eddies and turbulence



A vortex street around a cylinder. This can occur around cylinders and spheres, for any fluid, cylinder size and fluid speed, provided that the flow has a Reynolds number in the range ~40 to ~1000.

Backflow, eddies and turbulence

Downwind of obstacles, in this case, the Madeira and the Canary Islands off the west African coast, eddies create turbulent patterns called votex streets.