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In the case of a boundary layer separation (flow separation), the flow can no longer follow the profile of the body around which it flows and separates turbulently from it. When a fluid flows around a body, forces act between the fluid and the surface due to the viscosity. These intermolecular forces are the caue for the drag, among other things. However, due to the forces acting, the surface of the solid body also tries to bind the fluid to itself. This also leads to the fluid adhering to the surface (no-slip condition). The layer above this adherent fluid layer will not be able to simply tear itself away from it, because intermolecular attraction and pressure forces also act between the layers. As a result, any flow flowing around a body is tempted to follow the profile of the surface. When flowing around a body, the fluid tries to follow the profile of the surface! Figure: Attaching of the flow around the wing of an airplane As long as the contour of a body has smooth transitions and the internal cohesion of the fluid (viscosity) is large enough to resist the inertial forces, a flow can follow the contour. A typical hydrodynamic boundary layer develops around the body, the thickness of which is largely influenced by the viscosity. Figure: Hydrodynamic boundary layer around the profile of a wing In the case of sharp transitions or when flowing around blunt bodies, however, the fluid is often no longer able to follow the profile. The boundary layer or flow begins to detach itself from the body surface. This is referred to as a boundary layer separation or flow separation. Downstream of the separation point, vortices often form, resulting in a turbulent flow. A flow separation is particularly dangerous on the wings of an aircraft, as this also causes a loss of lift and the aircraft is in danger of crashing. In aviation such a dangerous flow separation is called stall. In the case of a boundary layer separation (flow separation), the flow can no longer follow the profile of the body around which it flows and separates turbulently from it. Figure: Boundary layer separation (flow separation) on a blunt body As already mentioned, the boundary layer separation is obvious at sharp transitions. However, a stall can also occur even with smooth transitions. This is the case if the flow slows down considerably when flowing around a body. As a result, the static pressure can increase so much that it suddenly pushes the flow in the opposite direction. This results in a recirculation area, which causes a flow separation. Since a deceleration of the fluid occurs with every body, the danger of boundary layer separation therefore also exists with every body around which the fluid flows! The Reynolds number plays a decisive role here, since it describes the relationship between the existing inertial forces and the acting viscosity forces in a fluid. The higher the Reynolds number, the greater the inertia compared to the viscosity and the higher the risk of boundary layer separation. If the Reynolds numbers are sufficiently high, even with streamlined bodies, flow separation will eventually be unavoidable. Using the example of the flow around a cylinder, the processes in the fluid are explained in more detail. In the ideal case, a laminar boundary layer forms around the cylinder and the flow is completely attached to the surface. The laminar flow in the boundary layer displaces the undisturbed external flow. Conversely, however, the external flow imposes its pressure on the boundary layer and thus influences its course. The flow in the boundary layer and in the undisturbed external flow therefore influence each other. Figure: Laminar flow around a cylinder with turbulent flow separation Within the boundary layer, the imposed pressure does (almost) not change in the direction perpendicular to the surface. The pressure gradient in y-direction is therefore negligible (p/y). Only along the surface in the direction of the flow the pressure changes. According to the Bernoullis principle, the pressure depends on the velocity of the undisturbed external flow. When flowing around a flat plate, the velocity of the undisturbed external flow would be constant and thus also the pressure along the x-direction (p/x=0). When flowing around a curved body, however, the flow velocity changes and thus there is also a pressure gradient in x-direction. In case of a cylinder, the fluid at first is forced upwards and downwards in order to flow around the cylinder. However, according to the continuity equation (conservation of mass), the same mass must still be moved around the cylinder, so that the flow velocity increases as a result. At the thickest point of the cylinder, the maximum flow velocity is finally reached. Animation: Boundary layer separation of a flow around on a cylinder However, according to Bernoullis principle, a change in kinetic energy is directly linked to a change in static pressure. In this case, the increase in kinetic energy is at the expense of the pressure (energy). The static pressure thus decreases to a minimum up to the thickest point of the cylinder. The pressure gradient in x-direction is negativ in this area (p/x0). This pressure gradient acting against the actual direction of flow is called adverse pressure gradient. Note that this pressure gradient is mathematically positive and not negative, as the pressure increases in the positive x-direction. Depending on the shape of the body, the resulting adverse pressure gradient can become very large due to the decrease in speed and the boundary layer thickness increases significantly. In the case of the cylinder, the adverse pressure gradient even becomes so large that the flow is forced back against the actual flow direction. This results in a backflow area and the laminar flow detaches itself from the contour at this point. A so-called turbulent wake is formed behind the body. Such a turbulent wake can often be seen with ships in water and is also called dead water. Figure: Turbulent wake of a ship From a mathematical point of view, flow separation begins at that point on the surface where the flow is pushed back so strongly that the velocity gradient in the y-direction becomes zero (there is now a inflection point in the velocity profile!). According to Newtons law of fluid friction, this means that the shear stress at the wall, the so-called wall shear stress w, also becomes zero. \begin{align}&\boxed{\tau_w = \eta \cdot \left(\frac{\partial v}{\partial y}\right)_\text{wall}\overset{!}{=}0} ~~~~~\text{condition for flow separation}\\[5px]\end{align} The separation of the boundary layer takes place at the point where the wall shear stress becomes zero! The fluid particles follow the pressure drop which acts against the main flow direction (recirculation area). Because after the separation point the flow no longer adheres the surface of the body, the skin friction drag is almost zero. At the same time, however, the pressure drops considerably due to the energy dissipation in the turbulent wake. This leads to a significant increase in pressure drag, which is far greater than the reduction in skin friction drag. In total, the parasitic drag (air resistance) thus increases very strongly in the event of a flow separation. The separation of the boundary layer reduces the skin friction drag, but the pressure drag increases much more, so that the overall drag significantly! The flow around a body can not only be laminar, but also turbulent at increased Reynolds numbers. In general, a laminar flow around the body should be aimed for, since this reduces flow losses to a minimum. However, this is only the case if it is ensured that no boundary layer separation occurs. If, on the other hand, this cannot be ensured, then turbulent boundary layers should be aimed for. This may sound a paradox, but a turbulent boundary layer can usually follow the profile of a body longer than a laminar flow. The reason for this is the increased transport of momentum between the fluid layers, which leads to a steeper velocity profile within the boundary layer. Figure: Velocity profile in a laminar and turbulent boundary layer With a turbulent boundary layer, the velocity in the y-direction increases faster than with a laminar boundary layer. This means a larger velocity gradient near the wall and thus higher velocity components in the boundary layer. The resulting higher kinetic energy of the boundary layer can counteract the adverse pressure gradient more, so to speak. In the case of a turbulent boundary layer, the separation point thus shifts downstream. The turbulent wake becomes narrower with the shifting of the separation point. This reduces the flow losses and thus the pressure drag, which ultimately results in a reduction of the overall drag. Turbulent boundary layers adhere longer to the surfaces of the body around which flow occurs. The (pressure) drag is significantly lower. If there is a risk of flow separation, turbulent boundary layers should be aimed for. This fact is taken advantage of, for example, with golf balls. The dimples in the golf ball cause vortices and lead to a turbulent flow around the golf ball. The separation point shifts downstream and the drag is reduced to only a quarter, which makes the golf ball fly much further. Figure: Dimples on a golf ball to create a turbulent flow around it Animation: Flow around a golf ball and a ball with smooth surface So-called turbulators (vortex generators) on the wings of aircraft act in a similar way. Often many small vanes are mounted on the wing for this purpose. These vanes create a transition from a laminar to a turbulent flow. The turbulent boundary layer, which remains longer on the wing, not only reduces drag but also the risk of hard stall. Another possibility to achieve a targeted turbulent flow around wings is the use of so-called blast turbulators. Air is blown out through small holes in the wing. This also causes the laminar flow to change into a turbulent flow. Figure: Turbulators (vertex generators) on the wing of an airplane to generate a turbulent flow around it Turbulators can also be found in racing cars. These are designed to move the flow separation as far back as possible so that the flow is still attached in the rear of the car for as long as possible. Depending on the outline of the body being flowed around, a flow that has been detached can also reattach itself to the surface. The figure below shows the laminar flow around a vehicle. At point A, the flow separates and below it forms a kind of circulating air cushion, so that the flow can reattach to the surface at point B. This area is also called the separation bubble. A separation bubble is a recirculation area in a flow field, which is created by the separation and reattachment of the flow! Figure: Separation bubble on a car A separation bubble can also form when air flows around airfoils. The laminar flow around the wing separates at one point and reattaches itself to the wing downstream, provided the angle of attack is not too high. In the area between the laminar separation point and the point of turbulent reattachment a laminar separation bubble forms (laminar because the flow before the separation point is laminar). Figure: Laminar separation bubble on the airfoil of an aircraft The transition from laminar separation and turbulent reattachment takes place by disturbances in the flow, which build up like waves and finally become unstable. This wave-like build-up of the flow is also known as Tollmien-Schlichting waves. As already explained, such a separation bubble has a considerable influence on the pressure distribution over the wing. The drag rises strongly, which is why separation bubbles on airfoils should be avoided. This is where the turbulators come into play once again. They force the turbulent transition so that, ideally, the more energetic boundary layer remains connected to the wing without separation, or at least the separation point is shifted as far back as possible. A boundary layer can also be separated from the pipe wall in the case of flows through pipes. This is the case, for example, with sharp edges around which the flow is diverted. Separation bubbles are formed at the edges. Such dead spots resulting from flow separation mean flow losses and should be avoided. This can be achieved constructively, for example, by attaching guiding devices. Figure: Dead spaces of a pipe flow due to flow separation Animation: Dead spaces of a pipe flow due to flow separation Whether or not a flow separation takes place depends to a decisive degree on the Reynolds number. For a cylinder, in practice no separation takes place below a Reynolds number of 4. At higher Reynolds numbers up to about 40, the boundary layer separates. In the turbulent wake, two counter-rotating vortices are formed due to the conservation of angular momentum. As the Reynolds number increases (about over 80), these vortices become unstable and start to oscillate until they finally detach periodically. The characteristic swirling wake is also known as Krmn vortex street. Figure: Karman vortex street The Krmn vortex street is the periodic vortex separation around a body at high Reynolds numbers! A Krmn vortex street can be seen on satellite images, for example, when air currents flow around a mountain top. Also on Jupiter, the cloud formation around the Great Red Spot shows a Krmn vortex street. Figure: Krmn vortex street on Jupiter (Great Red Spot) The vortex shedding frequency f is given by the dimensionless Strouhal number Sr. It results from the characteristic length L (e.g. diameter of a cylinder) and the flow velocity v: \begin{align}&\boxed{Sr= \frac{f \cdot L}{v}} ~~~~~\text{Strouhal number}\\[5px]\end{align} The Strouhal number is usually in the range of 0.1 to 0.3, so that in many practical cases a value of 0.2 can be assumed. For such cases, the vortex shedding frequency f can be calculated with the following formula: \begin{align}&\boxed{f=Sr \cdot \frac{v}{L}} ~~~~~\text{often assumed: } Sr = 0.2\\[5px]\end{align} If, for example, a overhead power line with a diameter of 30 mm is flowed around with a wind speed of 15 m/s, this results in a vortex shedding frequency in the order of 100 Hz. Since these frequencies are in the audible range, this can be perceived as a low buzzing noise. Animation: Vortex shedding with a frequency of 100 Hz on a power line However, the periodic vortex shedding can sometimes bring a great danger. The structures around which the flow passes can begin to oscillate very strongly due to resonance if the vortex shedding frequency corresponds to the natural frequency of the structure. The famous collapse of the Tacoma Narrows Bridge in 1940 was attributed to such a phenomenon. Boundary layer theory explains how fluids behave near a solid surface, a concept thats critical to everything from airplane wings to water pipes. In mechanical engineering, this theory unlocks the secrets of friction, drag, and heat transfer, shaping how we design systems that interact with moving fluids. Its where the invisible meets the practical.This detailed guide dives into boundary layer theory, covering its foundations, behaviors, and engineering significance. Whether youre a student exploring fluid mechanics or an engineer refining a design, this resource will shed light on this essential topic.Boundary layer theory describes the thin region of fluid near a solid surface where viscosity dominates, slowing the flow compared to the freer-moving fluid farther away. Introduced by Ludwig Prandtl in 1904, it separates flow into two zones: the boundary layer, where friction matters, and the outer flow, where its negligible.This theory is vital for understanding how fluids stick to surfaces, affecting drag on vehicles or pressure drops in pipes. By analyzing this layer, engineers can predict and control fluid behavior in real-world systems.Boundary layer theory rests on several core elements that define its role in fluid mechanics. Below, we explore these building blocks that engineers use to master fluid-surface interactions.Laminar Boundary LayerIn a laminar boundary layer, fluid flows smoothly in parallel layers near the surface. Its thin and predictable, with low friction, making it common at lower speeds or over streamlined shapes like airfoils.Turbulent Boundary LayerA turbulent boundary layer features chaotic, swirling motion, thickening the layer and increasing friction. It occurs at higher velocities, impacting drag and heat transfer in systems like turbines or fast-moving vehicles.Boundary Layer ThicknessThe thickness of the boundary layer grows along a surface as fluid slows near it. Engineers measure this to assess drag and optimize designs, balancing efficiency with performance.Separation and TransitionBoundary layer separation happens when flow detaches from the surface, often causing drag or stalls. The transition from laminar to turbulent flow within the layer also affects system behavior, requiring careful analysis.Boundary layer theory is a game-changer in mechanical engineering, influencing designs where fluids meet solids. Its insights drive efficiency and innovation across industries.In aerodynamics, it minimizes drag on aircraft and cars by shaping surfaces to delay separation. In heat exchangers, turbulent boundary layers boost heat transfer. From pipelines to wind turbines, this theory helps engineers fine-tune systems for peak performance.Engineers study boundary layers using tools like wind tunnels, where flow visualization reveals laminar or turbulent patterns. Velocity profiles are measured with probes to map the layers growth and behavior near surfaces.Computational Fluid Dynamics (CFD) offers detailed simulations, predicting separation points and transition zones. These analyses help engineers reduce energy losses, enhance lift, and design smarter, more efficient systems.Boundary layer theory bridges the gap between fluid motion and solid surfaces, offering engineers a lens to optimize designs with precision. Its a cornerstone of fluid mechanics that turns complex flow into actionable solutions.As engineering pushes forward, this theory remains vital, guiding advancements in transportation, energy, and beyond. Understanding it equips engineers to harness fluid dynamics for a more efficient, innovative future.

What is boundary layer separation. Why boundary layer separation occurs. What is boundary layer in fluid mechanics. What is boundary layer theory in fluid mechanics.