

**Reynolds number**

In fluid mechanics, the Reynolds number (Re) is a dimensionless quantity that is used to help predict similar flow patterns in different fluid flow situations. The concept was introduced by Stokes in 1851, but the Reynolds number is named after Reynolds (1842–1912), who popularized its use in 1883.

The Reynolds number is defined to be the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. Reynolds numbers frequently arise when performing scaling of fluid dynamics problems, and as such can be used to determine dynamic similitude between two different cases of fluid flow. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow:

*laminar flow* occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion;

*turbulent flow* occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

In practice, matching the Reynolds number is not on its own sufficient to guarantee similitude. Fluid flow is generally chaotic, and very small changes to shape and surface roughness can result in very different flows. Nevertheless, Reynolds numbers are a very important guide and are widely used.

**Laminar flow**

Laminar flow (or streamline flow) occurs when a fluid flows in parallel layers, with no disruption between the layers. At low velocities the fluid tends to flow without lateral mixing, and adjacent layers slide past one another like playing cards (Fig 1). There are no cross currents perpendicular to the direction of flow, nor eddies or swirls of fluids. In laminar flow the motion of the particles of fluid is very orderly with all particles moving in straight lines parallel to the pipe walls. In fluid dynamics, laminar flow is a flow regime characterized by high momentum diffusion and low momentum convection.



**Fig 1.** The streamlines associated with laminar flow resemble a deck of cards. This flow profile of a fluid in a pipe shows that the fluid acts in layers and slides over one another.

When a fluid is flowing through a closed channel such as a pipe or between two flat plates, either of two types of flow may occur depending on the velocity of the fluid: laminar flow or turbulent flow. Laminar flow tends to occur at lower velocities, below the onset of turbulent flow. Turbulent flow is a less orderly flow regime that is characterized by eddies or small packets of fluid particles which result in lateral mixing. In nonscientific terms laminar flow is "smooth", while turbulent flow is "rough".

The type of flow occurring in a fluid in a channel is important in fluid dynamics problems. The dimensionless Reynolds number is an important parameter in the equations that describe whether flow conditions lead to laminar or turbulent flow. In the case of flow through a straight pipe with a circular cross-section, at a Reynolds number below the critical value of approximately 2040 fluid motion will ultimately be laminar, whereas at larger Reynolds number the flow can be turbulent. The Reynolds number delimiting laminar and turbulent flow depends on the particular flow geometry, and moreover, the transition from laminar flow to turbulence can be sensitive to disturbance levels and imperfections present in a given configuration.



**Fig 2.** In the case of a moving plate in a liquid, it is found that there is a layer or lamina which moves with the plate, and a layer which is essentially stationary if it is next to a stationary plate.

When the Reynolds number is much less than 1, *Creeping motion or Stokes flow occurs*. This is an extreme case of laminar flow where viscous (friction) effects are much greater than inertial forces. The common application of laminar flow would be in the smooth flow of a viscous liquid through a tube or pipe. In that case, the velocity of flow varies from zero at the walls to a maximum along the centerline of the vessel. The flow profile of laminar flow in a tube can be calculated by dividing the flow into thin cylindrical elements and applying the viscous force to them. For example, consider the flow of air over an aircraft wing. The boundary layer is a very thin sheet of air lying over the surface of the wing (and all other surfaces of the aircraft). Because air has viscosity, this layer of air tends to adhere to the wing. As the wing moves forward through the air, the boundary layer at first flows smoothly over the streamlined shape of the airfoil. Here the flow is called laminar and the boundary layer is a laminar layer.



**Fig 3.** An object moving through a gas or liquid experiences a force in direction opposite to its motion. Terminal velocity is achieved when the drag force is equal in magnitude but opposite in direction to the force propelling the object. Shown is a sphere in Stokes flow, at very low Reynolds number.

**Turbulent flow**

In fluid dynamics, turbulence or turbulent flow is a flow regime characterized by chaotic and suspectedly stochastic property changes. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time.

While there is no theorem relating the non-dimensional Reynolds number (Re) to turbulence, flows at Reynolds numbers larger than 5000 are typically (but not necessarily) turbulent, while those at low Reynolds numbers usually remain laminar. In Poiseuille flow, for example, turbulence can first be sustained if the Reynolds number is larger than a critical value of about 2040; moreover, the turbulence is generally interspersed with laminar flow until a larger Reynolds number of about 4000.

In turbulent flow, unsteady vortices appear on many scales and interact with each other. Drag due to boundary layer skin friction increases. The structure and location of boundary layer separation often changes, sometimes resulting in a reduction of overall drag. Although laminar-turbulent transition is not governed by Reynolds number, the same transition occurs if the size of the object is gradually increased, or the viscosity of the fluid is decreased, or if the density of the fluid is increased.



Flow visualization of a turbulent jet. The jet exhibits a wide range of length scales, an important characteristic of turbulent flows.

Turbulence is highly characterized by the following features:

• Irregularity: Turbulent flows are always highly irregular. This is why turbulence problems are always treated statistically rather than deterministically. Turbulent flow is always chaotic but not all chaotic flows are turbulent.

• Diffusivity: The readily available supply of energy in turbulent flows tends to accelerate the homogenization (mixing) of fluid mixtures. The characteristic which is responsible for the enhanced mixing and increased rates of mass, momentum and energy transports in a flow is called "diffusivity".

• Dissipation: To sustain turbulent flow, a persistent source of energy supply is required because turbulence dissipates rapidly as the kinetic energy is converted into internal energy by viscous shear stress.

• Energy cascade: Turbulent flow can be realized as a superposition of a spectrum of velocity fluctuations and eddies upon a mean flow. The eddies are loosely defined as coherent patterns of velocity, vorticity and pressure. Turbulent flows may be viewed as made of an entire hierarchy of eddies over a wide range of length scales and the hierarchy can be described by the energy spectrum that measures the energy in velocity fluctuations for each wave number. The scales in the energy cascade are generally uncontrollable and highly non-symmetric. Nevertheless, based on these length scales these eddies can be divided into three categories.

• Integral length scales: Largest scales in the energy spectrum. These eddies obtain energy from the mean flow and also from each other. Thus these are the energy production eddies which contain the most of the energy. They have the large velocity fluctuation and are low in frequency. Integral scales are highly anisotropic and are defined in terms of the normalized two-point velocity correlations. The maximum length of these scales is constrained by the characteristic length of the apparatus. For example, the largest integral length scale of pipe flow is equal to the pipe diameter. In the case of atmospheric turbulence, this length can reach up to the order of several hundreds kilometers.

• Kolmogorov length scales: Smallest scales in the spectrum that form the viscous sub-layer range. In this range, the energy input from nonlinear interactions and the energy drain from viscous dissipation are in exact balance. The small scales are in high frequency which is why turbulence is locally isotropic and homogeneous.

• Taylor microscales: The intermediate scales between the largest and the smallest scales which make the inertial subrange. Taylor micro-scales are not dissipative scale but passes down the energy from the largest to the smallest without dissipation. Some literatures do not consider Taylor micro-scales as a characteristic length scale and consider the energy cascade contains only the largest and smallest scales; while the latter accommodate both the inertial sub-range and the viscous-sub layer. Nevertheless, Taylor micro-scales is often used in describing the term “turbulence” more conveniently as these Taylor micro-scales play a dominant role in energy and momentum transfer in the wavenumber space.

Turbulence causes the formation of eddies of many different length scales. Most of the kinetic energy of the turbulent motion is contained in the large-scale structures. The energy "cascades" from these large-scale structures to smaller scale structures by an inertial and essentially inviscid mechanism. This process continues, creating smaller and smaller structures which produces a hierarchy of eddies. Eventually this process creates structures that are small enough that molecular diffusion becomes important and viscous dissipation of energy finally takes place. The scale at which this happens is the Kolmogorov length scale.

Although it is possible to find some particular solutions of the Navier-Stokes equations governing fluid motion, all such solutions are unstable to finite perturbations at large Reynolds numbers. Sensitive dependence on the initial and boundary conditions makes fluid flow irregular both in time and in space so that a statistical description is needed. Kolmogorov proposed the first statistical theory of turbulence, based on the aforementioned notion of the energy cascade (an idea originally introduced by Richardson) and the concept of self-similarity. As a result, the Kolmogorov microscales were named after him. It is now known that the self-similarity is broken so the statistical description is presently modified.















