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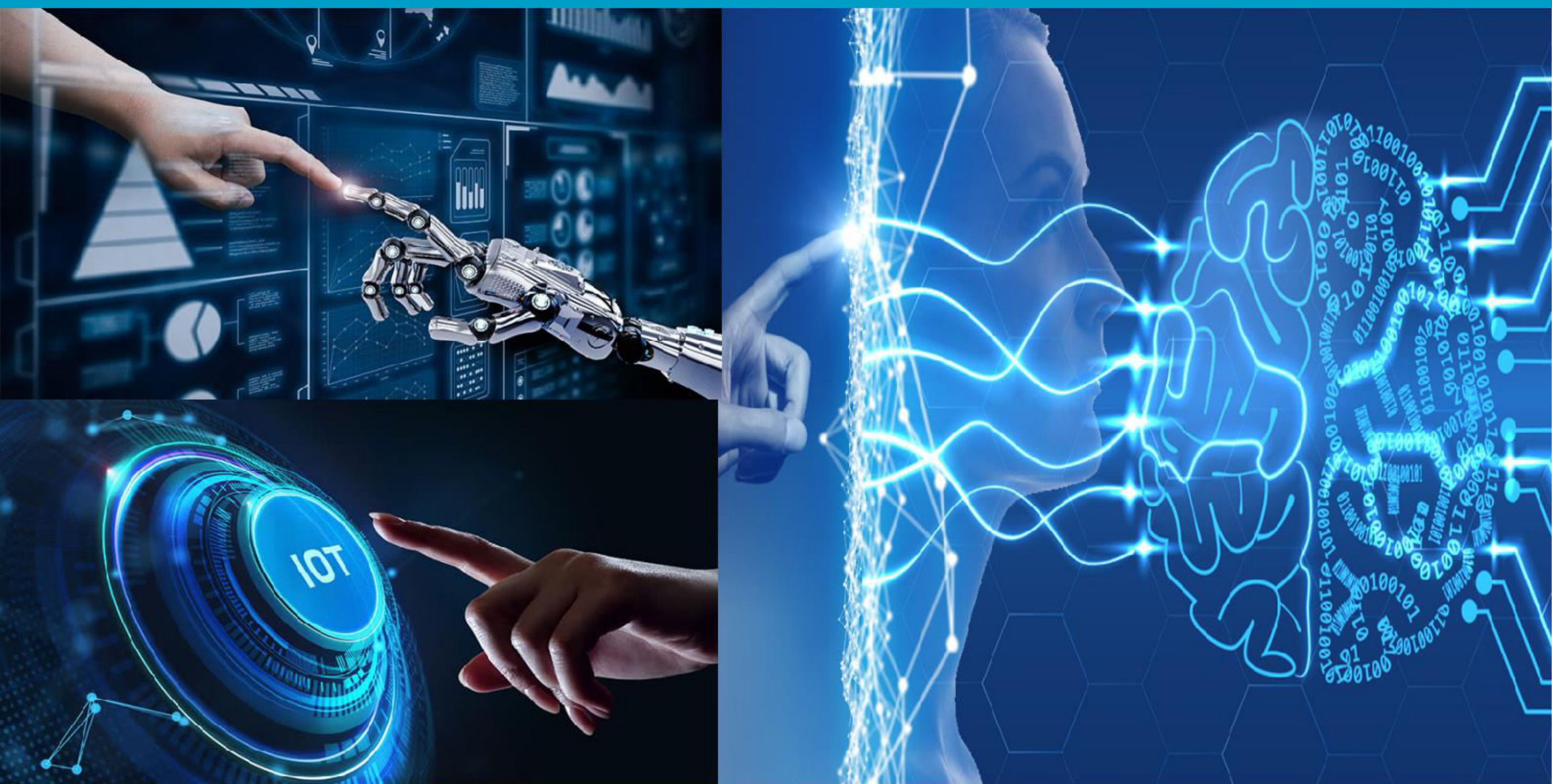

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An Analysis on the Propagation of Turbulent Flow

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ABSTRACT: In Fluid Dynamics, a turbulent flow refers to an irregular flow in which eddies, whirlpools, and flow instabilities occur. It is governed by high-momentum convection and low-momentum diffusion. It is in contrast to the laminar regime, which occurs when a fluid flows in parallel layers with no disruption between the layers. The turbulence regime is extremely frequent in natural phenomena and engineering applications; some examples are the rise of cigarette smoke, waterfalls, blood flow in arteries, and most of the terrestrial atmospheric recirculation.In terms of engineering applications, the turbulent regime occurs in the aerodynamics of all vehicles such as cars, planes, and ships; but also, in many industrial applications such as heat exchangers, quenching processes, or continuous casting of steel.turbulent flow, type of fluid (gas or liquid) flow in which the fluid undergoes irregular fluctuations, or mixing, in contrast to laminar flow, in which the fluid moves in smooth paths or layers. In turbulent flow the speed of the fluid at a point is continuously undergoing changes in both magnitude and direction.

KEYWORDS: Fluid, turbulent, flow, eddies, diffusion.

I. STRUCTURE OF TURBULENT FLOW

In 1920, Lewis Fry Richardson summarized his works about the structure of turbulence for meteorological applications through a celebrated rhyme published in Weather Prediction by Numerical Process1:

Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity.

This principle was motivated by energetical considerations; big eddies are highly inertial and tend to be unstable. Their motion feeds smaller eddies thanks to a local transfer of kinetic energy. These smaller eddies undergo the same process, giving rise to even smaller eddies that inherit the energy of their parent eddy, and so on.

This transfer of energy is usually called energy cascade and it is mainly inertial, thus almost no energy dissipation occurs until reaching a sufficiently small length scale such that the viscosity of the fluid can effectively dissipate the kinetic energy. This process has been depicted in Figure 1.

Richardson’s studies highlight an essential feature of turbulent flows: they are energy-demanding. A turbulent flow will dissipate energy and decay to a laminar flow at the smallest scales unless it is fed by an external source of energy.

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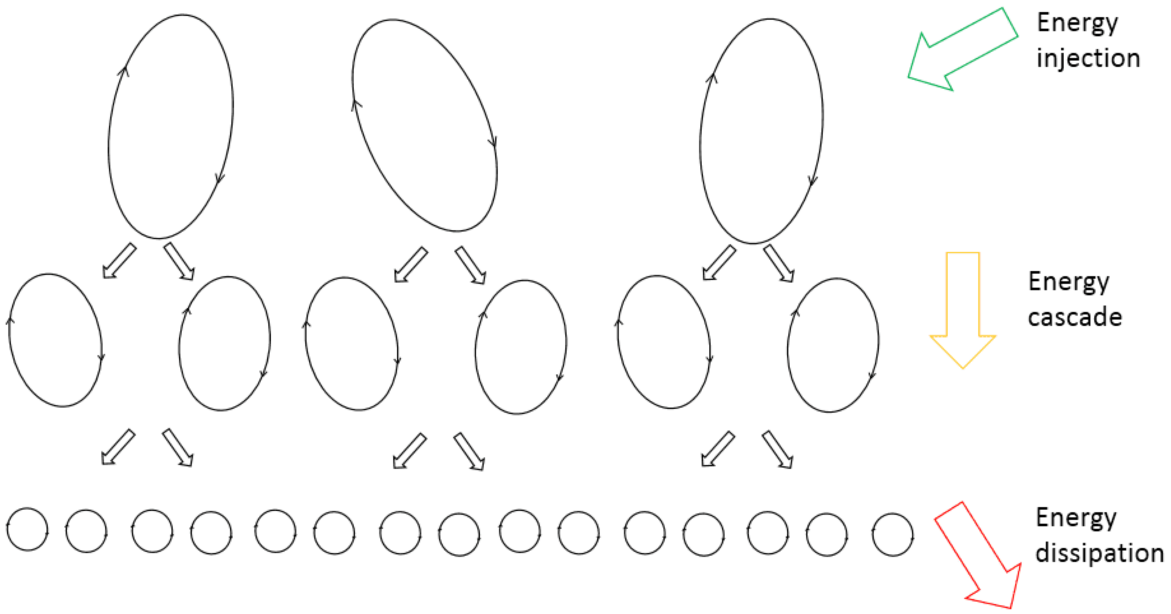

Figure 1

Richardson's energy cascade shows the disintegration of parent eddies into successive smaller eddies until energy dissipation occurs.

II. INTRODUCTION

In fluid dynamics, turbulence or turbulent flow is fluid motion characterized by chaotic changes in pressure and flow velocity. It is in contrast to a laminar flow, which occurs when a fluid flows in parallel layers, with no disruption between those layers.[1]

Turbulence is commonly observed in everyday phenomena such as surf, fast flowing rivers, billowing storm clouds, or smoke from a chimney, and most fluid flows occurring in nature or created in engineering applications are turbulent.[2][3]:2 Turbulence is caused by excessive kinetic energy in parts of a fluid flow, which overcomes the damping effect of the fluid's viscosity. For this reason, turbulence is commonly realized in low viscosity fluids. In general terms, in turbulent flow, unsteady vortices appear of many sizes which interact with each other, consequently drag due to friction effects increases. This increases the energy needed to pump fluid through a pipe.

The onset of turbulence can be predicted by the dimensionless Reynolds number, the ratio of kinetic energy to viscous damping in a fluid flow. However, turbulence has long resisted detailed physical analysis, and the interactions within turbulence create a very complex phenomenon. Richard Feynman described turbulence as the most important unsolved problem in classical physics.

The turbulence intensity affects many fields, for examples fish ecology, air pollution, precipitation and climate change.

Examples of turbulence

1. Laminar and turbulent water flow over the hull of a submarine. As the relative velocity of the water increases turbulence occurs.

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2. Turbulence in the tip vortex from an airplane wing passing through coloured smoke
3. Smoke rising from a cigarette. For the first few centimeters, the smoke is laminar. The smoke plume becomes turbulent as its Reynolds number increases with increases in flow velocity and characteristic length scale.
4. Flow over a golf ball. (This can be best understood by considering the golf ball to be stationary, with air flowing over it.) If the golf ball were smooth, the boundary layer flow over the front of the sphere would be laminar at typical conditions. However, the boundary layer would separate early, as the pressure gradient switched from favorable (pressure decreasing in the flow direction) to unfavorable (pressure increasing in the flow direction), creating a large region of low pressure behind the ball that creates high form drag. To prevent this, the surface is dimpled to perturb the boundary layer and promote turbulence. This results in higher skin friction, but it moves the point of boundary layer separation further along, resulting in lower drag.
5. Clear-air turbulence experienced during airplane flight, as well as poor astronomical seeing (the blurring of images seen through the atmosphere).
6. Most of the terrestrial atmospheric circulation.
7. The oceanic and atmospheric mixed layers and intense oceanic currents.
8. The flow conditions in many industrial equipment (such as pipes, ducts, precipitators, gas scrubbers, dynamic scraped surface heat exchangers, etc.) and machines (for instance, internal combustion engines and gas turbines).
9. The external flow over all kinds of vehicles such as cars, airplanes, ships, and submarines.
10. The motions of matter in stellar atmospheres.
11. A jet exhausting from a nozzle into a quiescent fluid. As the flow emerges into this external fluid, shear layers originating at the lips of the nozzle are created. These layers separate the fast moving jet from the external fluid, and at a certain critical Reynolds number they become unstable and break down to turbulence.
12. Biologically generated turbulence resulting from swimming animals affects ocean mixing.
13. Snow fences work by inducing turbulence in the wind, forcing it to drop much of its snow load near the fence.
14. Bridge supports (piers) in water. When river flow is slow, water flows smoothly around the support legs. When the flow is faster, a higher Reynolds number is associated with the flow. The flow may start off laminar but is quickly separated from the leg and becomes turbulent.
15. In many geophysical flows (rivers, atmospheric boundary layer), the flow turbulence is dominated by the coherent structures and turbulent events. A turbulent event is a series of turbulent fluctuations that contain more energy than the average flow turbulence. The turbulent events are associated with coherent flow structures such as eddies and turbulent bursting, and they play a critical role in terms of sediment scour, accretion and transport in rivers as well as contaminant mixing and dispersion in rivers and estuaries, and in the atmosphere.

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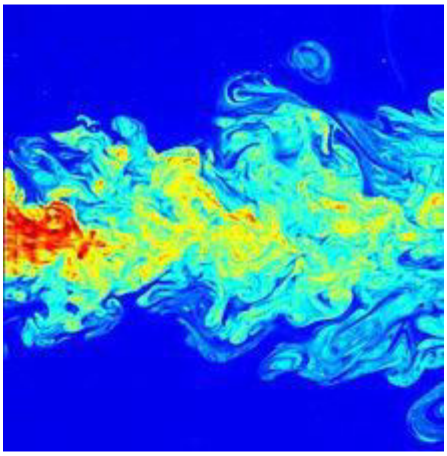
Features



Flow visualization of a turbulent jet, made by laser-induced fluorescence. The jet exhibits a wide range of length scales, an important characteristic of turbulent flows.

Turbulence is characterized by the following features:

Irregularity
Turbulent flows are always highly irregular. For this reason, turbulence problems are normally treated statistically rather than deterministically. Turbulent flow is chaotic. However, 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.

Turbulent diffusion is usually described by a turbulent diffusion coefficient. This turbulent diffusion coefficient is defined in a phenomenological sense, by analogy with the molecular diffusivities, but it does not have a true physical meaning, being dependent on the flow conditions, and not a property of the fluid itself. In addition, the turbulent diffusivity concept assumes a constitutive relation between a turbulent flux and the gradient of a mean variable similar to the relation between flux and gradient that exists for molecular transport. In the best case, this assumption is only an approximation. Nevertheless, the turbulent diffusivity is the simplest approach for quantitative analysis of turbulent flows, and many models have been postulated to calculate it. For instance, in large bodies of water like oceans this coefficient can be found using Richardson's four-third power law and is governed by the random walk principle. In rivers and large ocean currents, the diffusion coefficient is given by variations of Elder's formula.

Rotationality

Turbulent flows have non-zero vorticity and are characterized by a strong three-dimensional vortex generation mechanism known as vortex stretching. In fluid dynamics, they are essentially vortices subjected to stretching associated with a corresponding increase of the component of vorticity in the stretching direction—due to the conservation of angular momentum. On the other hand, vortex stretching is the core mechanism on which the turbulence energy cascade relies to establish and maintain identifiable structure function.

In general, the stretching mechanism implies thinning of the vortices in the direction perpendicular to the stretching direction due to volume conservation of fluid elements. As a result, the radial length scale of the vortices decreases and the larger flow structures break down into smaller structures. The process continues until the small scale structures are small enough that their kinetic energy can be transformed by the fluid's molecular viscosity into heat. Turbulent flow is always rotational and three dimensional.For example, atmospheric cyclones are rotational but their substantially two-dimensional shapes do not allow vortex generation and so are not turbulent. On the other hand, oceanic flows are dispersive but essentially non rotational and therefore are not turbulent.

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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. 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.

Via this energy cascade, turbulent flow can be realized as a superposition of a spectrum of flow velocity fluctuations and eddies upon a mean flow. The eddies are loosely defined as coherent patterns of flow 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 flow velocity fluctuations for each length scale (wavenumber). 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.

The Onset of Turbulence

The onset of turbulence can be, to some extent, predicted by the Reynolds number, which is the ratio of inertial forces to viscous forces within a fluid which is subject to relative internal movement due to different fluid velocities, in what is known as a boundary layer in the case of a bounding surface such as the interior of a pipe. A similar effect is created by the introduction of a stream of higher velocity fluid, such as the hot gases from a flame in air. This relative movement generates fluid friction, which is a factor in developing turbulent flow. Counteracting this effect is the viscosity of the fluid, which as it increases, progressively inhibits turbulence, as more kinetic energy is absorbed by a more viscous fluid. The Reynolds number quantifies the relative importance of these two types of forces for given flow conditions, and is a guide to when turbulent flow will occur in a particular situation.

This ability to predict the onset of turbulent flow is an important design tool for equipment such as piping systems or aircraft wings, but the Reynolds number is also used in scaling of Fluid Dynamics problems, and is used to determine dynamic similitude between two different cases of fluid flow, such as between a model aircraft, and its full size version. Such scaling is not always linear and the application of Reynolds numbers to both situations allow scaling factors to be developed. A flow situation in which the kinetic energy is significantly absorbed due to the action of fluid molecular viscosity gives rise to a laminar flow regime. For this the dimensionless quantity the Reynolds number (Re) is used as a guide.

With respect to laminar and turbulent flow regimes:

- 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.

The Reynolds number is defined as

$$R_e = \frac{\rho v L}{\mu}$$

where:

- ρ is the density of the fluid (SI units: kg/m^3)
- v is a characteristic velocity of the fluid with respect to the object (m/s)
- L is a characteristic linear dimension (m)
- μ is the dynamic viscosity of the fluid (Pa·s or N·s/m^2 or kg/(m·s)).

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While there is no theorem directly relating the non-dimensional Reynolds number 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;[24] moreover, the turbulence is generally interspersed with laminar flow until a larger Reynolds number of about 4000.

The 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.

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