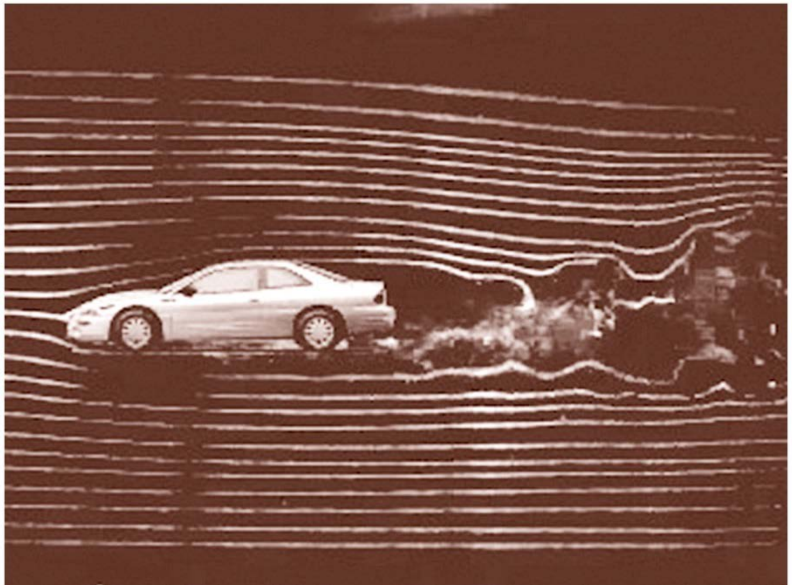
Chapter 8

Origin of Turbulence and Turbulent Shear Stress



Chapter 8 Origin of Turbulence and Turbulent Shear Stress

Contents

8.1 Introduction

8.2 Sources of Turbulence

8.3 Velocities, Energies, and Continuity in Turbulence

8.4 Turbulent Shear Stress and Eddy Viscosities

8.5 Reynolds Equations for Incompressible Fluids

8.6 Mixing Length and Similarity Hypotheses in Shear flow

Objectives

- Learn fundamental concept of turbulence
- Study Reynolds decomposition
- Derive Reynolds equation from Navier-Stokes equation
- Study eddy viscosity model and mixing length model

8.1 Introduction

8.1.1 Origin of turbulence

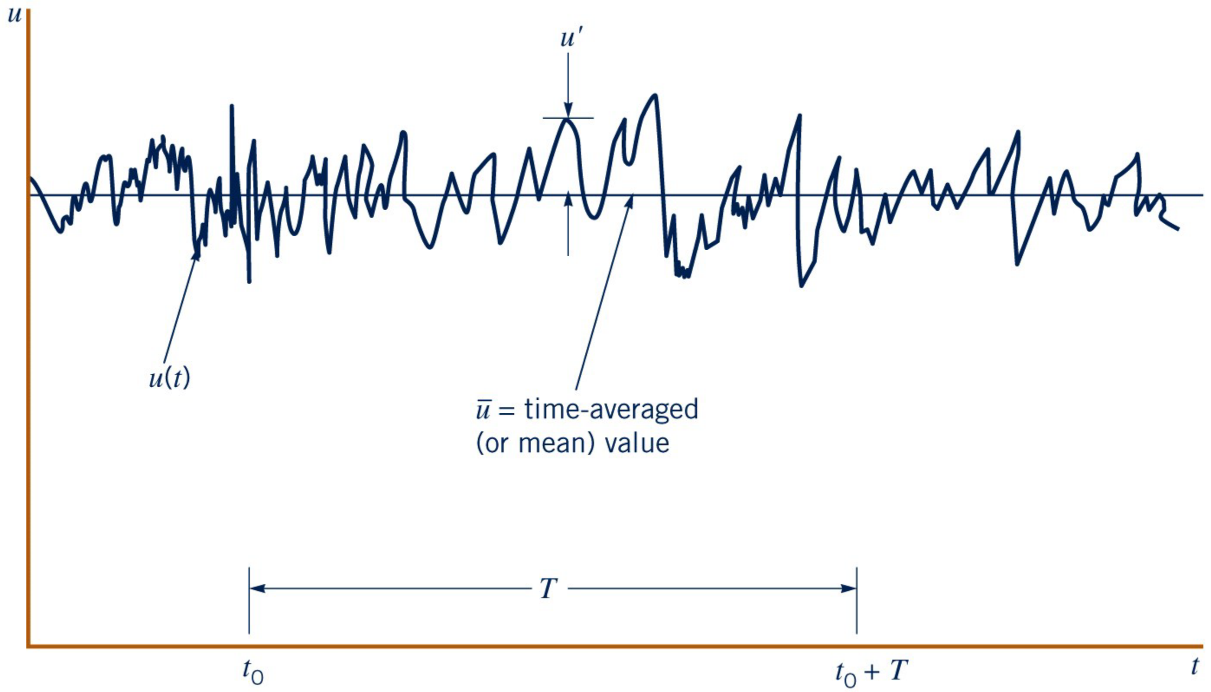
- Hinze (1975): Turbulent fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned.

statistically distinct average values: mean flow, primary motion

random fluctuations: non-periodic, secondary motion, instantaneously unsteady, varies w.r.t. time and space

$$u = \bar{u} + u'$$

8.1 Introduction

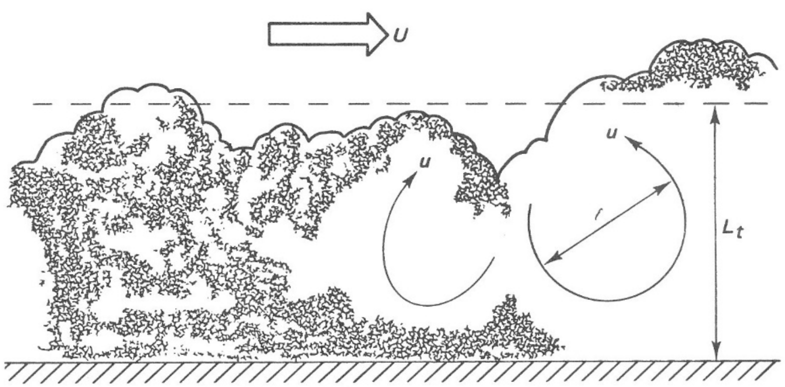


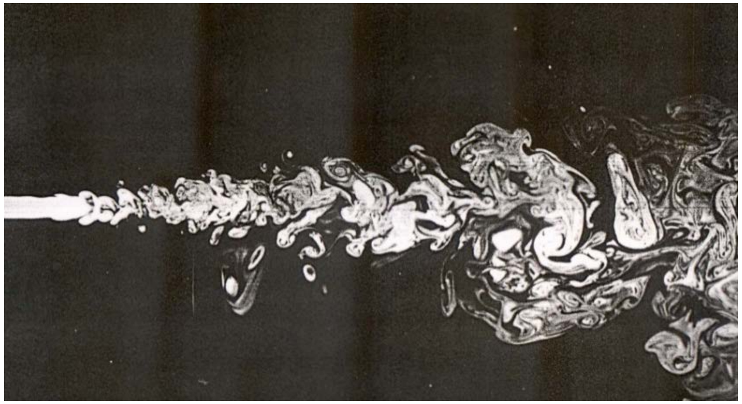
8.1 Introduction

- **Types of turbulence**

Wall turbulence: turbulence generated and continuously affected by actual physical boundary such as solid walls → Ch. 9

Free turbulence: absence of direct effect of walls, turbulent jet → AEH II

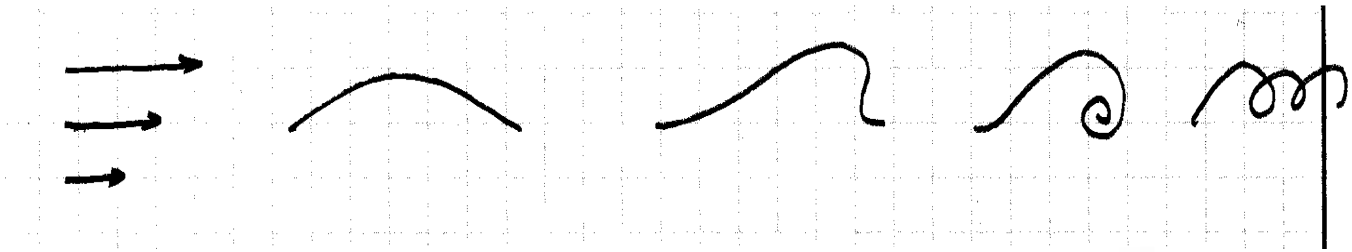


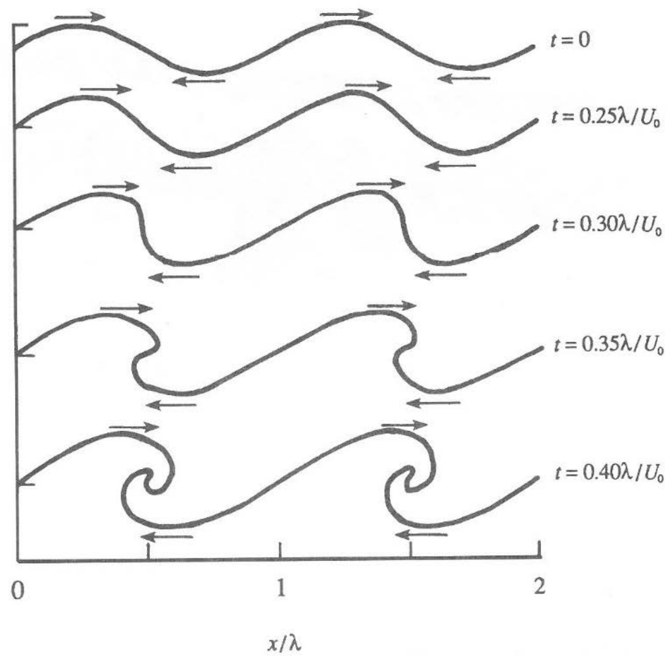


8.1 Introduction

- **Origin of turbulence**

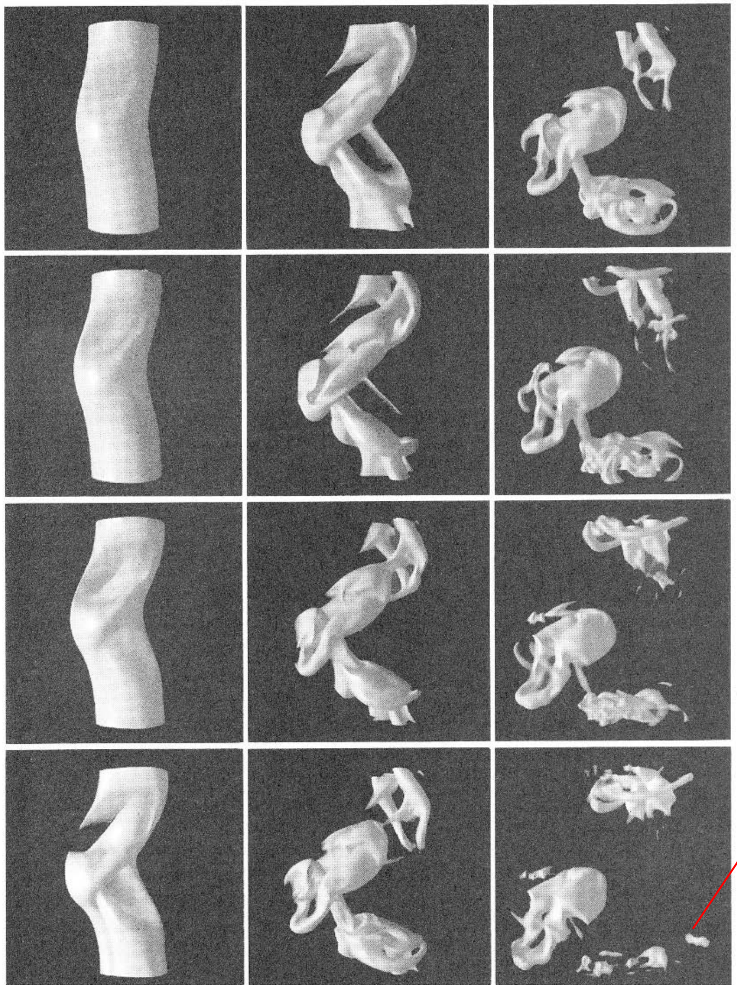
  (1) Shear flow instability





8.1 Introduction

vortex stretching,
folding,
sheetification

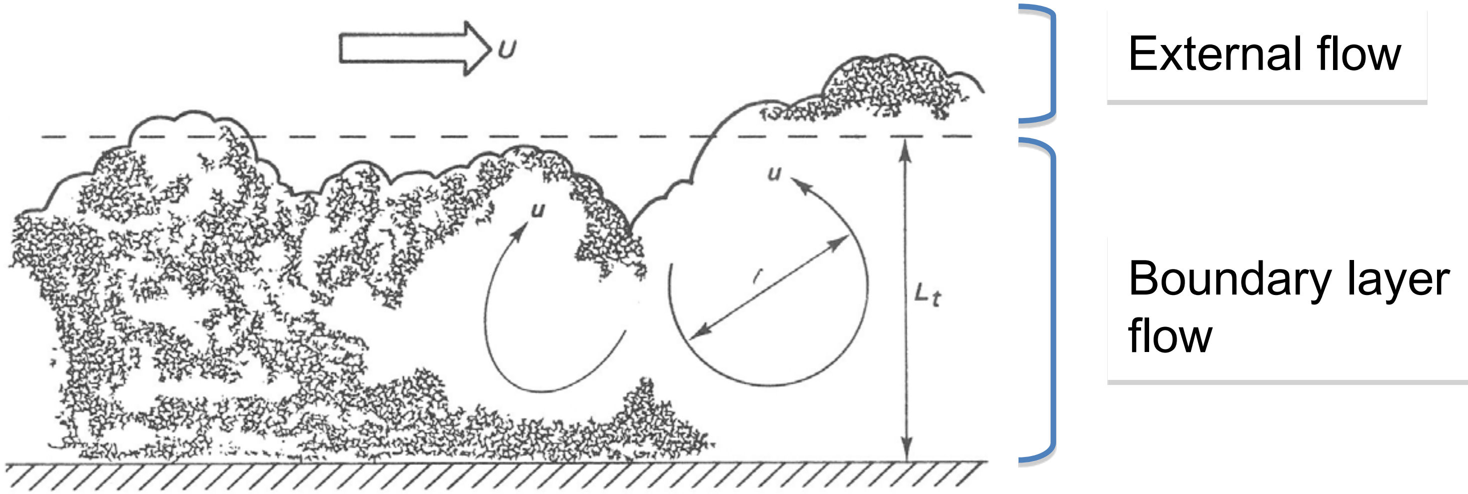


Smaller size vortex

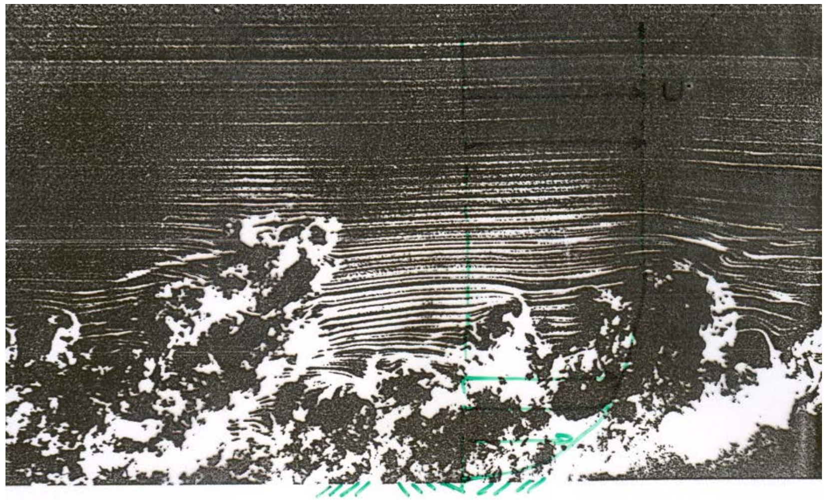
8.1 Introduction

(2) Boundary-wall-generated turbulence

~ wall turbulence



8.1 Introduction



Outer zone

Boundary layer

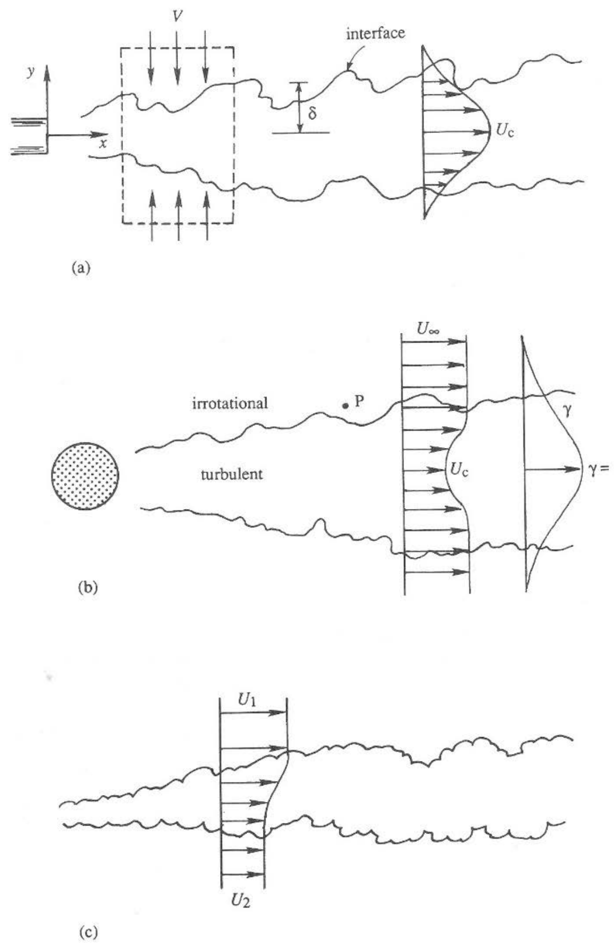
157. Side view of a turbulent boundary layer. Here a turbulent boundary layer develops naturally on a flat plate 3.3 m long suspended in a wind tunnel. Streaklines from a smoke wire near the sharp leading edge are illuminated by a vertical slice of light. The Reynolds number is 3500 based on the momentum thickness. The intermittent nature of the outer part of the layer is evident. *Photograph by Thomas Corke, Y. Guezennec, and Hassan Nagib.*

158. Turbulent boundary layer on a wall. A fog of tiny oil droplets is introduced into the laminar boundary layer on the test-section floor of a wind tunnel, and the layer then tripped to become turbulent. A vertical sheet of light shows the flow pattern 5.8 m downstream, where the Reynolds number based on momentum thickness is about 4000. *Falco 1977*

8.1 Introduction

(3) Free-shear-layer-generated turbulence

~ free turbulence



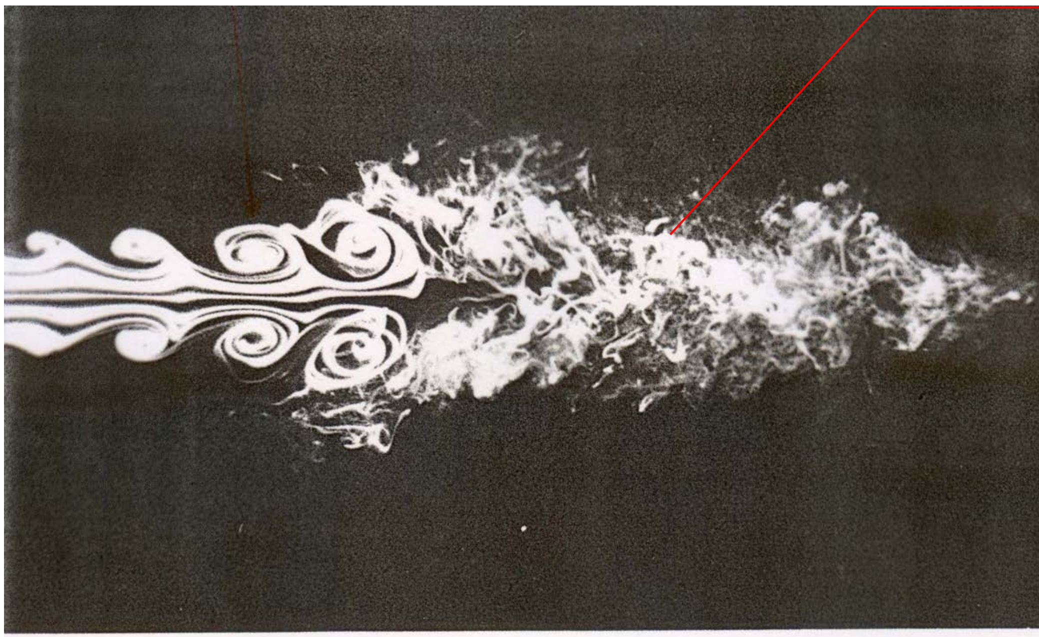
Jet

Wake

Shear layer

8.1 Introduction

Turbulent jet

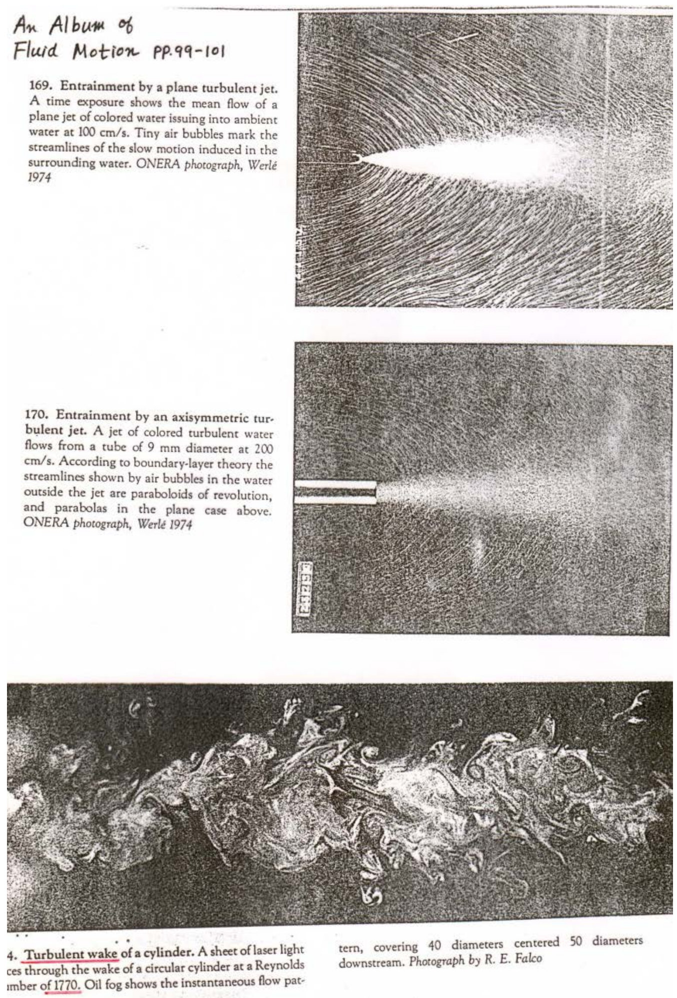


102. Instability of an axisymmetric jet. A laminar stream of air flows from a circular tube at Reynolds number 10,000 and is made visible by a smoke wire. The edge of the jet develops axisymmetric oscillations, rolls up into vortex rings, and then abruptly becomes turbulent. *Photograph by Robert Drubka and Hassan Nagib*

8.1 Introduction

. **Turbulent water jet.** Laser-induced fluorescence ws the concentration of jet fluid in the plane of symmetry of an axisymmetric jet of water directed downward water. The Reynolds number is approximately 2300. The spatial resolution is adequate to resolve the Kolmogorov scale in the downstream half of the photograph *Dimotakis, Lye & Papantoniou 1981*

8.1 Introduction



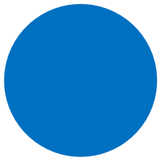
An Album of Fluid Motion pp.99-101

169. **Entrainment by a plane turbulent jet.** A time exposure shows the mean flow of a plane jet of colored water issuing into ambient water at 100 cm/s. Tiny air bubbles mark the streamlines of the slow motion induced in the surrounding water. *ONERA photograph, Werlé 1974*

170. **Entrainment by an axisymmetric turbulent jet.** A jet of colored turbulent water flows from a tube of 9 mm diameter at 200 cm/s. According to boundary-layer theory the streamlines shown by air bubbles in the water outside the jet are paraboloids of revolution, and parabolas in the plane case above. *ONERA photograph, Werlé 1974*

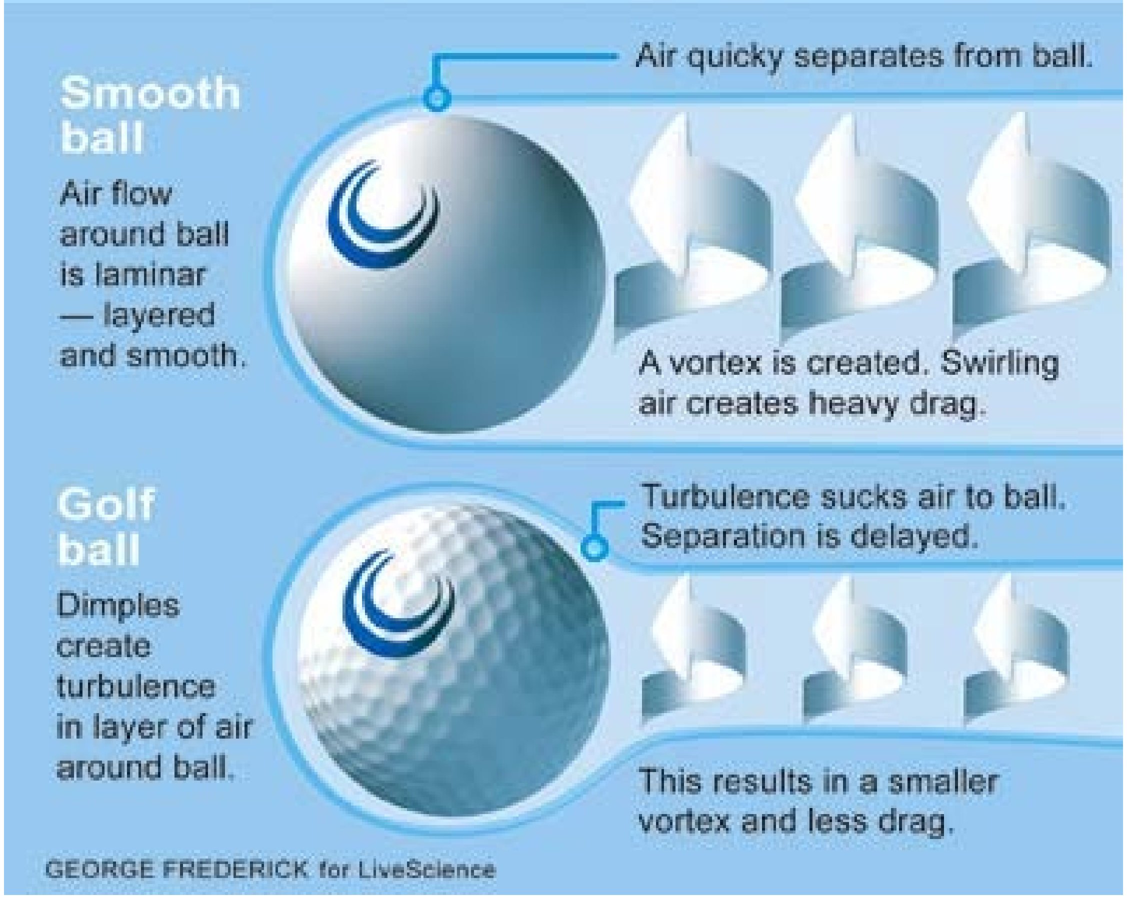
4. **Turbulent wake of a cylinder.** A sheet of laser light ces through the wake of a circular cylinder at a Reynolds imber of 1770. Oil fog shows the instantaneous flow pattern, covering 40 diameters centered 50 diameters downstream. *Photograph by R. E. Falco*

Turbulent jet



Wake behind the cylinder

8.1 Introduction



8.1 Introduction

8.1.2 Nature of turbulence

(1) Irregularity

~ randomness - small scale eddies

~ need to use statistical methods to turbulence problems

~ Turbulent motion can also be described by Navier-Stokes Eq.

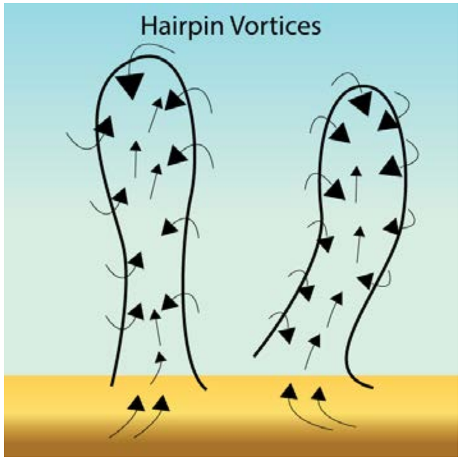
[Cf] coherent structure 상관구조

~ large scale eddies

~ interact with mean flows

~ correlated each other with time and space

~ ordered motion



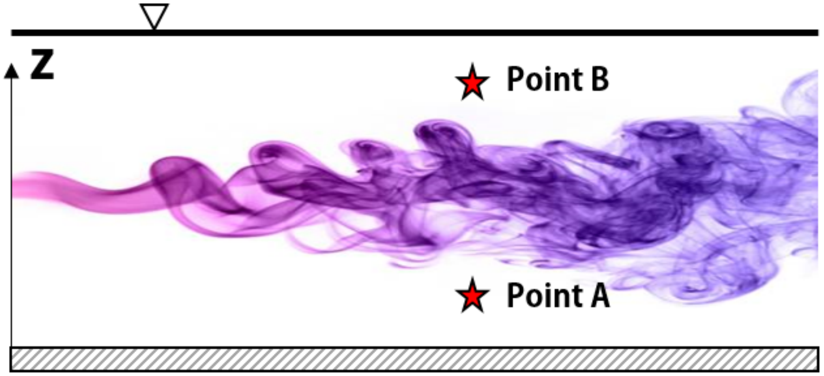
8.1 Introduction

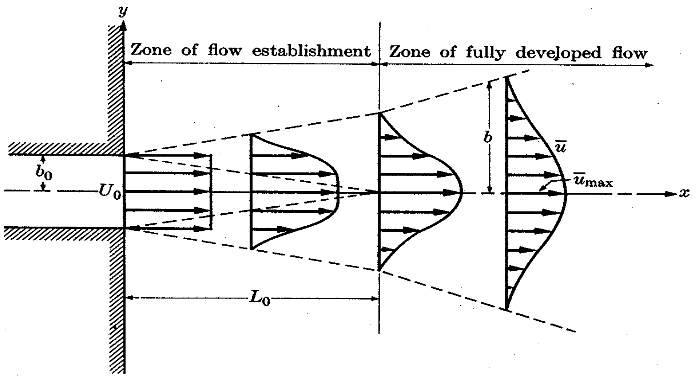
(2) Diffusivity

~ causes rapid mixing and increased rates of momentum, heat, and mass transfer

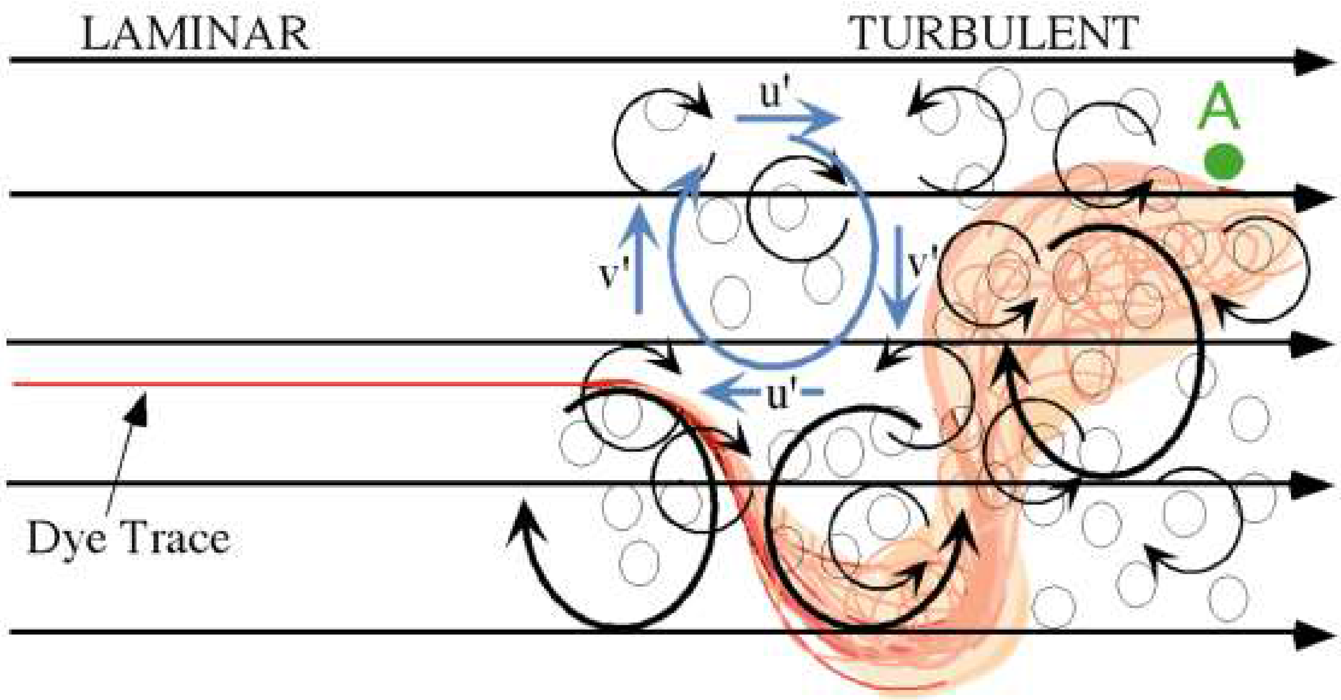
~ exhibit spreading of velocity fluctuations through surrounding fluid

~ the most important feature as far as practical applications are concerned; it increases heat transfer rates in machinery, it increases mass transfer in water





8.1 Introduction



8.1 Introduction

(3) Large Reynolds numbers

~ occur at high Reynolds numbers

~ Turbulence originates as an instability of laminar flows if *Re* becomes too large.

pipe flow $\mathrm{Re}_c = 2{,}100$

boundary layer $\mathrm{Re}_c = \dfrac{U\delta^*}{\nu} = 600$

2D sheet flow $\mathrm{Re}_c = \dfrac{Vy_0}{\nu} = 500$

8.1 Introduction

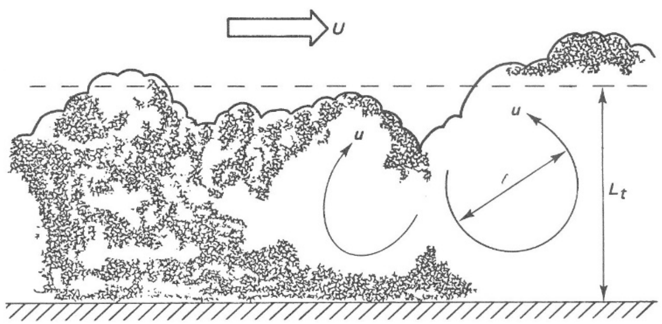
(4) Three-dimensional vorticity fluctuations

~ Turbulence is rotational and three-dimensional.

~ high levels of fluctuating vorticity

~ need to use vorticity dynamics

~ small eddies tend to be isotropic

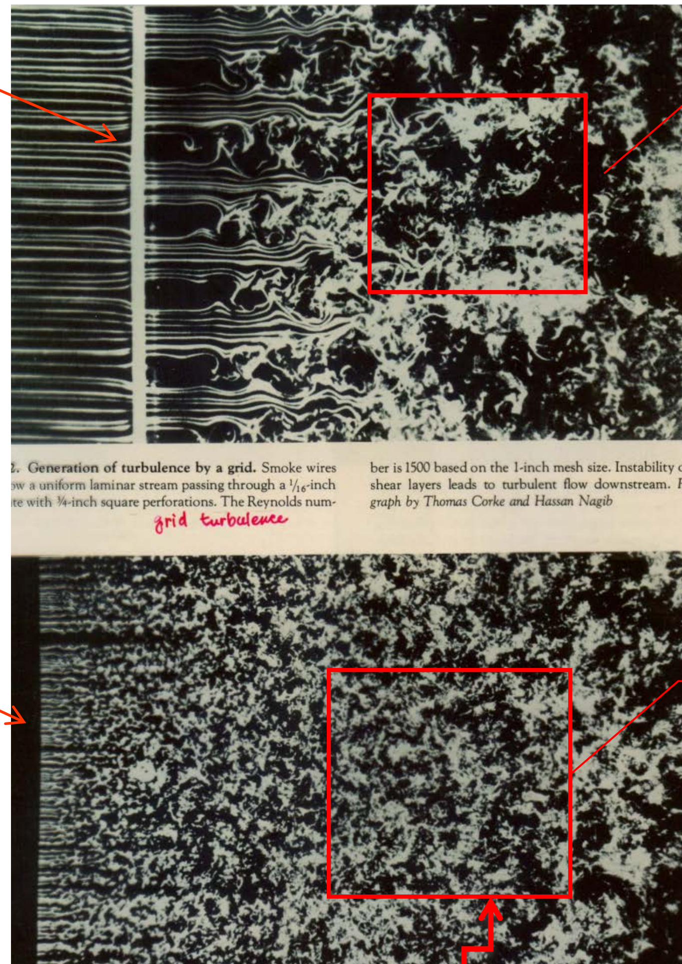


[Cf] The 2-D flows like cyclones, random (irrotational) waves in the ocean are not turbulent motions.

8.1 Introduction

Coarse grid

Fine grid



Non-isotropic turbulence

Isotropic turbulence

8.1 Introduction

(5) Dissipations

~ deformation work increases the internal energy of the fluid while dissipating kinetic energy of the turbulence

~ needs a continuous supply of energy to make up for viscous losses.

~ main energy supply comes from mean flow by interaction of shear stress and velocity gradient

~ If no energy is supplied, turbulence decays rapidly.

~ random motions that have insignificant viscous losses such as random sound waves are not turbulent

[Re] *Energy cascade*

main flow → large scale turbulence → small scale turbulence→ heat

8.1 Introduction

(6) Continuum

~ continuum phenomenon

~ governed by the equation of fluid mechanics: Navier-Stokes Eq. + Continuity Eq.

~ larger than any molecular length scale

(7) Flow feature

~ feature of fluid flows not fluid itself

~ Most of the dynamics of turbulence is the same in all fluids.

~ Major characteristics of turbulent flows are not controlled by the molecular properties of the fluid.