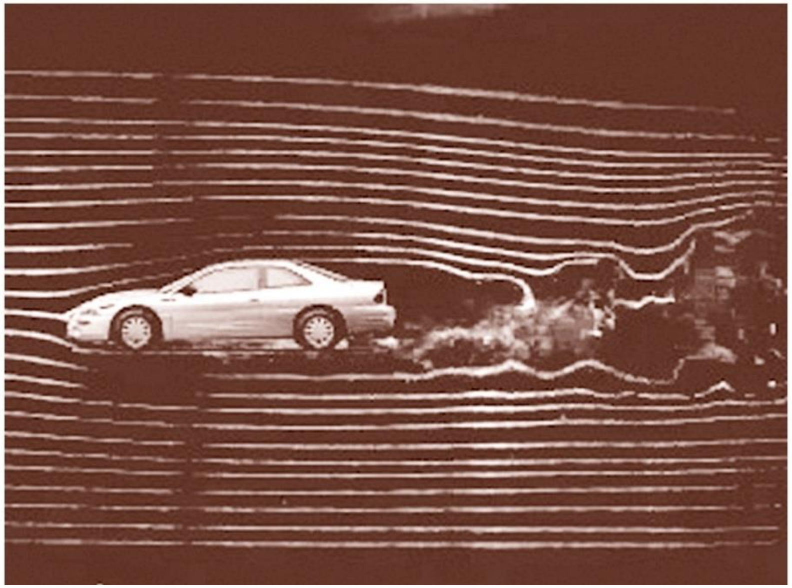
Lecture 18

Origin of Turbulence (1)



Lecture 18 Origin of Turbulence (1)

Contents

18.1 Introduction

Objectives

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

18.1 Introduction

18.1.1 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

$$u = \bar{u} + u' \tag{18.1}$$

$$\bar{u} = \frac{1}{T}\int_0^T u\,dt \tag{18.2}$$

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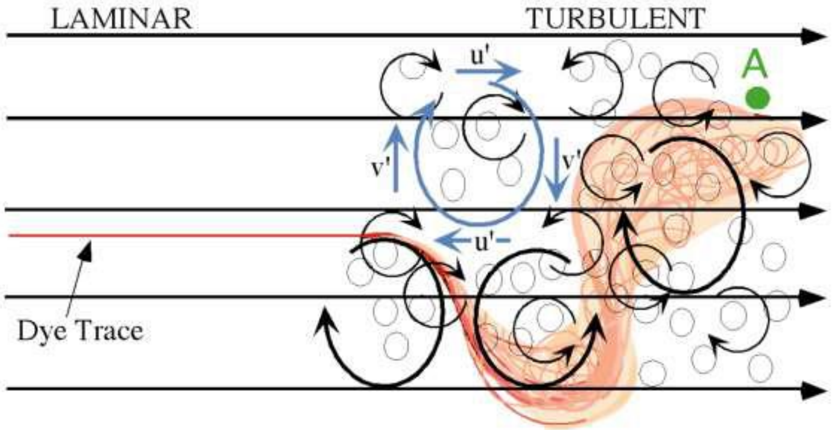
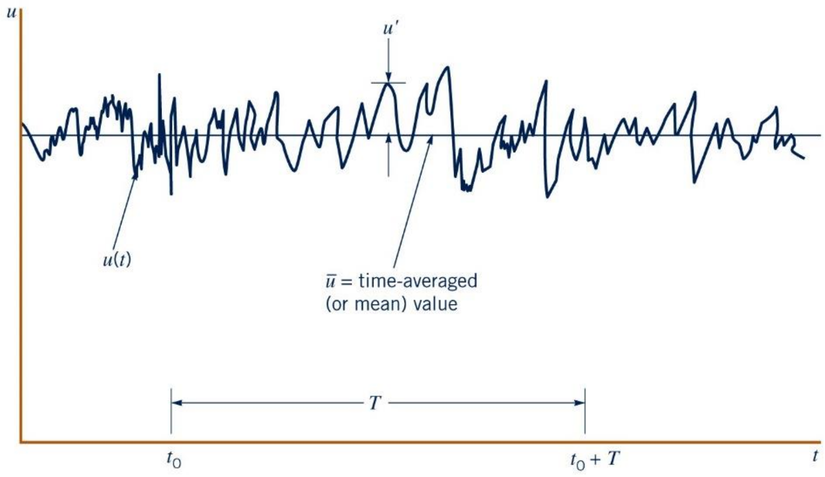


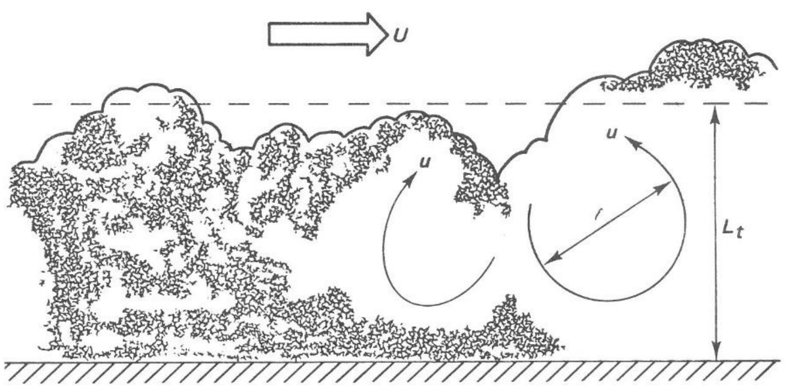


18.1 Introduction

- **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



18.1 Introduction

- **Source of turbulence**

(1) Surface of flow discontinuity

- sharp jump in velocity between two adjacent layers

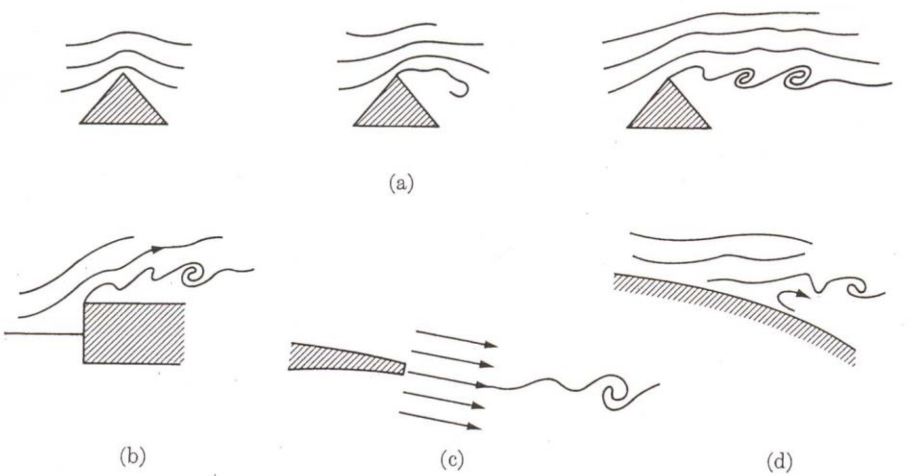


FIG. 11–1. Eddy formation at velocity discontinuity surfaces: (a) sharp projection; (b) bluff body; (c) trailing edge; (d) boundary-layer separation.

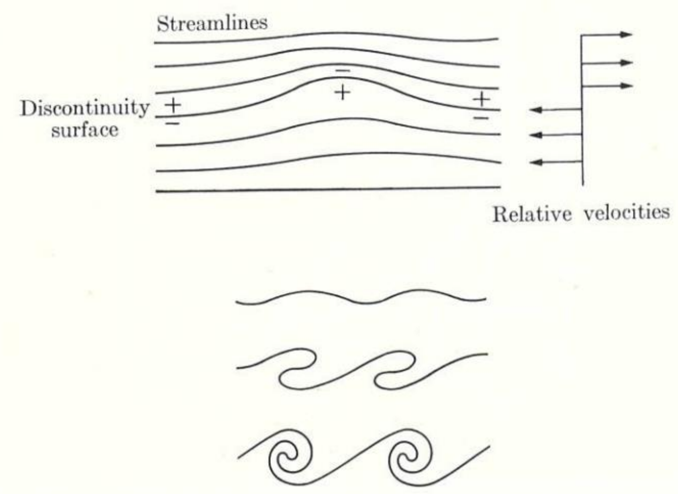
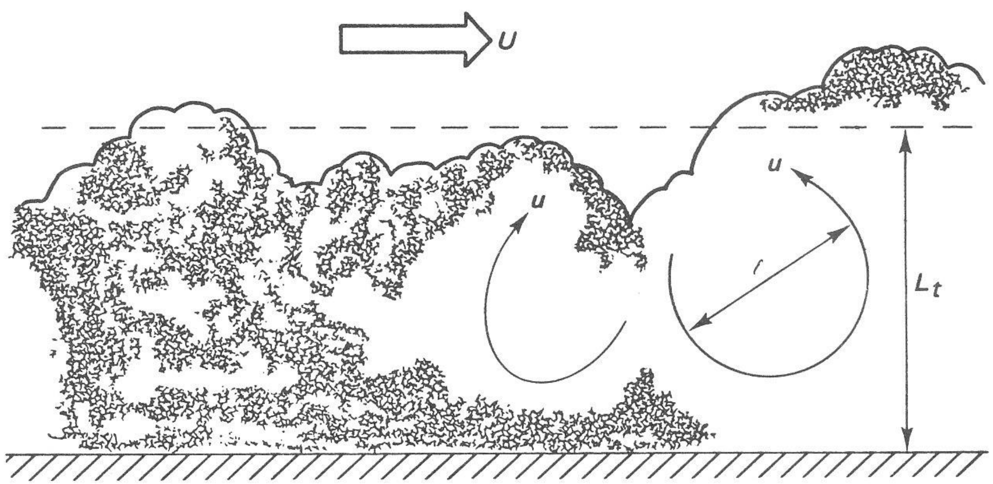


FIG. 11–3. Eddies arising from waves at a surface of discontinuity.

18.1 Introduction

(2) Boundary-wall-generated turbulence

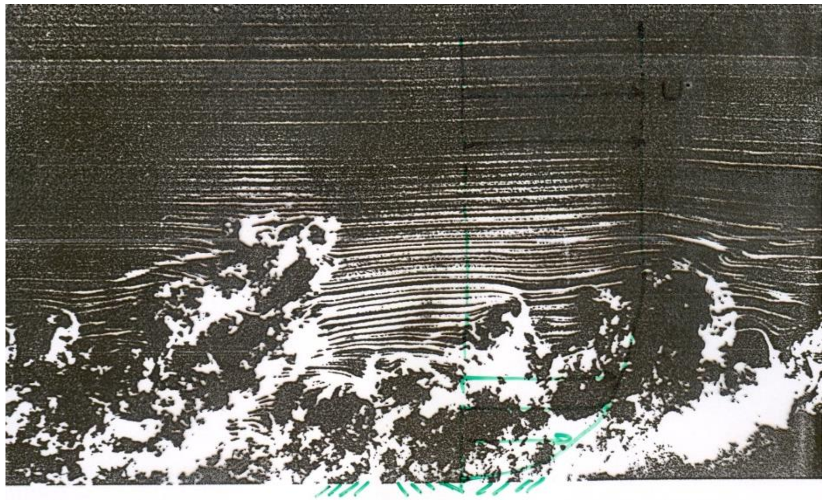
~ wall turbulence



External flow

Boundary layer flow

18.1 Introduction



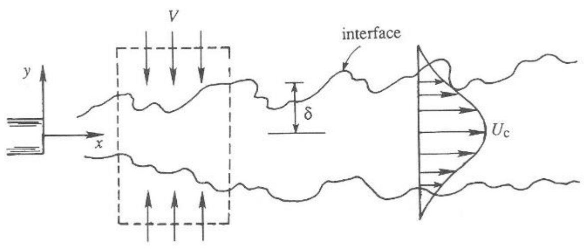
157. Side view of a turbulent boundary layer. Here a turbulent boundary layer develops naturally on a flat plate 3.3 m long suspended in a wind tunnel. Streaklines from a smoke wire near the sharp leading edge are illuminated by a vertical slice of light. The Reynolds number is 3500 based on the momentum 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*

18.1 Introduction

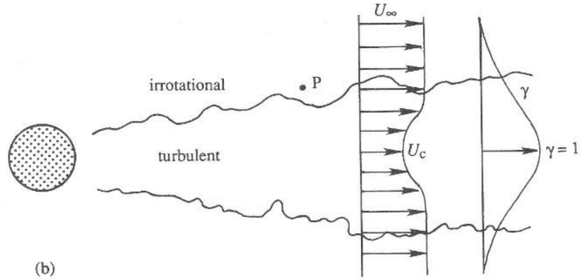
(3) Free-shear-layer-generated turbulence

~ free turbulence



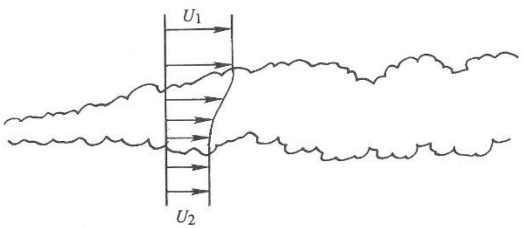
(a)

Jet



(b)

Wake

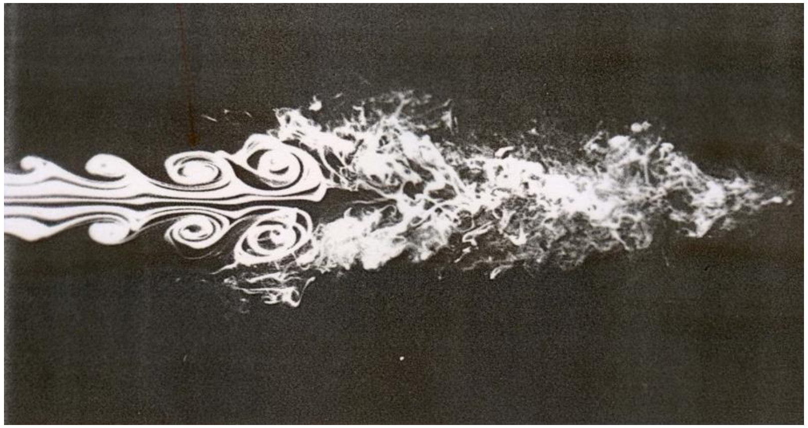


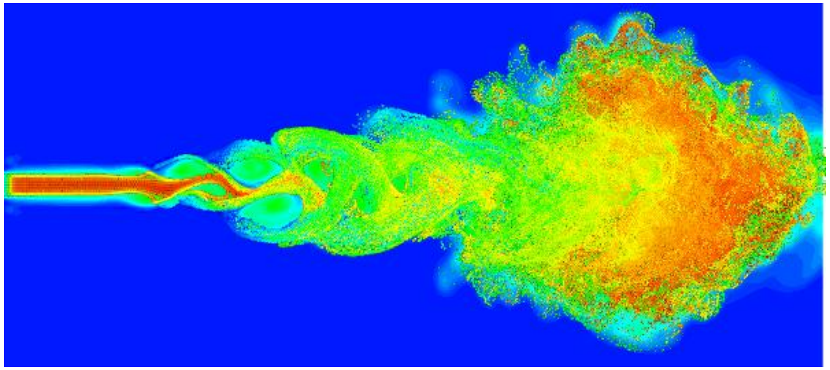
(c)

Shear layer

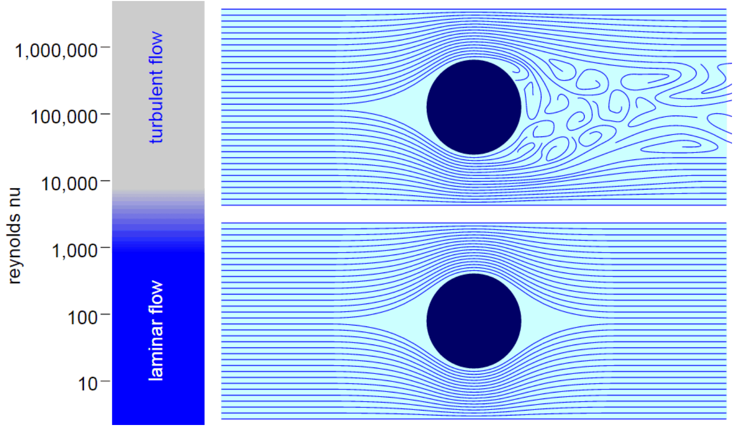
18.1 Introduction

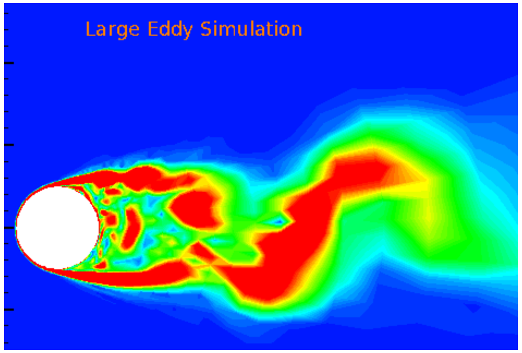
Turbulent jet





Turbulent wake





18.1 Introduction

18.1.2 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.

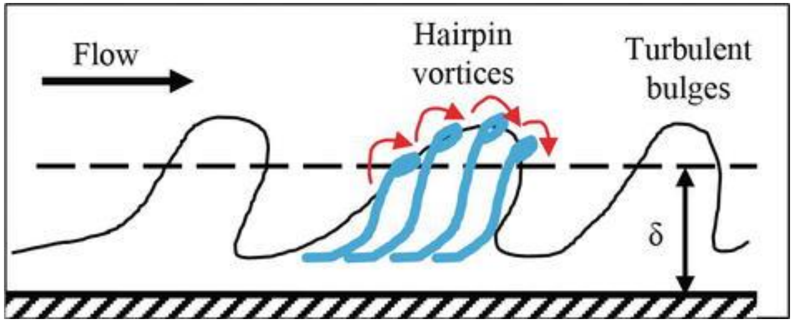
[Cf] coherent structure 상관구조

~ large scale eddies

~ interact with mean flows

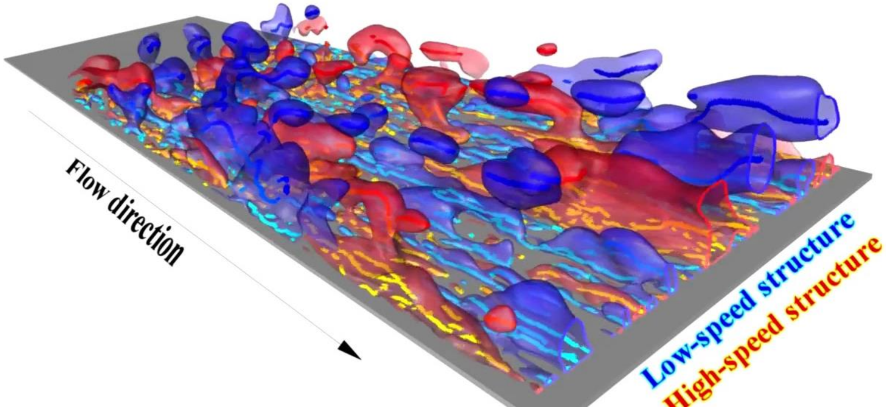
~ correlated each other with time and space

~ ordered motion

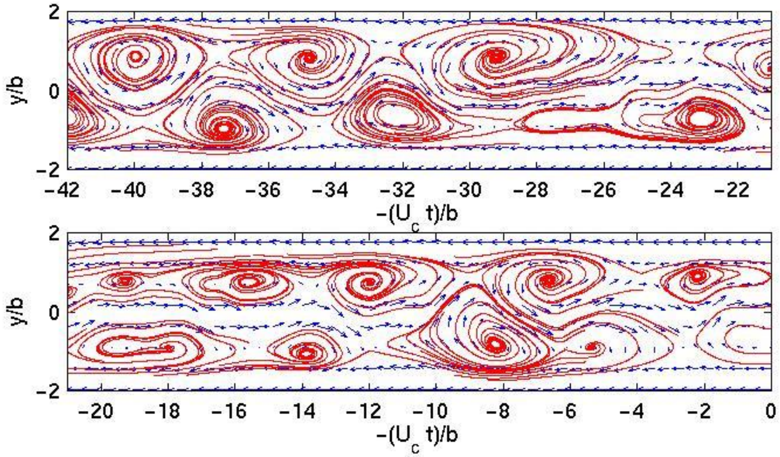


18.1 Introduction

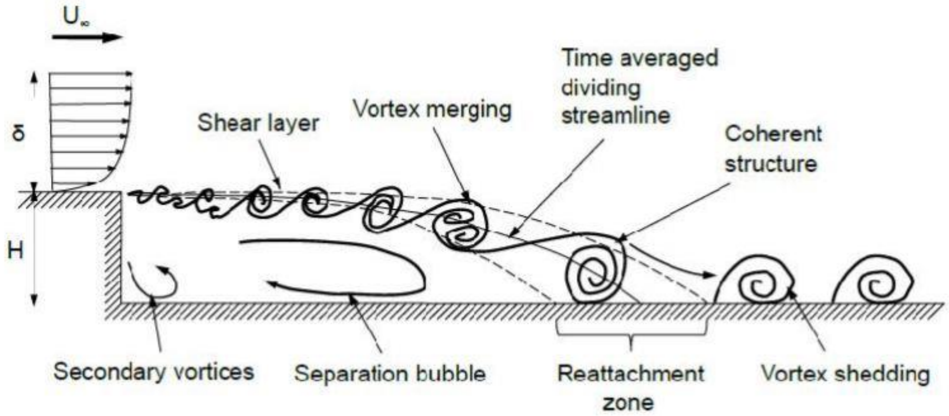
Coherent structure in turbulent boundary layers



Large-scale coherent structure in turbulent jet



Coherent structure in shear layer



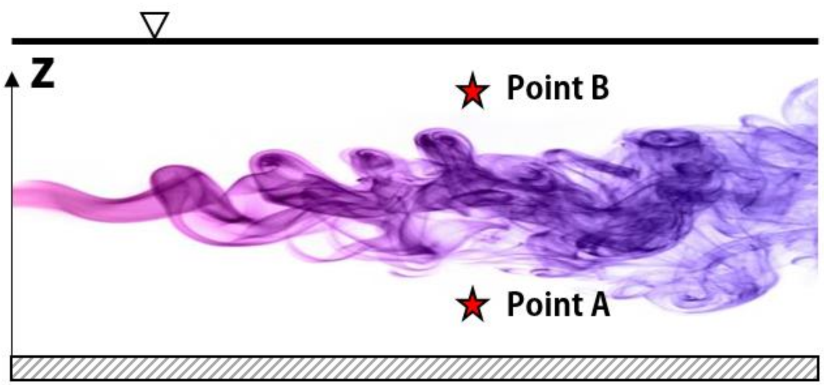
18.1 Introduction

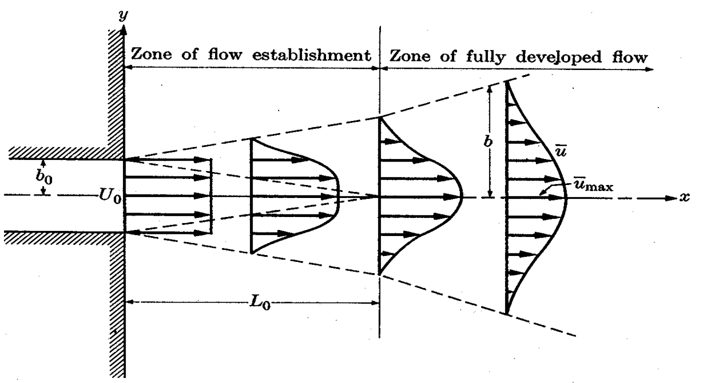
(2) Diffusivity

~ 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





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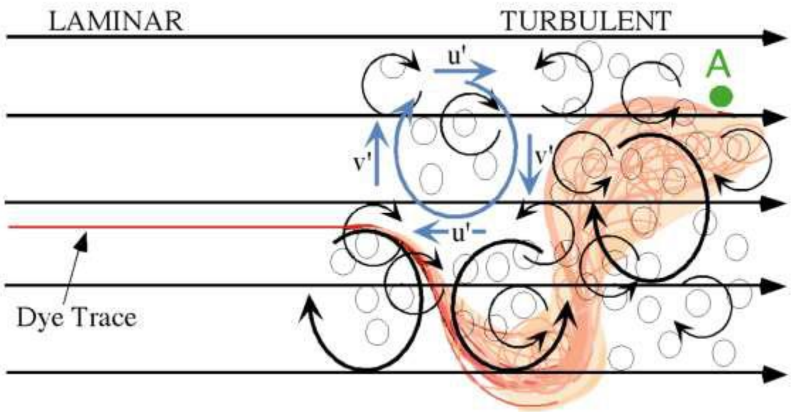
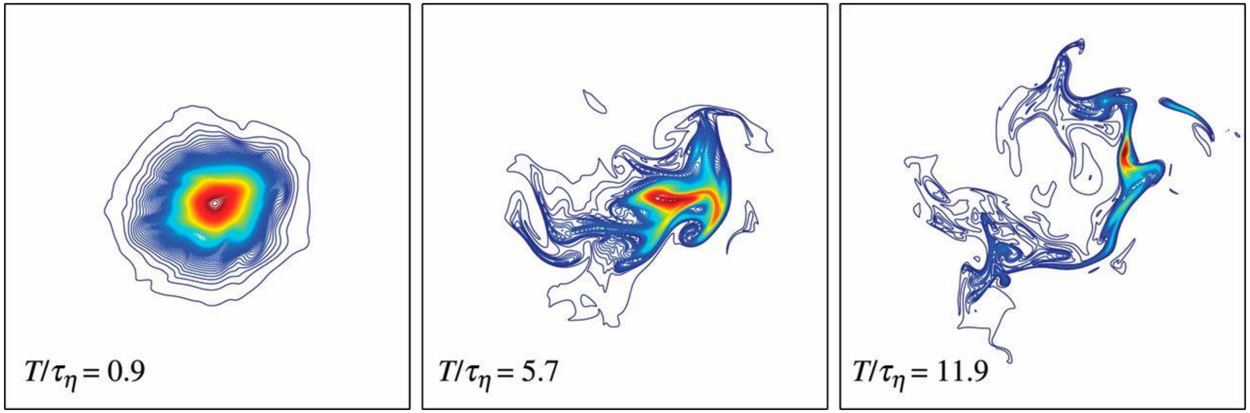




18.1 Introduction

(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: $\mathrm{Re}_c = \frac{U\delta^*}{\nu} = 600;\ \mathrm{Re}_x = \frac{Ux}{\nu} = 500{,}000$

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

18.1 Introduction

(4) Three-dimensional vorticity fluctuations

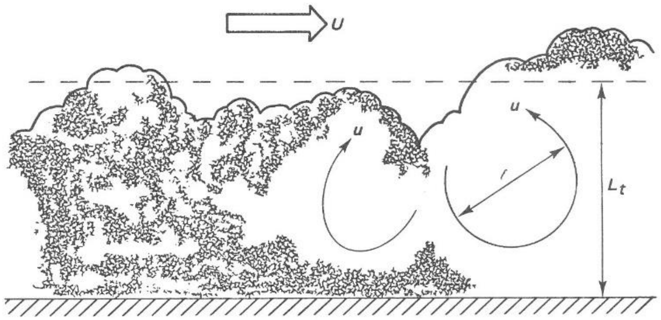
~ Turbulence is rotational and three-dimensional.

~ high levels of fluctuating vorticity

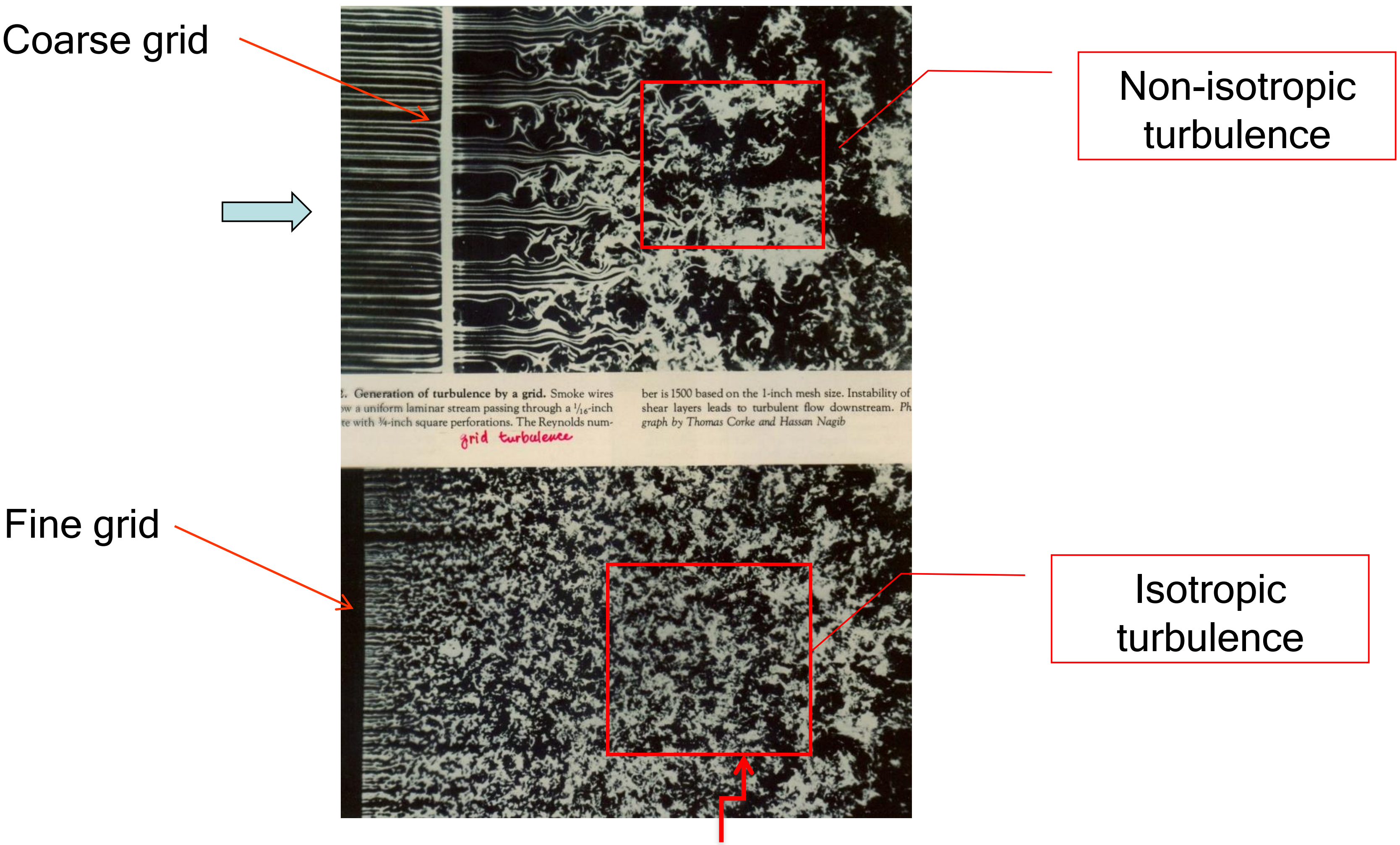
~ need to use vorticity dynamics

~ However, small eddies tend to be isotropic.

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



18.1 Introduction



18.1 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 (Energy cascade).

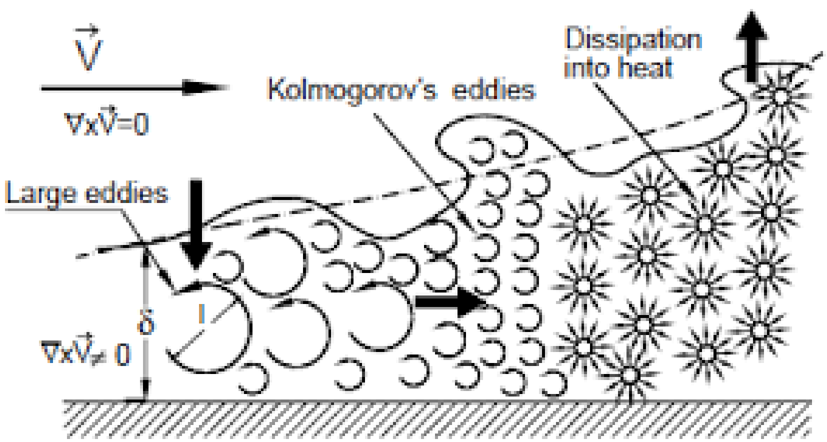
~ If no energy is supplied, turbulence decays rapidly.

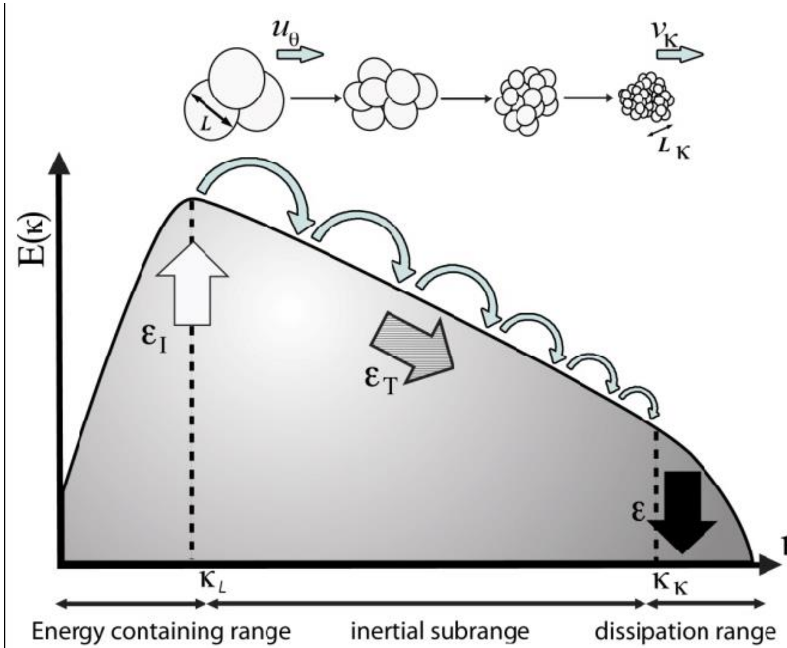
[Cf] Random motions that have insignificant viscous losses such as random sound waves are not turbulent.

18.1 Introduction

[Re] *Energy cascade*

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





18.1 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.