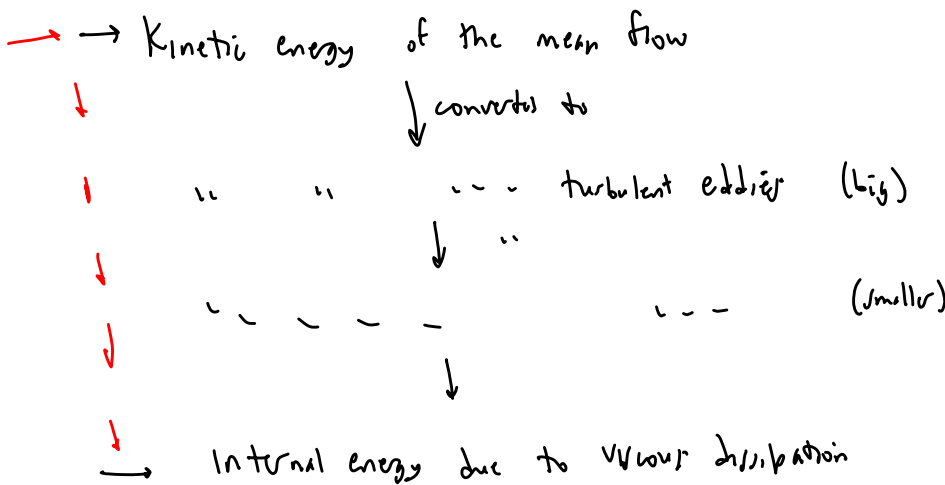


Today, we will:

- Discuss turbulent dissipation in more detail – boundary layers, grid turbulence, momentumless wakes
- Discuss other features of turbulence
- Begin to discuss the equations of turbulence – notation and terminology, types of averages, etc.

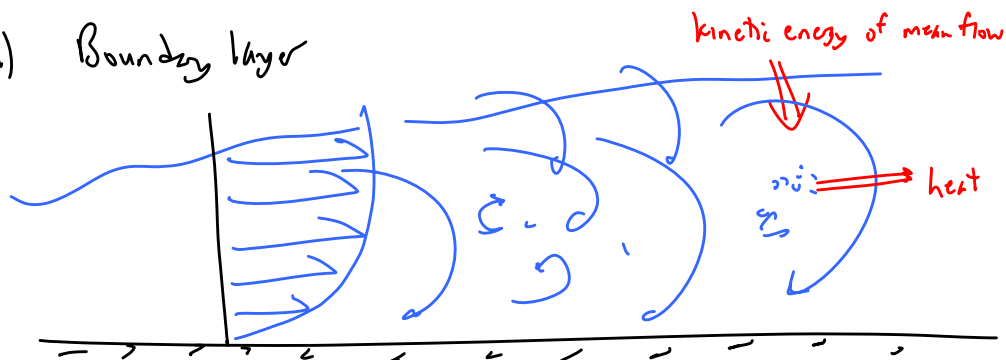
Last time: The characteristics of Turbulence:

- Randomness – unpredictable, irregularity
- Nonlinearity (amplitudes of fluctuations are not negligibly small)
- Diffusivity (mixing)
- 3-D – fluctuating vorticity at a wide range of scales
- Dissipation – Turbulence needs a continuous supply of energy to sustain itself



⚠ In order for turbulence to sustain itself, it must have a continuous supply of kinetic energy from the mean flow

E.g.s 1) Boundary layer

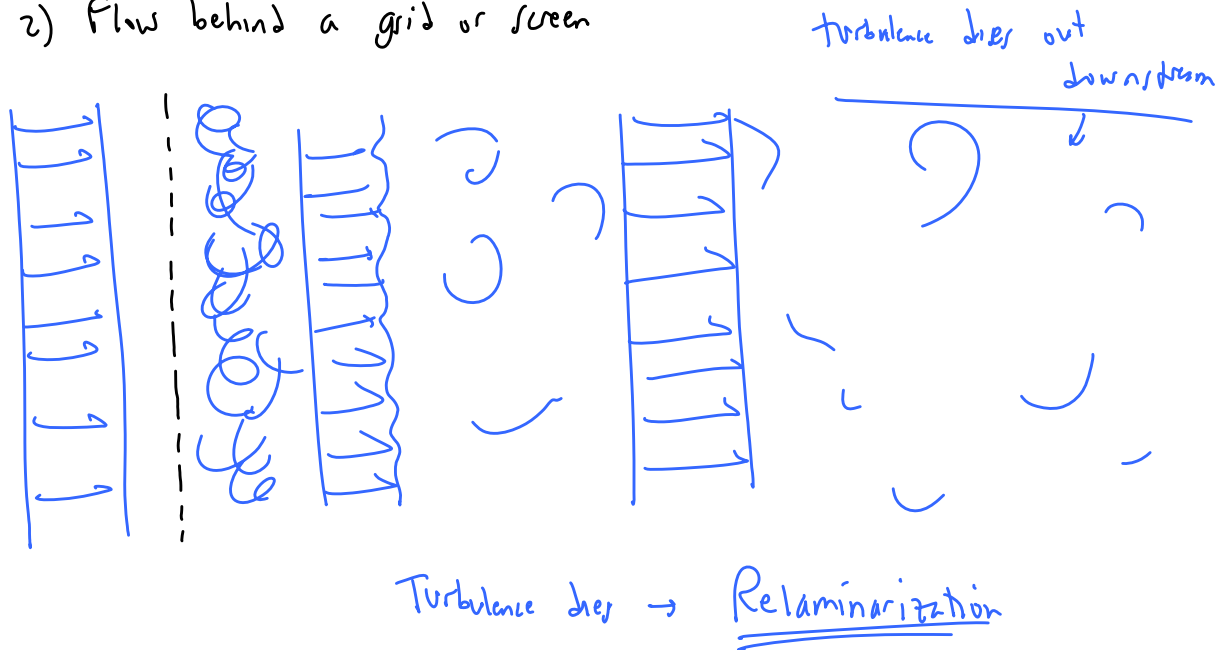


- A mean shear (mean velocity gradient) is required to enable k.e. transfer from the mean flow to the turbulent eddies

- More, the turbulence sustains itself. (by continually drawing k.e. from the mean flow)

e.g. with no mean shear

2) Flow behind a grid or screen



3) Momentumless Wake \rightarrow W.J. Park 1980s

- Regular 2-D wake

U_0



- Momentumless wake

U_0



eventually re-laminarizing

3. Other features of turbulence

a. Turbulence is a continuum phenomenon

↓
even the smallest eddies are larger than any
molecular scale

* b. Turbulence is a property of fluid flow not a property of fluids

↓
not like density, viscosity — it is a kinematic property

↙ every turbulent flow is different

Most Turbulence models treat the turbulence as a fluid property

e.g. "eddy viscosity"

↓
This is only an approximation

B. Notation & Terminology

Use Kundu's notation

(same notation as we used for stability analysis)

1. Notation

$$\tilde{u}_i = U_i + u_i$$

↑
instantaneous
or total flow
quantity

↑
mean
part
(do some kind of
average of \tilde{u}_i)

↑
fluctuating part
(the "turbulence")

Similarly,

$$\tilde{p} = P + p$$

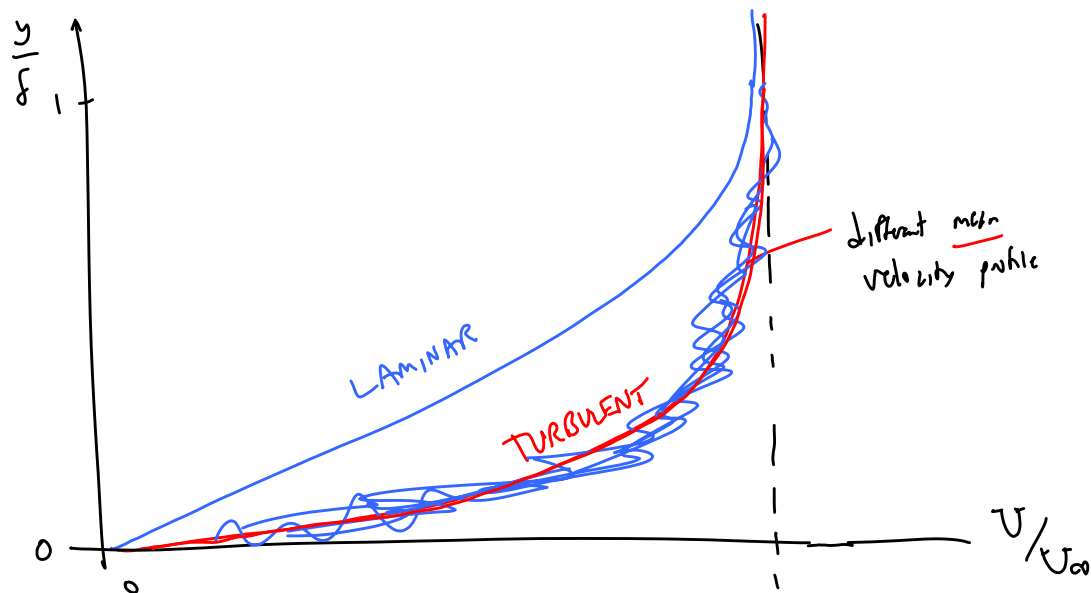
$$\tilde{T} = \bar{T} + T'$$

$$\tilde{\rho} = \bar{\rho} + \rho'$$

★ U, P, \bar{T} , etc. are not the laminar basic state!

★ Turbulence is not laminar flow with added fluctuations!

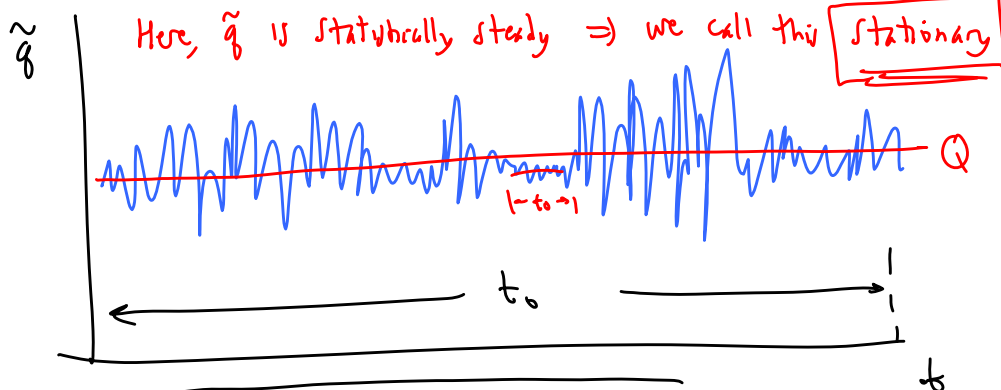
Eg. flat plate BL



2. Types of averages

a. Time average

Use \tilde{q} = any fluctuating quantity
= instantaneous or total flow variable

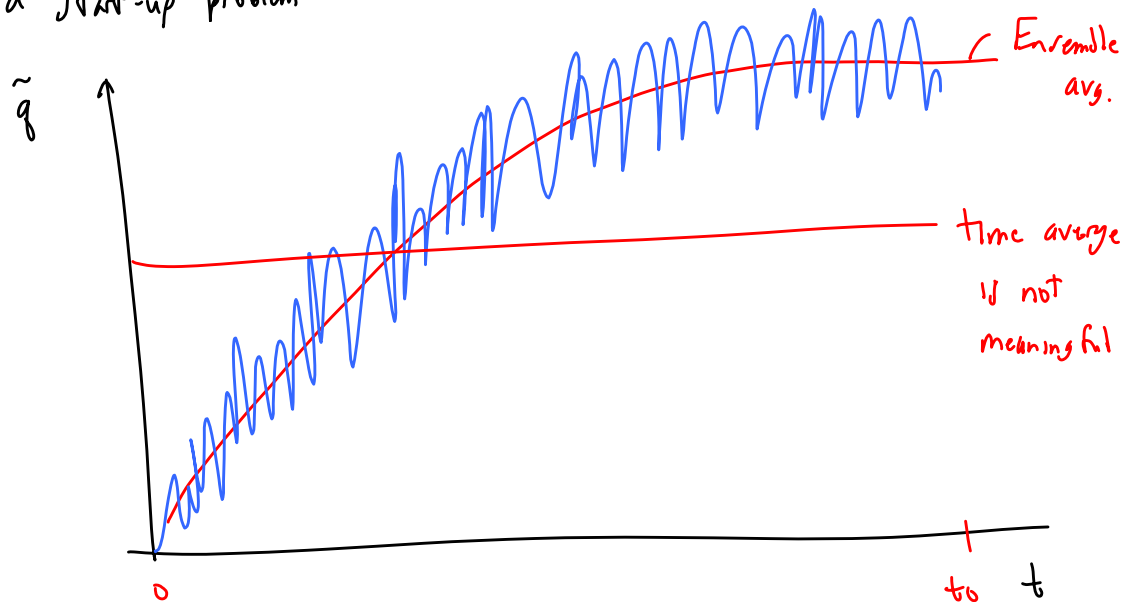


$$[\tilde{q} = Q + q]$$

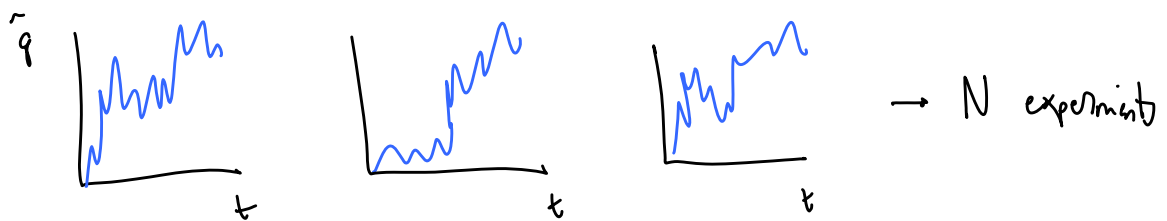
$$\star \text{ Time average} = \overline{\tilde{q}} \equiv \lim_{t_0 \rightarrow \infty} \frac{1}{t_0} \int_0^{t_0} \tilde{q} dt$$

b. Ensemble Average - used for non-stationary turbulent flows

e.g. a start-up problem



Ensemble avg. \rightarrow repeat the start-up experiment many times



Average each run at a certain time i repeat for all times

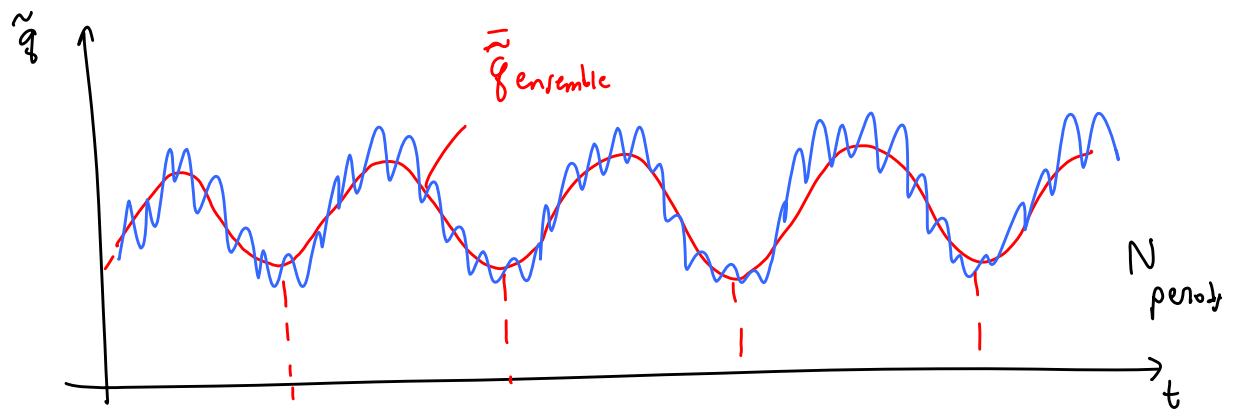
\rightarrow ensemble average

$$\overline{\tilde{q}}_{\text{ensemble}}(t) = \frac{1}{N} \sum_{i=1}^N \tilde{q}^{(i)}(t) = \text{ENSEMBLE AVG.}$$

$i = \text{experiment \# or "record" \#}$

For a stationary process, the time average = the ensemble avg. = Q

c. Phase Avg. — for periodic flow



$\phi = \text{Phase } 0 \quad 360^\circ$

$$\bar{q}_{\text{ensemble}}(\phi) \equiv \frac{1}{N} \sum_{i=1}^N \tilde{q}^i(\phi)$$

So, a phase average is really just a special case of an ensemble average in which the "experiment" is repeated every period — Each period is one record, i , i ; we take N records to compute the phase average.