Turbulence

SOE3211/2 Fluid Mechanics lecture 5

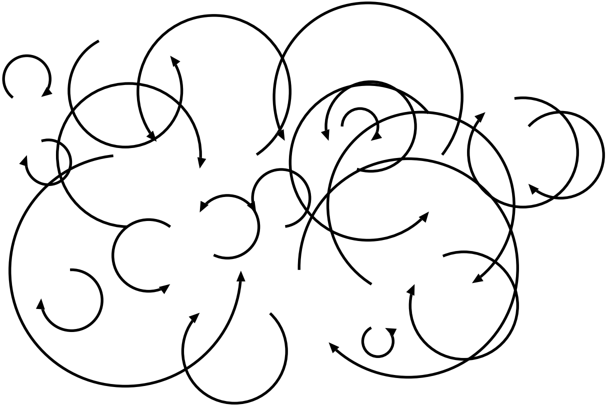
Turbulence (A)

Turbulence is difficult to define precisely – easier to discuss its properties :

- state of fluid motion characterised by complex, chaotic motion
- quasi-random motions
- often described in terms of turbulent eddies of different scales in the flow
- *vorticity* represents strength of eddies

Where does it occur?

- Wall turbulence : walls (turbulent b.l.), pipes etc
- Free turbulence : wakes, jets



Individual eddies obey NS equations (one solution technique is to compute them – Direct Numerical Simulation, DNS).

Individual eddies interact + tend to break up.

Energy in turbulence

1. starts off in large scale eddies
2. is transmitted to smaller and smaller eddies
3. until it ends up in the smallest possible eddies

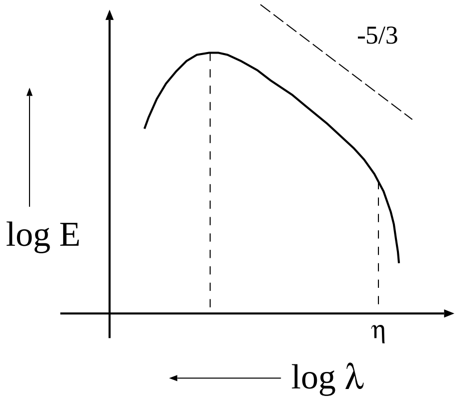
The smallest eddies are those dominated by viscous effects : their energy is dissipated as heat.

This pattern is known as the *turbulent cascade*.

If we plot the energy $\log E$

versus a characteristic length of the eddy $\log \lambda$

we get an *energy spectrum* :



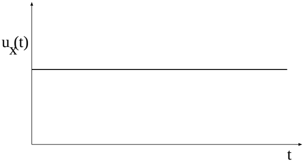
Note

1. Kolmogorov length scale η where viscous effects dominate, i.e. $\mathcal{R}e_\eta = \frac{u'\eta}{\nu} \sim 1$
2. Slope of energy cascade is $-5/3$

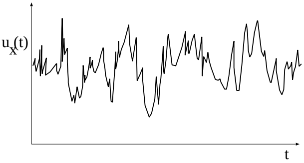
Description of turbulence (v2) (A)

Question : how are we going to characterise such a complex flow?

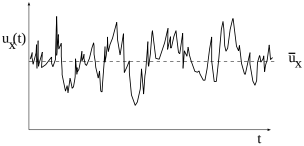
Imagine measuring u_x in a laminar flow :



In a turbulent flow the graph would look like this :



Describe this as 'fluctuations' around an 'average' value



Define the *time average* of u_x

$$\overline{u_x} = \frac{1}{\Delta t}\int_t^{t+\Delta t} u_x(t)dt$$

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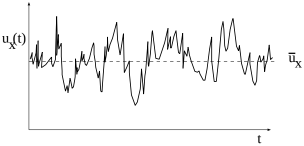

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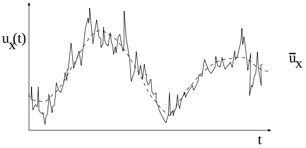
$$\overline{u_x} = \frac{1}{\Delta t}\int_t^{t+\Delta t} u_x(t)dt$$

How big is Δt? Depends on the case :

- If the flow is *quasi-steady*, Δt can be as long as practical.
- If the flow varies with timescale t_{var} (eg. a periodic flow) $\Delta t \ll t_{var}$

Non-steady flow :



However the time average only describes *part* of the flow. Introduce the fluctuation u_x'

$$u_x(t) = \overline{u_x} + u_x'$$

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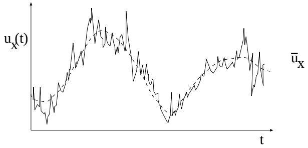

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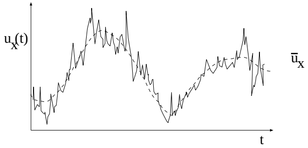


However the time average only describes *part* of the flow. Introduce the fluctuation u'_x

$$u_x(t) = \overline{u_x} + u'_x$$

Fairly obviously, $\overline{u'_x} = 0$

However

$$\overline{{u'_x}^2} \neq 0$$

$\frac{1}{2}\overline{u_x'^2}$ is one component of a kinetic energy

$$k = \frac{1}{2}\left(\overline{u_x'^2} + \overline{u_y'^2} + \overline{u_z'^2}\right)$$

– the *turbulent kinetic energy*

If the turbulence is isotropic, then

$$\overline{u_x'^2} = \overline{u_y'^2} = \overline{u_z'^2} = \overline{u'^2},$$

and

$$k = \frac{3}{2}\overline{u'^2}$$

We can also consider the rate of dissipation of turbulent kinetic energy. This is usually denoted ϵ.

Effects of turbulence (A)

2 main effects here :

1. Dissipation of flow energy – the turbulent motion contains kinetic energy unrelated to the mean motion of the fluid
2. Diffusive effects

Consider a particle in the flow. This particle will be swept along by successive eddies, and thus be transported from its starting point.

Neighbouring particles may see different eddies, and end up a long way apart.

Similar to the 'random walk' molecular process for real diffusion in gases

– thus turbulence produces a *diffusive* effect.

Turbulent Boundary Layers (A)

We note the following

1. There has to be a laminar region close to the wall
    - *wall layer/viscous sublayer*
    - $\tau_{visc} \gg \tau_{turb}$
2. Far from the wall there will be a turbulent region where $\overline{u}$ regains the free stream velocity
    - *free turbulent/log-law region*
    - $\tau_{visc} \ll \tau_{turb}$
3. In between : an intermediate region
    - *wall turbulent/transition region*
    - $\tau_{visc} \sim \tau_{turb}$

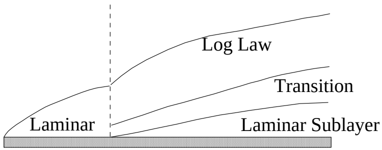
Often write the group

$$\frac{yu_\tau}{\nu} = y^+, \qquad u_\tau = \sqrt{\frac{\tau_0}{\rho}}$$

and refer to distances measured in *wall units*

- Viscous sublayer $0 < y^+ < 5$
- Transition $5 < y^+ < 30$
- Free turbulent $y^+ > 30$

The boundary layer may start laminar + become turbulent



Transition will depend on $\mathcal{R}e_x$, as defined before :

$$\mathcal{R}e_x = \frac{U_\infty x}{\nu}$$

- Above $\mathcal{R}e_x \sim 5 \times 10^5$ the b.l. is turbulent.
- Below $\mathcal{R}e_x \sim 10^5$ it is laminar
- Transitional for intermediate values
- Turbulence can be triggered early by rough surfaces
- Or can remain laminar if the surface is very smooth