Characteristics of Turbulence

1. _______: The randomness or irregular nature of turbulent flows makes a solely deterministic approach to the turbulence problem impossible. Therefore, one must rely on statistical or conditional methods.

Note: Turbulent flows are always random and chaotic. But not all chaotic flows are turbulent.
Characteristics of turbulence?

2. **The large diffusive nature of turbulence**, causes rapid mixing & increased rates of mass, momentum and energy transfer.

- In fact, the rates of transfer and mixing are orders of magnitude greater than those due to molecular diffusion.

Note:

i) If a flow looks random but does not exhibit the spreading of velocity fluctuations throughout the surrounding fluid, it is not turbulent.

ii) If a flow is chaotic, but not diffusive, it is not turbulent.

3. **Turbulent flows always occur at high Re** (i.e., inertia or non-linear) forces dominate the viscous forces.

High Reynolds number turbulent jet
4. Turbulence is a continuum phenomenon governed by the equations of fluid mechanics. Even the smallest scales of motion occurring in a turbulent flow are larger than any molecular length scale.

5. Turbulence is rotational, three-dimensional, and characterized by high levels of fluctuating vorticity. These random vorticity fluctuations which characterize turbulence could not maintain themselves if the velocity fluctuations were two-dimensional.
Characteristics of turbulence?

6. __________: All turbulent flows are dissipative.

Viscous shear stresses perform deformation work, which increase the internal energy of the fluid (increased temperature) at the expense of the kinetic energy of the turbulence.

Note:
- Turbulent flows die out quickly when no energy is supplied.
- Random motions that have insignificant viscous losses, such as random sound waves, are not turbulent.

Characteristics of turbulence?

Note:

a) Turbulence is not tied to the ____________________.

b) Navier-Stokes (NS) eqs can not describe the average flow field when it is turbulent, unless, you statistically weigh the equations, boundary conditions and initial conditions.

c) Statistical studies of the equations of motion always lead to a situation in which there are more unknowns than equations. This is called the closure problem.

d) Large Eddy Simulation/Direct Numerical Simulation of the NS eq requires a large number of grid points, is expensive to run, and still has a way to go to solve engineering problems.

e) Full numerical simulations are typically restricted to lower Re where the range of wavelengths is small. However in Large Eddy Simulation (LES), the less-important, small scale motions are modelled empirically and are not restricted in this way.
Origin of Turbulence: Instabilities

1. Turbulence arises from instabilities at large Reynolds numbers.

\[ Re_L = \frac{\rho UL}{\mu} = \frac{UL}{\nu} \]

where \( L = x, D, D_h, \) etc.

**Low Re the flow is laminar:** Smooth streamlines and highly ordered motions slide over one another.

**High Re the flow is turbulent:** Fluctuating velocity and highly disordered motion.

**Transition:** The flow fluctuates between laminar and turbulent flows.

Most flows engineering and nature encountered in practice are turbulent

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Origin of Turbulence: Instabilities

- Swirling clouds highlight the Karman vortex produced as the wind flows around the island forming large, spinning eddies.

The high point of the island is nearly a mile (1.6 km) above sea level.

http://landsat.gsfc.nasa.gov/earthesart/vortices.html

Image taken 9/15/1999
Origin of Turbulence: Instabilities

- As air flows over and around objects in its path, spiraling eddies, known as Von Karman vortices may form.
- Vortices in this image were created when easterly winds moved across the Alaska's Aleutian Islands.

(http://landsat.gsfc.nasa.gov/earthasart/vonkar.html)

Figures corresponding to different flow states are as follows:

- **Figure a** corresponds to a stable condition (i.e. laminar flow), no matter what type of disturbance is added.
- **Figure b** represents a flow in which the slightest disturbance will turn it turbulent.
- **Figure c** implies a flow state where a disturbance neither grows or decays.
- **Figure d** represents flows which are stable to small disturbances, but when a critical disturbance level is exceeded, the flow becomes unstable.
Origin of Turbulence: Instabilities

3. A free shear layer (jet or wake) becomes unstable at $Re_\delta^* \sim 4$ (Re based on the displacement thickness, $\delta^*$).

\[ Re_\delta^* = \frac{U\delta^*}{v} \sim 4 \]

Origin of Turbulence: Instabilities

- Flow around a cylinder begins to separate and form a wake @ Re $\sim 5$. The formation of vortices remain stable until Re $\sim 30$.

- Above this Re the flow begins to oscillate and shed vortices. Beyond a critical Re the flow transitions & becomes turbulent.
Origin of Turbulence: Instabilities

4. A boundary layer in a zero pressure gradient becomes unstable at Reynolds number based on the displacement thickness;

\[ \text{Re}_d^* = \frac{U_\delta^*}{\nu} \approx 600 \]

Or based on “x”

\[ \text{Re}_x = \frac{U_x}{\nu} \approx 2.8 \times 10^6 \]

• This image demonstrates the transition process also observed in the streamwise velocity fluctuations recorded over a flat plate (next side).

Origin of Turbulence: Stabilities
5. Osborne Reynold (1883) concluded that the critical Reynold's number for laminar pipe flow to become turbulent, $Re_D$, based on the pipe diameter:

$$Re_D = \frac{UD}{\nu} \sim 2,300$$

Note: If great care is taken to avoid the generation of small disturbances (dependent on inlet conditions), which trigger the transition, the critical $Re_D$ can be increased.

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### Origin of Turbulence: Instabilities

- Recall an outstanding characteristic of turbulent motions was an ability to enhance rates of mass, momentum & energy transfer.
- Let's examine a simple diffusion problem. Consider a room with a radiator placed in the lower left hand corner.

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### Diffusivity of Turbulence

- Recall an outstanding characteristic of turbulent motions was an ability to enhance rates of mass, momentum & energy transfer.
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Diffusivity of Turbulence

Case I --

---The End---
Diffusivity of Turbulence

**Case II** - Assume fairly weak motions, such as those generated by weak buoyancy forces resulting from the small density differences between the radiator and the surrounding gas.
Note:

a) Molecular diffusion is still required to even out the small scale irregularities in the temperature distribution.

b) Comparing the two time scales, one can see that diffusion by random motions is far more effective than molecular diffusion.
c) Ratio of the turbulent time scale, $t_t$ to molecular time scale, $t_m$ can be related to the inverse of the Peclet # ($Pe$).

\[
\frac{1}{Pe} = \frac{t_t}{t_m} \approx \frac{L}{L^2 \alpha} = \frac{\alpha}{uL} \tag{1.8}
\]

Recall;

For the above example the $Pe \approx 31,000$ and it has a similar form to a Reynolds number.

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d) To help explain this enhanced mixing, the idea of eddy diffusivity was introduced. Unfortunately, the idea of eddy diffusivity is a dangerous one because it treats the turbulence as a property of the fluid, rather than a property of the flow (which it is).

Yet because it simplifies the mathematics, it was/is often used.

- This image ~240 km by 320 km reveals two large ocean circulation features, called eddies, at the northernmost edge of the icepak in the Weddell Sea off Antarctica.
- These eddies play an important role in ocean circulation and the transportation of heat toward the pole. The ocean eddies are 40km to 60km in diameter.
- The dark areas are new ice and the lighter green areas are small ice floes that are swept along by the ocean currents.
- First year seasonal ice is shown in the darker green areas and the open ocean to the north (top) is blue. (From André Baker)
Eddy Diffusivity

- To demonstrate the concept of eddy diffusivity, let's define a turbulent flow where the turbulence can be sometimes represented by a simple constant $K$,

$$\frac{\partial \theta}{\partial t} = K \frac{\partial^2 \theta}{\partial x_i \partial x_i} \quad (1.9a)$$

where $K$ represents the turbulent eddy diffusivity just as the kinematic viscosity, $\nu$ represents the molecular diffusivity.

- Performing an order of magnitude analysis on Eq. (1.9a)

or

$$ \quad (1.9b)$$

Eddy Diffusivity

- Recall the turbulence time scale is related by Equation (1.4)

$$ t_1 \sim \frac{L}{u}$$

equating $t_1$ above to Eq. (1.9b), one obtains

$$ K \sim u L \quad (1.10)$$

- If the turbulent eddy diffusivity $K = \text{constant}$, then $u$ and $L$ must adjust themselves accordingly in a turbulent flow field.

- Therefore, the eddy diffusivity (or eddy viscosity) may be compared with the kinematic viscosity or the thermal diffusivity in the following way, assuming the Prandtl number ($Pr$) $\approx 1.0$

$$ \quad (1.11)$$
Eddy Diffusivity

\[ Re = \frac{uL}{v} \approx \frac{K}{\nu} \quad (1.11b) \]

for air

\[ Pr_{air} = \frac{\nu}{\alpha} = 0.73 \]

where \( \alpha = \frac{k}{\rho c} = \frac{\text{thermal conductivity}}{\text{density} \times \text{specific heat}} \)

- Therefore, the above Re (Eq 1.11a) could also be considered as a ratio of

- As previously stated for turbulent flows, the Re must be large, therefore,

\[ (1.12) \]