Turbulence in Fluids

Introduction to Turbulence

Benoit Cushman-Roisin
Thayer School of Engineering
Dartmouth College

Mayon Volcano, The Philippines

View the 1960s classic movie from the series on Fluid Mechanics titled “Turbulence”

at [https://www.youtube.com/watch?v=1_0yqLOqwnI](https://www.youtube.com/watch?v=1_0yqLOqwnI)

**Takeaways:**

1. Turbulence is all around us. It is a common occurrence.

2. Turbulence has three defined characteristics
   - Disordered flow: many length and time scales
     Never reproducible in details, but averages are very reproducible
     Unpredictability, unrepeatability: chaotic, sensitive to details, unstable
   - Efficient mixing
   - Role of vorticity: across length scales and three-dimensional

3. Laminar versus turbulent flows
   Role of the Reynolds number ($Re$)
   Transition for sufficiently high $Re$, tripping perturbations

4. Intermittency at transitional Reynolds numbers

5. Momentum transfer between regions of faster and slower flow

6. The higher $Re$, the wider spread of length scales in the turbulent flow
Importance of the Reynolds number

Fig. 1.2. Planar images of concentration in a turbulent jet: (a) \( \text{Re} = 5,000 \) and (b) \( \text{Re} = 20,000 \). From Daehn and Dimotakis (1990).

Source: Pope, 2000, page 5

Note:
- Velocity average is well defined.
- The velocity value never departs from the average for very long.

Fig. 1.3. The time history of the axial component of velocity \( U_x(t) \) on the centerline of a turbulent jet. From the experiment of Tong and Warhaft (1995).

Source: Pope, 2000, page 5
There does not exist yet a unifying theory of turbulence, not even one for the statistical properties of a turbulent flow.

Many unsuccessful attempts had the following premises and outcomes:

1. Onset of instability: Linear perturbation techniques applied to laminar flows
   Hope was that learning about the start of turbulence would illuminate all of turbulence
   Outcome: Hope never realized

2. Turbulence closure: Search for the best way to parameterize the Reynolds stresses
   Hope was that one could solve for the average flow properties directly
   Outcome: Stuck with poorly performing eddy viscosity models

3. Statistical theory: Artful mathematical manipulations of perturbations correlations
   Hope was to arrive at a robust parameterization of Reynolds stresses
   Outcome: Wandering away; mathematics haven’t led to practical applications
   More a “reading” of turbulence than a tool to solve it

4. Fractal analysis: Capitalizing on the fact that intermittency appears fractal
   Hope was that fractal analysis was going to be the long-awaited tool
   Outcome: Only able to recapitulate already known physics with new terminology

So, the approach will necessarily be much more empirical and heuristic than in other branches of mechanics.

Turbulence can be detrimental or beneficial.

Think of various situations.
Can you name some detrimental and beneficial situations?

**Examples:**

**Detrimental:**
- Any situation when accurate predictions need to be made such as weather prediction
- Drag on rapidly moving objects
- Cases where noise is an issue (ex. helicopters)

**Beneficial:**
- Dilution of pollution
- Laundry, dishwashing
- Chemical reactions
Three distinct forms of turbulence

Shear instability
Usually associated with wall boundary or confined momentum inflow (ex. jet)
→ Shear Turbulence

Thermal instability
Usually associated with inverted buoyancy or confined thermal inflow (ex. plume)
→ Convective Turbulence

Cascade to smaller length scales
→ Inertial Turbulence

Inertial turbulence is isotropic and homogeneous. The other two forms of turbulence are clearly anisotropic and heterogeneous.