



Figure 3.1 Velocity profiles for laminar, turbulent and plug flows.⁶

well-known parabolic velocity profile. Hence there is a velocity gradient (du/dr) along the radial direction, consequently the fluid element at the centre exits the tube first and at the wall last, *i.e.* the fluid elements have different residence times in the tube. If we cook soup in a tubular device under laminar flow, the lighter liquid phase in the centre would flow faster and stay shorter in the tube than the heavier solids near the wall, leading to the former being undercooked and the latter overcooked.

In turbulent flows, the laminar parabolic velocity front is significantly flattened, however, there is still a laminar sub-layer remaining in the velocity profile where energies are dissipated and heat transfers are restricted. For a given fluid (ρ and μ) and tube diameter (d), the main criterion that separates the laminar from the turbulent flow is the fluid velocity, generally the net flow Reynolds number, $Re_n (= \rho du/\mu)$.

In plug flow, all the velocity components in the tube equal to that of the incoming flow, u , hence there is no velocity gradient in the radial direction, indicating complete mixing across the tube. Because of the velocity profile, all fluid elements travelling through the tube will have an equal residence time, like a 'plug', hence the name. When we use a plug flow device to cook the soup, the mixture of solids and liquid will evenly be cooked. From the above illustrations and descriptions, the definition of the plug flow is a type of flow that satisfies the following criteria:

- The velocity profile in the direction of flow (axial) is flat and $u_z = u$;
- There is no mixing in the axial direction;
- There is complete mixing in the radial direction.

3.2.2 How to Measure Plug Flow

Plug flow is easier to identify than to define; using a tracer is the most widely used methodology. In a tubular reactor, a tracer such as NaCl or KNO_2 with a known concentration and density can be injected at some point along the reactor and conductivity probes placed downstream to the injection point register the concentration of the tracer changing with time (so-called "C" curve or commonly known as the residence time distribution (RTD)), as shown in Figure 3.2. The C-curve spreads out gradually and levels off completely after an infinite length. The shape of the tracer spread is the measure