Chapter 6: Viscous Flow in Ducts

6.3 Turbulent Flow

Most flows in engineering are turbulent: flows over vehicles (airplane, ship, train, car), internal flows (heating and ventilation, turbo-machinery), and geophysical flows (atmosphere, ocean).

$\underline{V}(\underline{x}, t)$ and $p(\underline{x}, t)$ are random functions of space and time, but statistically stationary flows such as steady and forced or dominant frequency unsteady flows display coherent features and are amendable to statistical analysis, i.e. time and place (conditional) averaging. RMS and other low-order statistical quantities can be modeled and used in conjunction with the averaged equations for solving practical engineering problems.

Turbulent motions range in size from the width in the flow δ to much smaller scales, which become progressively smaller as the $Re = U\delta/\upsilon$ increases.

35

Fig. 1.1. A photograph of the turbulent plume from the ground test of a Titan IV rocket motor. The nozzle's exit diameter is 3 m, the estimated plume height is 1,500 m, and the estimated Reynolds number is 200×10^6. For more details see Mungal and Hollingsworth (1989). With permission of San Jose Mercury & News.

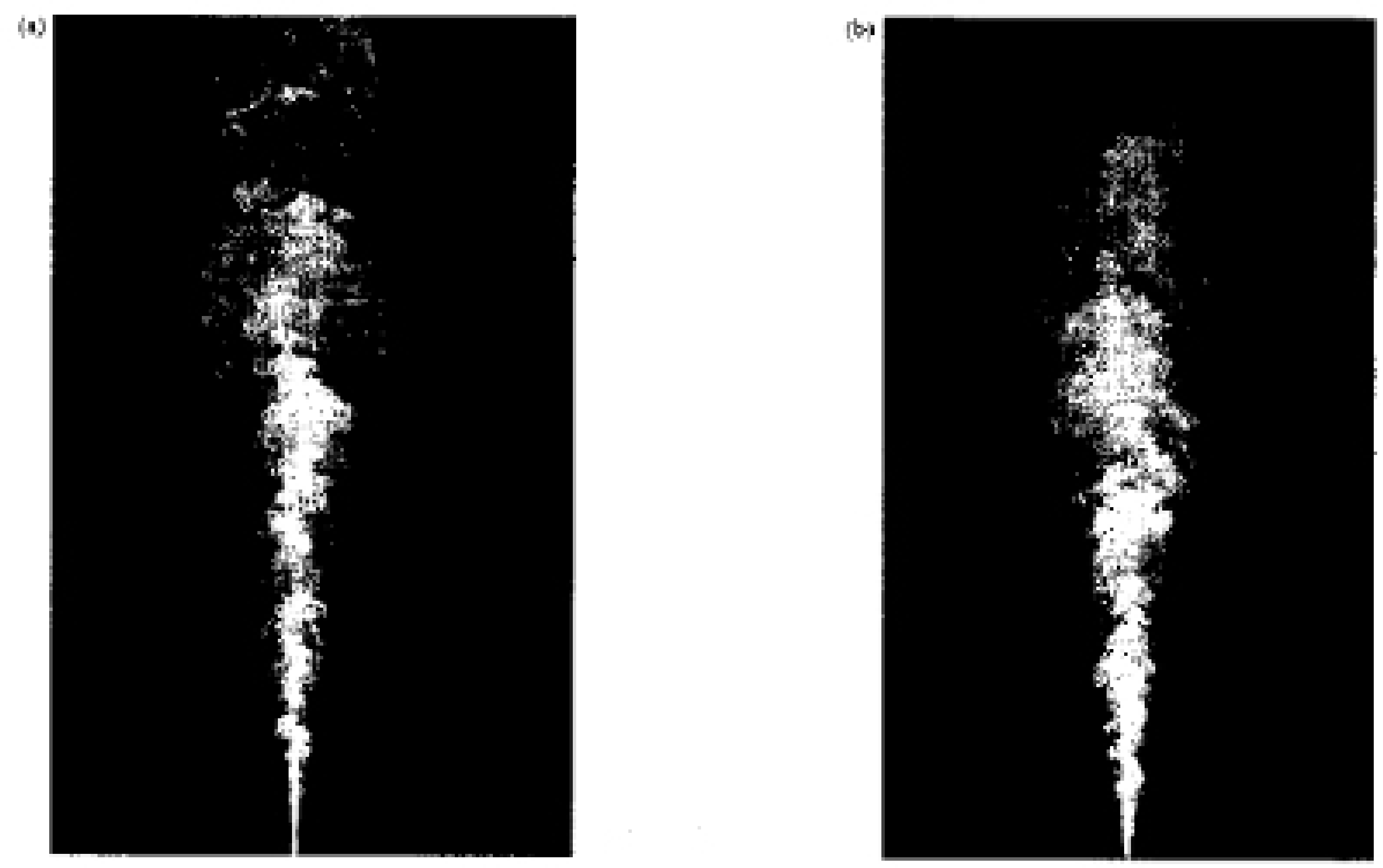

Fig. 1.2. Planar images of concentration in a turbulent jet: (a) Re = 5,000 and (b) Re = 20,000. From Dahm and Dimotakis (1990).

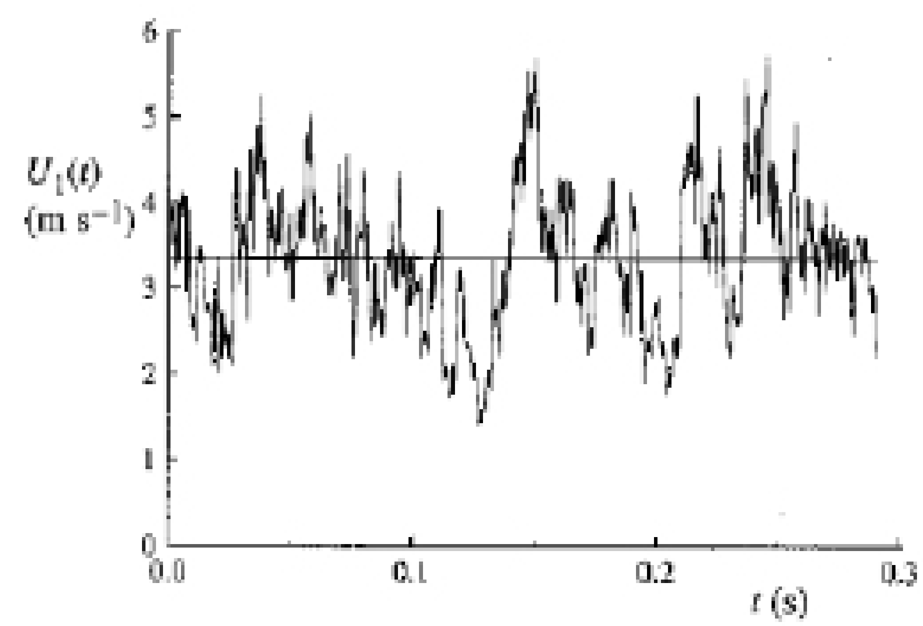

Fig. 1.3. The time history of the axial component of velocity $U_1(t)$ on the centerline of a turbulent jet. From the experiment of Tong and Warhaft (1995).

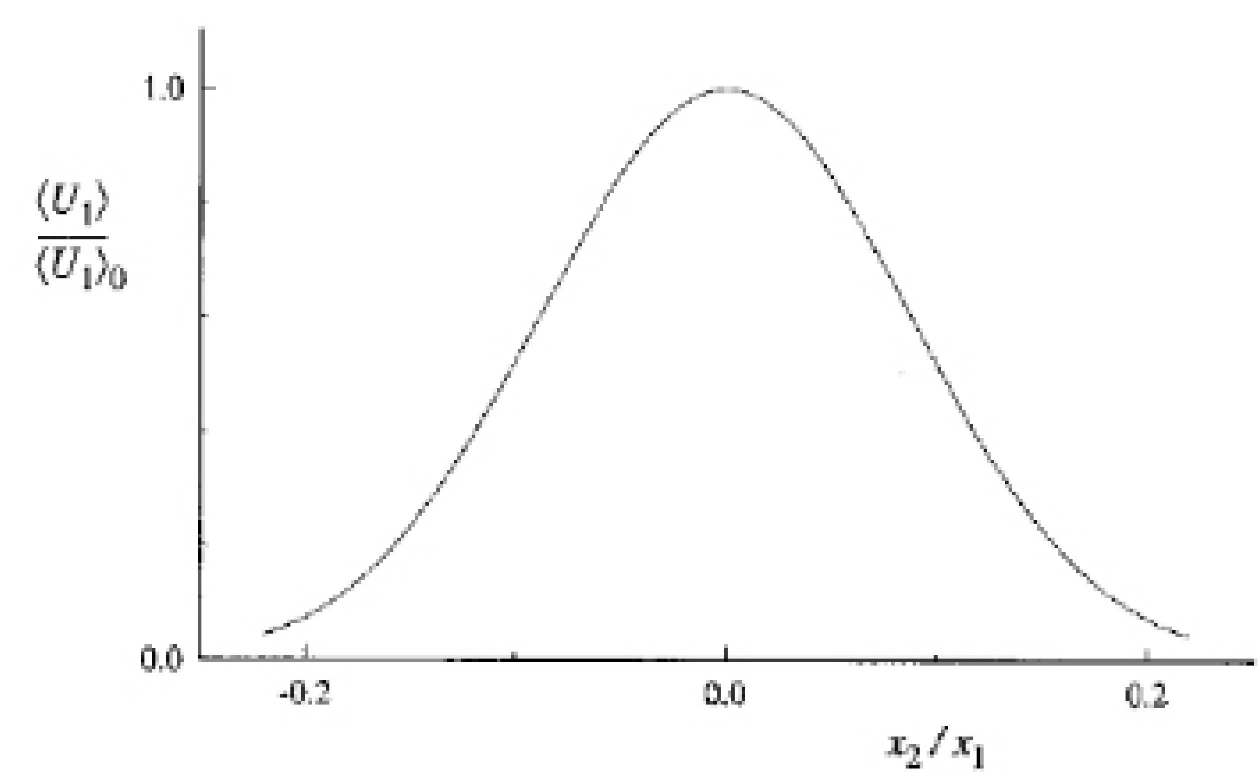

Fig. 1.4. The mean axial velocity profile in a turbulent jet. The mean velocity $\langle U_1 \rangle$ is normalized by its value on the centerline, $\langle U_1 \rangle_0$; and the cross-stream (radial) coordinate x_2 is normalized by the distance from the nozzle x_1. The Reynolds number is 95,500. Adapted from Hussein, Capp, and George (1994).

Physical description:

(1) Randomness and fluctuations:

Turbulence is irregular, chaotic, and unpredictable. However, for statistically stationary flows, such as steady flows, can be analyzed using Reynolds decomposition.

$$u=\bar{u}+u' \qquad \bar{u}=\frac{1}{T}\int_{t_0}^{t_0+T} u\; dT \qquad \bar{u}'=0 \qquad \bar{u}'^2=\frac{1}{T}\int_{t_0}^{t_0+T} u'^2\; dT$$

etc.

$\bar{u}$ = mean motion
u' = superimposed random fluctuation
$\bar{u}'^2$ = Reynolds stresses; RMS = $\sqrt{\bar{u}'^2}$

Triple decomposition is used for forced or dominant frequency flows

$$u=\bar{u}+u''+u'$$

Where u'' = organized oscillation

(2) Nonlinearity

Reynolds stresses and 3D vortex stretching are direct result of nonlinear nature of turbulence. In fact, Reynolds stresses arise from nonlinear convection term after