Turbulent flow

fan may be harnessed in various ways for propulsion; through a jet nozzle, or through a supplementary turbine to drive a fan, propeller, or helicopter rotor. The compression process is generally supplemented during flight by the ram pressure rise that the air experiences as it is slowed down in the process of being drawn into the engine. In the case of very high supersonic flight, this ram pressure ratio is extremely large, of the order of 50:1 for flight Mach number 5. See JET PROPULSION.

In the limiting case, the turbo-compressor is no longer necessary, and the engine design evolves into a ramjet, without any turbomachinery. Although the ramjet is an ideal engine for operation at these very high flight speeds, it is very inefficient at subsonic flight speeds and, indeed, it is useless for propulsion at the very low speeds appropriate to takeoff and landing. A turbosfan has the opposite and complementary characteristics: very high efficiency at low flight speeds, and very low efficiency in very high supersonic flight. The turbosfan is configured to exploit the advantages of both engine types and to provide for efficient propulsion over the entire flight spectrum from takeoff to high supersonic cruise.

Engine configuration. For operation at subsonic and transonic flight speeds, fuel and air are brought together in the middle of the engine, where the mixture is burned (see ILLUS.). The resultant hot, high-pressure gas stream is expanded through a turbine that drives the fuel and oxidizer pumps and also powers a large fan in the front of the engine. The front-fan discharge air bypasses the preburner and turbine and enters the main burner through a mixer, where it joins the gas stream exiting from the turbine. The stream of mixed gas is then accelerated through a variable-area exhaust nozzle to provide the required propulsive thrust. Thrust augmentation may be obtained by injecting an excess of fuel in the preburner so that, when the fan air is mixed with the fuel-rich turbine exhaust, additional combustion, or afterburning, takes place in the main burner. See AFTERBURNER.

At very high flight speed, with air at very high ram pressure entering the engine, the pumping action of the fan is no longer necessary and the fan may be feathered, or otherwise made inoperative, while permitting the ram air to pass through. Propulsion is now provided exclusively by the combustion of the ram air in the main burner with the fuel-rich gas stream from the preburner.

For aircraft that are designed to proceed from high-speed atmospheric flight to transatmospheric flight, a rocket chamber may be provided in the engine where fuel and oxidant are mixed in greater quantity than is possible in the preburner, and the exhaust stream may be discharged through the thrust nozzle without having to pass through the turbine.

Application. The turbosfan was invented in the late 1940s. A prototype of the basic engine system was prototyped in the United States in the late 1940s. Very intensive study and some preliminary development is under way in the United States, Japan, Russia, and Europe, with the goal being a new generation of very high-speed transport aircraft that may use the turbosfan or a related engine type. See AIRCRAFT ENGINE, AIRCRAFT PROPULSION.


Turbulent flow

A fluid motion in which velocity, pressure, and other flow quantities fluctuate irregularly in time and space. Figure 1 shows a slice of a water jet emerging from a circular orifice into a tank of still water. A small amount of fluorescent dye mixed in the jet makes it visible when suitably illuminated by laser light, and tags the water entering the tank.
In this and similar realizations of the flow, there is a small region close to the orifice where the dye concentration does not vary with position, or with time at a given position. This represents a steady laminar state. Generally in laminar motion, all variations (if they occur at all) of flow quantities, such as dye concentration, fluid velocity, and pressure, are smooth and gradient in time and space. Further downstream, the jet undergoes a transition to a new state in which the eddy patterns are complex, and flow quantities (including vorticity) fluctuate randomly at time and three-dimensional space. This is the turbulent state. See JET FLOW; LAMINAR FLOW.

Turbulence occurs nearly everywhere in nature (in the Earth’s boundary layer extending to more than a few hundred meters upward from the ground), the jet stream, cumulus clouds, rivers and oceans, the stellar atmosphere, interstellar gas clouds, and so forth) and in technology (in flow across airplanes, flow over turbine blades, flow of natural gas and oil in pipelines, combustion systems, and so forth). Two important characteristics of turbulence are the efficient dispersion and mixing of vorticity, heat, and contaminants. In flows over solid bodies such as airplane wings or turbine blades, or in confined flows through ducts and pipelines, turbulence is responsible for increased drag and heat transfer. Turbulence is therefore a subject of great engineering interest. On the other hand, as an example of collective interaction of many coupled degrees of freedom, it is also a subject at the forefront of classical physics. See DEGREE OF FREEDOM (MECHANICS); DIFFUSION; HEAT TRANSFER; PIPE FLOW; PIPELINE.

Figure 1 demonstrates the principal issues associated with turbulent flows. The first is the mechanism (or mechanisms) responsible for transition from the steady laminar state to the turbulent state; even though, for both states, the governing equations (the Navier-Stokes equations) are the same, and the same smooth and symmetric boundary conditions are imposed on the flow everywhere. A second issue concerns the description of fully developed turbulence typified by the complex state far downstream of the orifice. To understand and describe the essential features of these spatial patterns, their interactions, and statistical evolution, and to develop on this basis a rational theory capable of predicting flow features, is at the heart of turbulence theory. Finally, it is of technological importance to be able to alter the flow behavior to suit particular needs. Delaying transition to turbulence, or preventing it, or affecting the speed rate of the jet, or decreasing the drag of an airplane wing, or reattaching a turbulent flow some dis-
tance downstream of where it has become tur-

tent are some examples. Together, these three as-

pects—the origin of turbulence, the dynamics of

duly developed turbulence, and the control of tur-

tent flows—constitute the turbulence problem.

The problem assumes other complications when ef-

fects such as buoyancy, compressibility, electro-

magnetic conductivity, and chemical reactions are

included. In spite of sustained efforts, turbulence has

remained unsolved. Less is known about eddy

motion on the scale of centimeters and millimeters

than about atomic structure on the submicrometer

scale, reflecting the complexity of the turbulence

problem. See NAVIER-STOKES EQUATIONS.

Origins of turbulence. A central role in determining

the state of fluid motion is played by the Reynolds

number. In general, a given flow undergoes a suc-

cession of instabilities with increasing Reynolds

number and, at some point, turbulence appears

more or less abruptly. It has long been thought

that the origin of turbulence can be understood

by sequentially examining the instabilities. This

sequence depends on the particular flow and, in

many circumstances, is sensitive to a number of

details even if the gross features in a given flow

are nominally fixed. The program of precisely

identifying the various instabilities culminating

in fully developed turbulence has not been carried

out for any flow, but a careful analysis of the perturbed

equations of motion has resulted in a good

understanding of the first two instabilities (primary

and secondary) in a variety of circumstances. See

REYNOLDS NUMBER.

Since the onset of turbulence resembles the onset

of complexity in nonlinear systems at general,

universality theories describing the onset of chaos

have been thought to bear on the transition to

turbulence in fluid flows. The spot of universality

is that, no matter what equations govern a low-

dimensional system, its behavior in the vicinity of

 bifurcations depends on certain generic features

in phase space. This issue is an active area of

research, and the experience so far has been

that the onset of chaos in specific types of flows

under special circumstances follows these theories,

at least to a very good approximation, but the

relation between chaos (or temporal stochasticity)

and fluid turbulence (which possesses temporal as

well as spatial randomness, and large-scale order

underlying the latter) remains unclear. See CHAOS.

Fully developed turbulence. Some of the principal
difficulties in fully developed turbulence are the

following: (1) The equations of motion are

nonlinear, possess by general solutions, and permit

few statements of general validity to be made;

there is no small parameter in the problem on

the basis of which approximate solutions can be

deduced rigorously. (2) There is no well-

understood working model of turbulence that

replicates its essential properties. (3) Turbulent

velocity fluctuations at small scales are strongly

non-Gaussian, this being an essential feature. (4) The

number of degrees of freedom is very large. See

DISTRIBUTION (PROBABILISTIC).

An estimate of the number of degrees of freedom

is given by the quantity $r \ell / \nu$, where $r$ is the

characteristic size of the large eddy in the flow

for an upper bound for the eddy scale either excited

by inherent instability or forced by an outside

agent, and $\nu$ is the smallest scale below which

eady motions are damped by viscosity. This

number increases with the flow Reynolds number

according to its $3 / 4$ power. Three-quarters of the

way downstream from the cowl in Fig. 1, the ratio

$r / \nu$ is of the order of 100. Although such flows can

now be computed directly, the prospect at high

Reynolds numbers remains discouraging—for the

atmosphere, $r$ is of the order of a few kilometers

whereas $\nu$ is of the order of a millimeter—even

though computational capabilities have continued

to increase rapidly and parallel processing has been

much considered as a tool for expanding the scope

of computation. See CONCURRENT PROCESSING,

SUPERCOMPUTER.

Quite often in engineering, the detailed motion is

not of interest, but only the long-time averages

or means, such as the mean velocity in a boundary

layer, the mean drag of an airplane or pressure loss

in a pipeline, or the mean spread $\sigma$ of a jet. It

is therefore desirable to rewrite the Navier-Stokes

equations for the mean motion. The basis for doing

this is the Reynolds decomposition, which splits

the overall motion into the time mean and fluctuation

about the mean. These macroscopic fluctuations

transport mass, momentum, and energy (in fact, by

orders of magnitude more efficiently than

molecular motion), and their overall effect is thus

perceived to be in the form of additional transport

or stress. This physical effect manifests itself as

an additional stress (called the Reynolds stress)

when the Navier-Stokes equations are rewritten

for the mean motion (the Reynolds equations). The

problem then is one of prescribing the Reynolds

stress, which contains the unknown fluctuations in

quadratic form. A property of turbulence is that

the Reynolds stress terms are comparable to the

other terms in the Reynolds equation, even when

fluctuations are a small part of the overall motion.

An equation for the Reynolds stress itself can

be obtained by suitably manipulating the Navier-

Stokes equations, but this contains third-order terms

involving fluctuations, and an equation for third-

order terms involves fourth-order quantities, and

so forth. Thus, at any stage of the process, which

can be continued indefinitely, there are more

unknowns than equations, that is, the system of

equations is not closed. This is the closure problem

in turbulence. The Navier-Stokes equations are

themselves damped, but the presence of nonlinearity

and the process of averaging result in nonclosure.

Given this situation, much of the progress in

the field has been due to (1) exploratory

experiments and numerical simulations of the

Navier-Stokes equations at low Reynolds numbers,
Turbulent flow

and (2) plausibility of hypotheses in conjunction with
dimensional reasoning, scaling arguments, and their
experimental verification.

Experiments. For long the central tool of
research in turbulence, are limited to measuring
a small number of parameters at a few positions
in high-Reynolds-number flows. Low-Reynolds-
umber flows (in at least some of their features)
can be quantitatively mapped in three dimensions
by using lasers and advanced optical techniques;
this Reynolds number range is also the one for
which numerical simulations are currently possible.
From a combination of such studies, it has been
learned, among other things, that the magnitude of
the dissipation rate of turbulent kinetic energy
is independent of viscosity (even though viscosity
is essential for dissipation); that the boundary
between the turbulent and nonturbulent regions
in high-Reynolds-number free shear flows such as
ejets is sharp and fractal-like; that the dissipation
of energy is highly intermittent in space; that some
events that appear to be dynamically significant
are also intermittent and perhaps quasi-stable; and
that, when the flow scales are suitably coarse-
grained, some degree of spatial order on scales
of order L is visible even at very high Reynolds
terms, especially if the flow development time
is observed. The true significance of each of these
features in accomplishing transport is still under
active research. See FRACTAL COMPLEXITY.

The intermittency in space of the turbulent
dissipation is shown at moderate (Fig. 2a)
and high (Fig. 2b) Reynolds numbers. The signal
becomes less space-filling or more intermittent
as the Reynolds number increases. In particular,
the big spikes in Fig. 2b are many times larger
than the corresponding ones in Fig. 2a. This
intermittency, representing the fact that there is
a limit to the mixing at small scales, is believed to be
an important feature of turbulence. It is not entirely
clear how this feature arises dynamically, but it can
be modeled by a simple multiplicative process.

A classic and celebrated hypothesis is the concept of
local isotropy, which assumes that
small scales of motion are isotropic irrespective
of the gross orientation of the mean flow, and
thus possess some universality. A second notion
is the separability between behaviors of highly
dispersive scale ranges so that a functional form
for average quantities of interest can be determined
for the intermediate scale range. For example, in the
turbulent boundary layer over a flat wall, this type
of argument leads to a logarithmic variation of mean
velocity with height for heights large compared to
the viscous scale and small compared to the
overall thickness of the boundary layer. Similarly,
intermediate scales that are large compared to a
but small compared to L (the so-called inertial range)
are expected to possess self-similarity leading to
power-law variations for the spectral densities
of energy, dissipation, variance of concentration
fluctuations, and so forth. These predictions have
received experimental support, and, in fact, they
seem to be realized under conditions where they are
not necessarily expected to be valid, based on
formal principles. This raises the possibility
that the basic theoretical arguments of this type
(which, incidentally, do not make much use of
the Navier-Stokes equations) have a much wider
range of validity. This should be emphasized when
these arguments predict an absolute number in the
inertial range, but not elsewhere. See BOUNDARY-
LAYER FLOW.

Certain specific questions of engineering interest
can be answered quickly by modeling the Reynolds
number in a variety of ways and closing the
Reynolds equations. The earliest model, based
on analogies with molecular motion, postulated
that the physical motion of eddies over well-
defined distances accomplishes transport. The
resulting eddy viscosity—essentially the product of
a characteristic velocity scale and a length scale
of turbulent motion—is the analog of molecular
viscosity. Even though there are circumstances
where the eddy viscosity approach works roughly,
the concept has many drawbacks and is not very
useful as a general idea; in any case, the eddy
viscosity varies from flow to flow and from point
to point in a given flow. In the next level of models,
separate equations are written for the length and
velocity scales making up eddy viscosity, but there are several unknown coefficients that have to be determined empirically. There are more common models, all of which resort to empiricism due to meterological quality at some level. In spite of this drawback, they are quite useful once the limits of their validity have been established. At present, they represent a practical way of computing high-Reynolds-number flows of technological interest. Another fruitful approach is the large-eddy simulation, which models the small-scale motion but simulates large eddies on the computer.

Control of turbulent flows. Unlike some other issues in turbulence, questions concerning flow control can be posed in specific terms. However, because of this specificity, a host of approaches to the control problem encompassing all circumstances is unlikely to succeed. Some typical objectives are the reduction of drag of an object such as an airplane wing, the suppression of combustion instabilities, and the suppression of vortex shedding behind bluff bodies. A surge of interest in flow control is due in part to the discovery that some turbulent flows possess a certain degree of spatial coherence at the large scale. An example of successful control, based on an unrelated idea, is the reduction of the skin friction on a flat plate by making small longitudinal grooves, the so-called riblets, on the plate surface, imitating shark skin.

Prospects. Progress in the turbulence problem depends on the capability to make accurate measurements in high-Reynolds-number flows, the increase in computer power, the invention of new tools for handling large streams of stochastic data, and a judicious combination of all of these. Unfortunately, simply computing or making measurements in a highly nonlinear system such as turbulent flow does not always add to understanding. Although several new analytical tools, graphical display capabilities, and data-compression and data-handling techniques are being explored, it is difficult to predict what true progress is likely to occur through the 1990s. It is clear, however, that turbulence will spur important activity in a number of disciplines at the forefront of science and technology; conversely, it will benefit from them. To the long run, perhaps, all these tools can enhance the qualitative understanding of turbulence, so we obtain quantitative data in a sensible way. This would resemble to some extent the situation in quantum chemistry. See FLUID FLOW: FLUID FLOW PRINCIPLES.


*Turmeric*

A dye or a spice obtained from the plant Curcuma longa, which belongs to the ginger family (Zingiberaceae). It is a stout perennial with short stem, toothed leaves, and short, thick rhizomes which contain the colorful condiment. As a natural dye, turmeric is orange-red or reddish brown, but it changes color in the presence of acids or bases. As a spice, turmeric has a decidedly musty odor and a pungent, bitter taste. It is an important ingredient in curry and is used to flavor and color butter, custards, pickles, and other food. See SPICE AND FLAVORING; ZINGIBERACEAE.

Perry D. Strasburg/Earl L. Core

*Turn and bank Indicator*

A combination instrument which provides an aircraft pilot with two distinct pieces of information: the aircraft's rate of turn about the vertical axis, and the relationship between this rate and the aircraft's angle of bank. It is also known as the needle and ball indicator or the turn and slip indicator.

The turn needle is operated by a gyroscope and indicates the rate at which the aircraft is turning about the vertical axis in degrees per second. Semirigid mounting of the gyro permits it to rotate freely about the lateral and longitudinal axes while restricting motion about the vertical axis (see ILLUS.). In a turn, gyrostic precession causes the rotor to tilt in the direction opposite the turn with a magnitude proportional to the turn rate. A mechanical linkage converts this precession to reversed movement of a turn needle, thus indicating proper turn direction. A spring attached between the gyro assembly and the instrument case holds the gyro upright when precession force is not