Research on

WALL TURBULENCE

THOMAS J. HANRATTY
University of Illinois
Urbana, IL 61801

Fluid mechanics research at the University of Illinois at Urbana is being conducted by Prof. Jonathan J. L. Higdon, Prof. A. J. McHugh and myself. Dr. Higdon is doing work in the areas of biological fluid mechanics and the mechanics of concentrated suspensions. Dr. McHugh is studying flow induced crystallization of polymers, and the flow behavior of dilute polymer latex suspensions. My own work is concerned with the structure of turbulence, turbulent mass transfer, atomization, droplet dispersion, flow over wavy surfaces and the modelling of air-liquid and solid liquid flow systems. This paper gives an account of research on the structure of turbulence close to a solid boundary.

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ONE OF THE FIRST topics covered in an elementary course in fluid dynamics is the experiment by Osborne Reynolds [1] in 1883 which showed that the preferred motion of fluid particles through a pipe at large flow rates is turbulent. On the basis of these experiments he explained why at high flows the law characterizing the frictional pressure loss abruptly changes from a linear to an approximately quadratic dependence on fluid velocity.

A simple force balance on a cylindrical element of fluid under fully developed conditions, as indicated in Fig. 1, shows that a shear stress τ can be defined which is related to the frictional pressure gradient $\left|\frac{\Delta P}{\Delta x}\right|$ and the radial location r by the equation

$$\tau = -\frac{r}{2}\left|\frac{\Delta P}{\Delta x}\right| \tag{1}$$

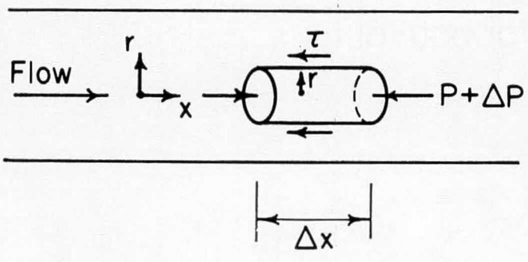


FIGURE 1

For laminar flows this shear stress can be related to the velocity gradient $\frac{dV}{dr}$ through Newton's law of viscosity

$$\tau = \mu\frac{dV}{dr} \tag{2}$$

and the velocity field can be calculated by substituting (2) into (1) and integrating. The kinetic theory of gases interprets τ as equal to the negative of the momentum flow per unit time through a unit area perpendicular to the r - axis. This momentum flux can be explained as due to the mixing by molecular motion of high and low velocity fluid in adjacent streamlines; the viscosity is related to the mean free path λ and velocity of the molecules c by the relation $\mu = kc\lambda$, where k is a proportionality constant.

For a turbulent flow the components of the velocity vector may be considered as the sum of time averaged and fluctuating quantities,

$$V_i = \overline{V}_i + u_i \quad . \tag{3}$$

Reynolds showed that the fluctuating flow can give rise to much larger fluxes of momentum than in purely laminar flow and defined the turbulent contribution to the fluid stress as $\tau^t_{ij} = -\rho\,\overline{u_i u_j}$, now called the Reynolds stress. Thus for fully developed flow in a pipe

$$\tau_{rx} = \mu\frac{d\overline{V}_x}{dr} - \rho\,\overline{u_r u_x} \quad , \tag{4}$$

where τ_{rx} is the x-component of the stress on a face perpendicular to the r-axis. Over most of the pipe cross section the mixing due to turbulence is much larger than the mixing due to molecular motion so that the velocity gradient need not be very large to maintain the fluid stress. However, in a thin region close to the wall $-\rho\,\overline{u_r u_x}$ is close to zero so that $\frac{d\overline{V}_x}{dr}$ must assume very large values in order to sustain the stress. This large variation of the Reynolds stress close to a wall accounts for the blunt shaped velocity profiles observed for turbulent flows. The region close to the wall where the Reynolds stresses are negligible has been called the viscous sublayer. It extends a distance from the wall y given as $y^+ = \frac{yv^*}{\upsilon} = 5$, where v^* is the friction velocity equal to $(\tau_w/\rho)^{1/2}$, υ is the kinematic viscosity, and ρ is the fluid density. The region where $\mu \frac{d\overline{V}_x}{dr}$ is making a significant contribution to the fluid stress is called the viscous wall region and is defined as $y^+ < 30$.

Considerable research has been done since the time of Reynolds which is useful in interpreting phenomena occurring in turbulent fields, but the main issues raised by his work are still unresolved: (1) What is the mechanism by which the flow through interaction with the bounding walls sustains the turbulence? (2) How can the variation of the Reynolds stresses in a flow field be predicted?

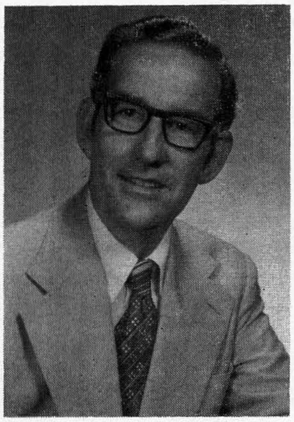
Engineering practice today is quite often based on early theoretical work which used physical models successful in treating laminar flows to predict the Reynolds stress. One approach defines a turbulent viscosity μ_t analogous to a molecular viscosity so that

$$-\rho\,\overline{u_r u_x} = \mu_t \frac{d\overline{V}}{dr} \,. \qquad (5)$$

Another uses mixing length concepts analogous to the mean free path defined in kinetic theory;

$$\mu_t = q\,l \quad , \qquad (6)$$

where q characterizes the magnitude of velocity fluctuations. A practical difficulty in using these theories is that an unknown spatial variation of μ_t or l is substituted for an unknown variation of $\overline{u_i u_j}$. A conceptual difficulty, which is perhaps more serious, arises because measured values of l are found to be of the same magnitude as the size of the container. This suggests that the Reynolds stress cannot be related to local properties of the velocity field, as implied in a Newtonian approach. The understanding and the prediction of the production of turbulence and of Reynolds stress in a turbulent field therefore requires information on the structure of the fluctuating velocity field.



Thomas J. Hanratty has been a member of the Chemical Engineering faculty of the University of Illinois since 1953. He was educated at Villanova, Ohio State, and Princeton, Ph.D. (1953). His professional honors include the Colburn, Walker and Professional Progress Awards of the A.I.Ch.E. and the Curtis W. McGraw and Senior Research Awards of the A.S.E.E. He was elected to the National Academy of Engineering in 1974.

A considerable effort is now underway in a number of laboratories to determine the structure of turbulent flows and it is quite likely that some very meaningful breakthroughs will be made in the next ten years. This current effort has been made possible by the development of multiprobe measuring techniques and of computer methods for handling the data obtained from these measurements.

In my laboratories at the University of Illinois we are engaged in an extensive study of the structure of turbulence in the viscous wall region, where the production of turbulence is a maximum. One of the reasons for concentrating on the viscous wall region is that an understanding of the mechanics of this region could be the key to finding out how the turbulence is sustained. Another reason is that many processes of vital interest to chemical engineers are controlled by happenings very close to a boundary. In this paper I will outline some of the work we are doing to obtain structural information on the viscous wall region and how we are using this information to study mass transfer at boundaries and flow over wavy surfaces and to control turbulent fields.

In order to understand the difficulties involved in obtaining detailed flow information on the viscous wall region one has to realize the smallness of this region. For flow in a 5 cm pipe at a Reynolds number of 500,000 the dimensionless distance $y^+ = 30$ would correspond to a distance from the wall of only 0.08 mm. It is therefore advantageous to work in large diameter pipes at small Reynolds numbers. We have developed a test loop for water flows with a diameter of 19.4 cm that occupies five floors in our building. At a Reynolds number of 30,000 dimensionless distance $y^+ = 30$ would then correspond to a y of 3.5 mm. Even with this improvement of spatial resolution the use of conventional techniques to study the details of the flow in the viscous wall region is not an option.

In a Ph.D. thesis from this laboratory Reiss [2, 3, 4] invented a new method to study the flow close to the wall without interfering with it. Circular electrodes with diameters as small as 0.12 mm are embedded flush with the wall of a pipe through which an electrolyte is flowing. These electrodes are the cathodes of an electrolysis cell. The anode is a section of a pipe wall of much larger area than the cathode located downstream of the cathode. The electric current flowing in the electrolysis cell is then controlled by happenings at the cathode. The cathode is operated at a high enough voltage that the kinetics of the electrochemical reaction is not influencing the current flow and, yet, small enough that side reactions are not occurring. Reiss showed that under these conditions the average electric current could be related to time averaged value of the velocity gradient at the wall $\overline{S}_x$ and that the time variation of the current could be related to the time variation of the x-component of the fluctuating velocity gradient at the wall s_x. Thus the limiting behavior of the velocity field close to the wall could be determined using these techniques since

$$\overline{U}_x = \overline{S}_x y \quad y \to 0 \tag{7}$$

$$u_x = s_x y \quad y \to 0 \tag{8}$$

In theses by Mitchell [5, 6] and Sirkar [7, 8] other electrode configurations were investigated. It was found that a rectangular electrode with its long side perpendicular to the flow can be used to measure s_x and that rectangular electrodes at a slant to the mean flow are sensitive both to s_x and to s_z, the spanwise component of the fluctuating velocity gradient at the wall. By measuring the sum and the difference of the signals to two rectangular electrodes in a chevron arrangement both fluctuating components, s_x and s_z, can be measured at a given location on the wall. By measuring simultaneously the current flowing to arrays of these chevron electrodes it is possible to obtain structural information on the velocity field in the immediate vicinity of the wall. To do this we measure as many as 40 signals. This requires the use of a computer to handle and analyze the data. Of particular value are newly developed techniques for conditional averaging which enables us to study repeatable events.

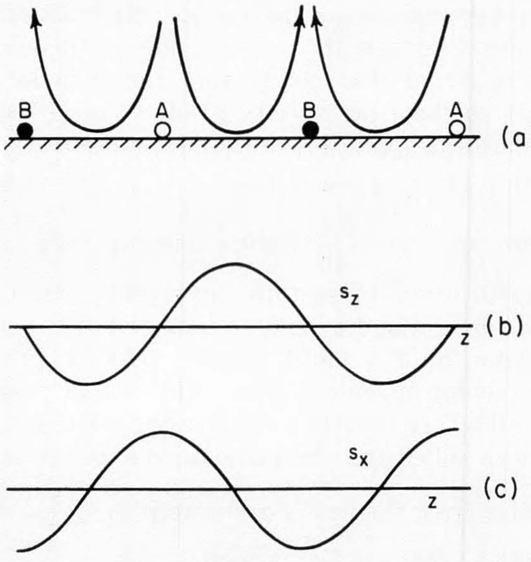


FIGURE 2

Studies with arrays of these electrodes have revealed that the flow in the viscous wall layer is dominated by an elongated secondary flow, of the type shown in Fig. 2a. It is approximately homogeneous in the flow direction, has a spanwise wavelength of $\lambda^+ = 100$, and evolves over a dimensionless period Tv^{*2}/υ approximately equal to 100. In theses by Sirkar [7, 9] and Fortuna [10, 11] it is suggested that these eddies control the transfer of momentum to the wall. High velocity or high momentum fluid is carried toward the wall by the secondary flow. Momentum is transferred to the wall as this secondary flow carries the high momentum fluid parallel to the wall. Momentum deficient or low velocity fluid is then ejected from the wall by the outward motion associated with the secondary flow. This model suggests the phase relation for the spatial variation of s_x and s_z shown in Fig 2 b, c. Detailed studies by Lee [12, 13] and Hogenes [14] of signals from arrays of wall electrodes as well as from a combined array of wall electrodes and fluid probes have confirmed this picture. It thus appears that the level of Reynolds stress production in a turbulent flow could be strongly dependent on the properties of these wall eddies. Experiments are now under way to show this directly.

The definition of this repetitive event at the wall through research in our laboratory and in other laboratories throughout the world has been a very significant forward step in understanding wall turbulence. However, there are a number of important questions which have to be resolved before a complete understanding can be obtained. What is the origin of these structures? Why do they scale in the manner observed? What are the details of interaction of these structures with the outer flow? How should these newly gained insights be used to help develop predictive models for the Reynolds stress?

The above long range questions are now being pursued by students in my research group. However, we are also using newly gained insights about the flow close to a wall to enable us to obtain a better understanding of some shorter range turbulence problems, such as mass transfer to a boundary [9, 15, 16, 17, 18] or flow over wavy surfaces [19, 20, 21, 22].

One of the first concepts presented to chemical engineering students when they are introduced to mass transfer is that of the "diffusion layer" which seems to have evolved from the work of Noyes and Whitney [24] and of Nernst [23]. It visualizes the existence of a stagnant fluid of thickness δ at a boundary and gives the mass transfer coefficient as $k = D/\delta$, where D is the molecular diffusion coefficient. Convective motions close to the boundary are pictured to control the mass transfer process by controlling the thickness δ. It has been recognized for some time that the flow in the immediate vicinity of a boundary is not laminar or stagnant and therefore δ has been labelled a "fictitious" film thickness. A number of attempts have been made to provide more realistic models which relate mass transfer rates to convective motions close to a boundary. These include surface renewal concepts, analogies between mass and momentum transfer and various pseudosteady state eddy models. The results recently obtained on flow close to a boundary suggest that these attempts to improve the diffusion layer concept are not correct. We are currently pursuing a description of the mass transfer process at solid-fluid and at gas-fluid boundaries which is consistent with the known fluid mechanics.

Our work at solid fluid interfaces is being aided by studies of the fluctuations of the local mass transfer rate at multiple locations in a large mass transfer surface. We find that the structure of the fluctuating mass transfer field resembles that of the flow oriented eddies but that its frequency is an order of magnitude smaller. A number of laboratories, as well as our own, are now trying to resolve this apparent paradox. I am reasonably confident that a very significant improvement in our understanding of turbulent mass transfer to solid boundaries will be obtained over the next few years.

An important unsolved problem in fluid mechanics is an understanding of the interaction of a turbulent fluid and a wavy surface; i.e. the variation of the pressure and shear stress along the wavy surface. Oceanographers have taken an active interest in this problem because of the need to understand the mechanism by which the wind feeds energy to the ocean. It also is of importance in a number of problems that concern chemical engineers, such as the atomization of fluids and the prediction of flow regimes in air-liquid flows. The key theoretical issue is to determine how the flow perturbations introduced by the wavy surface modulate the Reynolds stresses. We have been carrying out studies of flow over solid wavy surfaces in order to resolve this issue and have found out that the chief effect of the waves on the Reynolds stresses is being felt in the viscous wall region. The flow velocity increases close to the wave peaks and decreases close to the wave troughs because of the compression and spreading apart of the streamlines. According to the Bernoulli equation this change in fluid velocity is accompanied by changes in pressure. We are able to relate the modulation of the Reynolds stress to the effect of pressure gradient on turbulence properties in the viscous wall region. It would be quite challenging to be able to explain these results using the information that has been obtained on the structure of turbulence close to a wall.

Perhaps the most interesting practical aspect of the results currently being obtained on turbulence structure is the possibility of controlling turbulence by altering the properties of the repetitive cycle of events that are observed in the viscous wall region. One possibility cited above with reference to our studies of flow over wavy surfaces is the use of pressure gradients. Another which we are currently exploring is the use of oscillations in the mean flow. In these experiments a sinusoidal variation with an amplitude of about one tenth the mean flow and a frequency approximately equal to the frequency of the flow oriented eddies is being superimposed on the feed to test section of our turbulent flow loop.

The most dramatic result obtained by altering turbulent flow has been the finding that the addition of very small amounts of long chain polymers to a turbulent liquid flow can reduce pressure losses by a factor of two. We have been carrying out experiments [10, 25] with these drag-reducing polymers and have found out that their principal effect is to increase the spanwise dimension of the flow oriented wall eddies [26, 27]. One of the students, Larry Chorn, who participated in that research joined Atlantic Richfield after completing studies for his Ph.D. degree. He became involved with a project that was to explore the possibility of putting drag-reducing polymers in the Alaska pipeline. The net result of the Atlantic Richfield effort was to increase the throughput 190,000 barrels per day by using 15 ppm of polymer. ☐

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