REVIEWS

The Scientific Papers of G. I. Taylor. Vol. II: Meteorology, Oceanography and Turbulent Flow. Edited by G. K. BATCHELOR. Cambridge University Press, 1960. 515 pp. 75*s*. or $14.50.

This second volume of the collected scientific papers of G. I. Taylor carries the subtitle 'Meteorology, Oceanography and Turbulent Flow', but the whole has a homogeneity of outlook and subject which goes beyond that conveyed by the title and is perhaps not expected knowing the versatility of the author. This common subject is the nature and effects of turbulent flow, in the sea or the atmosphere or the laboratory and, by my count, forty of the forty-five papers relate to turbulence and only the five on tidal oscillations deal wholly with non-turbulent flow. Although there is much of interest for meteorologists and oceanographers, this volume may be regarded as an account of the development of the statistical theory of turbulence and the associated ideas that are fundamental to modern studies of turbulent flow. Acknowledging the importance and originality of this work, it is more interesting to trace the origin and development of the central ideas than simply to applaud the achievement.

When reading these papers, some I regret to say for the first time, I was surprised to see how much of the work on turbulence was published either between 1915 and 1919 or between 1935 and 1938. I formed the impression that G. I. Taylor arrived at his understanding of the nature of turbulent flow during the first period, and put it into mathematical form in the second period when advances in experimental techniques had made possible measurements of fluctuations.

Paper 1 in this volume, 'Eddy motion in the atmosphere', introduces the mixing-length theory of eddy transport, uses it to describe transport of momentum, heat and humidity, derives the variation of wind velocity and direction with height and, in passing, points out that Rayleigh's criterion for flow stability is inapplicable to channel flow because of the no-slip condition at the walls. The second, a discussion of Reynolds's analogy between heat and momentum transfer, describes the motion in the viscous (or 'laminar') sublayer and most of the fundamental concepts of turbulent flow appear in the following papers. Perhaps the most interesting feature is the continual insistence that turbulent motion must be three-dimensional, with its corollaries that vorticity is being produced by continuous extension of vortex-filaments and that the lack of scale effect in turbulent flow depends on a separation in the length-scales of the motions responsible for energy dissipation and for transport of heat and momentum. As far as I can make out, G. I. Taylor has never believed that an adequate description of any kind of turbulent flow could be obtained either by assuming two-dimensional flow or by linearizing the Navier-Stokes equations.

The second period commences with the formulation of the statistical theory of turbulence which has been the model and inspiration for nearly all subsequent investigations of turbulent flow. It is impossible to overrate the importance of this work but, after reading the papers of the first period, the impression persists that the early work contains the bones of the matter and that the theory was constructed explicitly only when the techniques of fluctuation measurement made the construction not merely a mathematical exercise but a tool for the quantitative investigation of the motion and for the detailed verification of the basic concepts. For this purpose the theory has been extremely successful, but it is curious that the basic simplifying assumption of isotropy now appears more as a catalyst than as an essential ingredient in the theory and survives only in the restricted form of local isotropy. If I were asked to say in what respects we are better informed than we were in 1938, I might point rather doubtfully at the imposing but chaotic mass of experimental material but the only new idea is that the eddies transferring heat and momentum are comparatively stable objects and that randomness and isotropy are characteristic of the dissipative eddies only.

Only two papers of significance in the theory of turbulence seem to have been published outside these periods and one, on turbulent diffusion by continuous movements, is perhaps singular in that no experimental material is presented. The other, on the vorticity transport theory, is most intriguing in its attitude to the mixing-length theory. It is accepted now that the mixing-length theory is wrong and misleading and that no one would use it except engineers and meteorologists who prefer to have some answer rather than none at all, but the case against it has been overstated. For a corrective, read this paper and notice the care taken to form an acceptable model of the diffusion process. Notice also the extreme caution with which Taylor uses the second relation of mixing-length theory which assumes that eddy diffusivity is a function of mean velocity gradient and of position in the flow. In fact, he derives a relation between temperature and velocity in a wake which does not depend on the second relation and which is in much better agreement with recent measurements than the explicit results which do assume the second relation.

One important development which finds no place in these pages is the theory of local isotropy, introduced by Kolmogoroff in 1941 and since then accepted as the proper framework for discussion of the small-scale motion. In some respects, this is a natural extension from the statistical theory and the idea that the motion responsible for eddy transport is not influenced appreciably by the nature of the dissipation process, but the basic assumption of universal equilibrium of the small-eddy motion does not appear to have been anticipated by Taylor and is, I believe, not easily reconciled with his view of the dissipation process as 'the formation of very small regions where the vorticity is very high' (p. 465) caused by continued stretching of vortex lines. This view emphasizes the connexion between motions on large and small scales, and seems to imply that the independence assumed in the theory of local isotropy is not complete and may not extend to some aspects of the motion. Some evidence that very small regions of high vorticity do exist (Sandborn, *J. Fluid Mech.* **6**, 1959, 221) and that the stretching process is persistent (Townsend, *Proc. Roy. Soc.* A, **209**, 1951, 418) confirms the connexion and indicates that universal equilibrium is not complete. On the other hand, it is difficult to believe that the small eddies of turbulent flow are not in some kind of universal equilibrium with a structure dependent on the rate of energy dissipation and perhaps the length scale of the large eddies. An improved theory of local isotropy which will reconcile our belief in some form of universal equilibrium with an accurate and realistic view of the dissipation process still lies in the future but it is a problem of very great interest.

Some readers of this volume will have other interests than the nature of turbulent flow, and for them I recommend it as a way of watching G. I. Taylor solve complex problems by close combination of theory and observation. Although a reader is denied the characteristic hand-waving (to illustrate extending vortex-filaments, for example), he may notice the clarity of thought, the ability to make an approximate calculation based on inexact measurements and so to produce an unbelievably precise answer, and, of course, the habit of having done the work twenty or more years ago.

A. A. TOWNSEND

Advances in Geophysics. Vol. 6: Atmospheric Diffusion and Air Pollution. Edited by F. N. FRENKIEL and P. A. SHEPPARD. New York: Academic Press, 1959. 471 pp. $12.00.

The study of atmospheric turbulence encompasses phenomena as diverse as the dispersal of radioactive debris in the stratosphere and evaporation from the ground, all of which have a complicated dependence on several variables. Research in such a field is likely to be successful only if it is planned soundly and workers appreciate the significance of what they are doing. The reviewer has found that in many cases this can be achieved most easily by distinguishing three stages in an investigation: first, general exploration; second, definition and exploitation of a simplified model exhibiting the main features of the phenomenon; and third, elaboration of the model to bring it into closer correspondence with reality. Although work on the three stages may proceed simultaneously, their confusion is a common cause of failure.

This point of view may be illustrated by a consideration of flow near the ground. Early exploratory work established the importance of the dynamic effects of a vertical gradient of potential temperature and its associated heat flux, and showed that the shear stress and heat flux often vary little in the first few tens of metres above the surface. This has led to the theoretical study of an idealized flow which is exactly steady in space and time and in which the shear stress and heat flux are constant. With this model and a few plausible assumptions, such as that the roughness length characterizing the surface does not affect the internal mechanism of the flow, it has been possible to deduce a number of important results from dimensional arguments. In particular, all dimensionless properties of the turbulence, such as, for example, the correlation coefficient between temperature and vertical velocity, must be functions of z/L, where L is the length introduced by Monin and Obukhov to represent the dynamical effects of the heat flux and is equal to $\bar{\rho}u_*^3/g\overline{\rho' w'}$ (u_* is the friction velocity). Of course, conditions in the real atmosphere depart considerably from those assumed in the model, and it is not surprising that observations do not always agree with the theoretical predictions. Indeed, the discrepancies may be of considerable practical importance, and one would not wish to discourage their study. However, it does seem clear that they will be understood only through an extensive quantitative investigation of the manner in which real conditions in individual cases depart from the ideal. At present, while our knowledge of the model flow is sparse, there would seem to be a good case for concentrating research on conditions as near the ideal as possible.

The volume under review contains the proceedings of an international symposium on atmospheric diffusion and air pollution, held at Oxford in August 1958. For a reader with the above background in mind, it may make depressing reading. The aim of the symposium was 'to bring together fluid dynamicists, meteorologists, oceanographers and other scientists in order to discuss atmospheric diffusion and some basic aspects of its application to air pollution studies'; and one might have expected the organizers to have chosen introductory speakers who would provide a clear exposition of the present state of their field and provide a firm framework on which the contributions of the later speakers could be hung. In fact, with the exception of that by A. J. Haagen-Smit, whose lecture on the chemistry of urban air pollution was rather far removed from the main theme of the conference, the introductory reviews were mainly historical and in some cases rather superficial; they failed to show what parts of the subject the speakers regarded as established or where and how it was growing.

The remainder of the meeting consisted of a succession of isolated papers of very variable quality, only a few of which can be mentioned here. F. Gifford made good use of a relatively new method of treating the plume of pollutant from a continuous fixed source: he considered the waving of the plume and the growth of its instantaneous width separately. H. H. Lettau presented the results of an analysis of surface friction in relation to the geostrophic wind and showed the dependence of the drag coefficient on the 'surface Rossby number', $\mathrm{Ro} = V_g/z_0 f$, the importance of which has been known for some time from 'Ekman spiral' calculations.

A number of papers were concerned with measurements of various spectra of turbulence near the ground, but in none of them were the results adequately related to any theoretical model. H. A. Panofsky and R. J. Deland gave a review of present knowledge of one-dimensional Eulerian spectra. H. E. Cramer also reported extensive measurements. He introduced the interesting idea of measuring correlations between quantities filtered so as to include only a narrow band of frequencies, but he made little use of it. J. S. Hay and F. Pasquill examined the relation between Lagrangian and Eulerian spectra, and interpreted their results in terms of a hypothesis that the Lagrangian time spectrum has the same shape as the Eulerian spectrum but with a time-scale differing by a constant factor. In the form in which it was presented this hypothesis is not strictly acceptable, since at a site with a different roughness the flow would be identical except for the superposition of a constant velocity which would alter the Eulerian time-scale but would leave the Lagrangian scale unchanged.

R. W. Davies deserves mention for the enthusiasm with which he organized the photographing of the smoke from a large oil fire.

What was probably the best original idea of the meeting came from E. L. Deacon. He suggested that estimates of the vertical heat flux near the surface might be obtained from measurements of the level of temperature and velocity fluctuations in the small scales of the inertial subrange. This is possible because the mean square velocity difference D_u and the mean square temperature difference D_T between two points a suitable small distance Δ apart are related to the rates of dissipation of mean square velocity (ϵ) and mean square temperature (γ) by

$$D_u = C_1 \epsilon^{\frac{2}{3}} \Delta^{\frac{2}{3}}, \quad D_T = C_2 \gamma \epsilon^{-\frac{1}{3}} \Delta^{\frac{2}{3}}.$$

It is easily seen on dimensional grounds that the heat flux is given by

$$\begin{aligned} \overline{w'T'} &= \gamma^{\frac{1}{2}} \epsilon^{\frac{1}{6}} z^{\frac{2}{3}} f_1(\mathrm{Ri}) \\ &= D_T^{\frac{1}{2}} D_u^{\frac{1}{2}} z^{\frac{2}{3}} \Delta^{-\frac{2}{3}} f(\mathrm{Ri}), \end{aligned}$$

where one may take for Richardson number $gT^{-1}\gamma^{\frac{1}{2}}\epsilon^{-\frac{5}{6}}z^{\frac{2}{3}}$, which is proportional to $gT^{-1}D_T^{\frac{1}{2}}D_u^{\frac{1}{2}}\Delta^{\frac{1}{3}}z^{\frac{2}{3}}$. The function f has to be determined empirically, of course, but this has to be done only once and the most favourable circumstances can be chosen. It is possible that this method for finding the heat flux will be useful at sea, since the motion of a boat or buoy should interfere very much less with measurements of small-scale fluctuations than with the direct determination of the heat flux through the covariance of T' and w'. One hopes that the idea is being pursued.

In short, the Proceedings form a book which is useful mainly as an ephemeral catalogue of current research and which rather few individuals will wish to buy.

T. H. ELLISON

Rheology: Theory and Applications. Vol. III. Edited by F. R. EIRICH. New York and London: Academic Press, 1960. 680 pp. $12.00.

This is the third of a series of three volumes on the subject of recent advances in rheology. The first two volumes of the treatise have been reviewed earlier in this journal (volume 3, page 110 and volume 5, page 652).

It is characteristic of the subject that there appears not to be general agreement about the meaning of the word *rheology*. 'The science of deformation and flow' is the definition given in volume I and most dictionaries, and it is directly traceable to the original definition when the word was adopted in 1929. By this definition rheology would include most of applied mechanics including elasticity and fluid mechanics as well as kinetic theory. But dictionaries do not establish definitions; they record them. It is usage, illusive though it may sometimes be, that determines the meaning of a word. Today rheology is generally accepted as the science of the deformation and flow of non-ideal matter, i.e. non-Hookean solids and non-Newtonian fluids. The contents of this and other works on rheology attest to this usage as does the lack of mention of the word in most books and papers on elasticity, fluid mechanics, and physics. As another example of accepted usage, we note that in *Applied Mechanics Reviews* Rheology is given a separate heading under Mechanics of Fluids along with Hydraulics, Incompressible Flow, etc.

As originally planned, volume III was to contain only a survey of general features of industrial rheology and specialized chapters on various materials and processes of technological importance. Rapid advances in the field, however, have tempered the original judgement. The survey chapter 'Rheology in industry' has been omitted and three other chapters added, two of which would probably have been placed in earlier volumes had that been possible. The first of these is 'The normal co-ordinate method for polymer chains', by B. H. Zimm. The author gives a lucid, absorbing introduction to the method of normal co-ordinate analysis as applied to the theory of high polymers. In this method a polymer molecule is idealized as a string of beads separated by springs and attached to them with universal joints. When normal co-ordinates are used, the equations of motion of this chain in a viscous liquid can be decomposed into sets of relatively simple, non-interacting equations. This permits calculation of a relationship between molecular structure and intrinsic viscosity which includes relaxation effects, and the limited calculations performed to date give results in good agreement with theory. This short chapter is a model of perfection of the difficult art of introducing a narrowly specialized subject to a sophisticated audience of widely varying training and interests.

The second of the chapters that might have appeared in an earlier volume is 'The principles of rheometry', by S. Oka. It is a catalogue of mathematical derivations for the behaviour of a wide variety of viscometers. The solutions given are mostly for inelastic, incompressible Newtonian fluids and are, in fact, all obtained from linearized forms of the Navier–Stokes equations. The usefulness of this chapter is severely impaired by lack of any mention of the relative merits of the instruments discussed.

As is to be expected, the remaining chapters vary greatly in style and manner of presentation; some are repetitive and tedious, though most are well-written. They vary even more, however, in the extent to which they are likely to be of interest to the readers of this journal. The subject 'Viscosity and elasticity of interfaces' is fascinating and of growing interest in fluid mechanics, but the chapter by this name is disappointing. Intriguingly incomplete, it is too short to convey adequately the ideas and problems of surface rheology, and it is further handicapped by the author's apparent confusion about units.

'The rheology of printing inks' contains some elementary hydrodynamics and a good description of the process of film splitting by rolls. It also contains a striking last sentence: 'The next decade should provide advances in this field rivaled in practical importance by no other branch of rheology.' The chapter 'Rheology of lubrication and lubricants' is written from the point of view of a physical chemist. To potential contributors to the theory of the fluid mechanics of lubrication, it is recommended as a guide to physical considerations that are relevant to the problem and which could easily be overlooked. Another chapter of interest is entitled 'Viscosity of suspensions of electrically charged particles and solutions of polymeric electrolytes'.

The remaining chapters are of lesser but varying interest to those whose primary work is in fluid mechanics. In order of appearance they are entitled: 'The rheology of Latex', 'Rheology of pastes and paints', 'Atomistic approach to the rheology of sand-water and of clay-water mixtures', 'The rheology of inorganic glasses', 'The rheology of concrete', 'The deformation of crystalline and cross-linked polymers', 'The rheology of adhesion', 'Rheology in moulding', 'Rheology of spinning', and 'Theory of screw extruders'.

This three-volumed treatise on rheology is now complete, and so we are in a position to evaluate its success, which will, of course, depend on the criteria used. A major purpose of a work of this sort is to introduce the scientific reader to various branches of rheology. Save for occasional lapses, this purpose has been well fulfilled both in choice of subject matter and in the manner of presentation. Future advances in rheology, however, will diminish the value of the treatise as introductory matter, and it must then serve as a point of reference for past work. For this purpose, too, it is a success. The impressive list of references in nearly every chapter admirably serve this end. It is likely that rheologists of the future will often turn to this work as an initial guide to past literature.

Another goal of the treatise, avowed in the preface of volume I, is to promote better understanding of the essential unity of rheology. Fortunately, this goal is of secondary importance, for here the work fails. In perusing the chapters one is impressed with the vast diversity of subject matter. On closer reading the diversity of approach becomes evident. Some authors, Weltmann for example, seem to write in a language that is different from that used by most of the others. But such is to be expected when chemists, physicists, engineers, and mathematicians all contribute to so huge a field.

Although the index of each volume is adequate, it is a nuisance to have to use three. If a fourth volume appears, a possibility mentioned in the preface of volume III, a comprehensive index to all four volumes would be a valuable inclusion.

The reviewer notes with pleasure that the cost of this volume is considerably less than that of its predecessors ($20 and $18). It is, in fact, but a few dollars more than seems reasonable to those of us who are at the purchasing end of the business.

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