J. Fluid Mech. (1981), *vol.* 106, *pp.* 103–130
Printed in Great Britain

Some connections between fluid mechanics and the solving of industrial and environmental fluid-flow problems

By J. C. R. HUNT

Department of Applied Mathematics and Theoretical Physics,†
University of Cambridge, Silver Street, Cambridge CB3 9EW

CONTENTS

1. Introduction

The publication of this 25th Anniversary Issue of the *Journal of Fluid Mechanics* is a fitting moment to consider some of the new ways in which *fluid flow* has been controlled and exploited and the relationship between these practical developments and the kind of scientific studies reported in this journal. From Leonardo to Lanchester to Lighthill the application of the understanding of fluid motions to the study and practice of flight, whether man-made or natural, has gone hand-in-hand with the scientific development of the subject. But, although from the earliest times fluid motion has been controlled and exploited for industrial and environmental

† Also Department of Engineering.

purposes, the connection between these applications of fluid flow and its scientific study is nothing like as direct or as widespread, perhaps because the costs and dangers of failure in these fields are somewhat less. It is particularly appropriate to discuss these aspects of fluid flow, because one of *JFM*'s most noticeable features has been the publication of papers on new ideas which already have had or may have some interesting non-aeronautical applications.

In this personal and I hope provocative essay I shall discuss some of the ways in which advances in fluid mechanics have led to better or new engineering designs, and have led to great improvements in the understanding and the control and exploitation of the environment. I also want to suggest how much of the progress and excitement in fluid mechanics research has come from the demands and stimuli provided by industrial and environmental problems. But I also want to emphasize how many of the new practical uses of fluid flow have developed without any benefit from the scientific study of fluid mechanics, a fact that fluid mechanics specialists should always remember with a due sense of humility! In the second section of this essay I amplify these general ideas, which in the third and fourth sections are illustrated by examples of industrial and environmental fluid flows.

2. Generalities

2.1. *The control or exploitation of fluid flows*

This activity, which can be conveniently referred to as 'designing' with fluid flow, involves at least one of the following techniques:

(1) introducing another flow, e.g. film cooling of turbine blades;

(2) introducing another fluid or changing the fluid, e.g. using long-chain molecules for drag reduction in pipes;

(3) modifying or introducing rigid or flexible solid devices into the flow; e.g. compression by pistons;

(4) generating forces in the body of the flow, e.g. extracting energy from or injecting energy into the flow by electromagnetic or electrostatic forces.

Thus most design with fluid flow must involve the thinking and the techniques of other sciences and technology, which may be biological as well as physical, as in the design of fishing equipment or flow processes in brewing. As will be noted in §4.3, some fluid-flow designs may also be significantly constrained by psychological, ergonomic or economic factors (Mayall 1979, p. 175). It is hardly surprising, therefore, that many design decisions in which there is a small but significant fluid-flow design element (e.g. in the design of a metallurgical process (§3.8) or in the establishment of some rules for the protection of the environment (§4.2)), are taken by engineers, scientists, entrepreneurs or planners whose general understanding of fluid flow is very limited. (A good example of this is the widespread and small-scale manufacture in the U.S.A. of flexible water-containing membrane vessels with internal baffles for supporting dynamic loads – namely, 'water beds' whose successful design depends on allowing for evidently complex fluid/solid interactions.)

2.2. *'Design' and the scientific study of fluid flow*

A fluid-flow 'design' usually involves a synthesis of the external or non-fluid-flow constraints with the relevant elements of fluid-flow knowledge, which would include:

(1) a general fluid-mechanical concept relevant to the particular design, perhaps in an intuitive or pictorial form;

(2) experience of previous or similar fluid-flow designs;

(3) quantitative flow calculations.

The extent to which any of these elements is based on the scientific study of fluid flow varies greatly, as does the relative influence and ordering of these ingredients in different designs. Rational procedures may have even less part to play in the actual synthesis of a design, usually because there are too many alternative ways of fitting fluid flows to the external constraints. Perhaps this is why the scientific approach to fluid mechanics seems so irrelevant to many fluid-flow designers, and I suspect that this will remain the position while the design process is so different from the solving of well-posed scientific or mathematical problems. Aircraft designs and elements of turbo-machinery design are certainly based on fluid mechanics research; quantitative calculations are made to within a few percent, say, in the case of aircraft drag. These calculations are involved in the design from the earliest stages. However, even in these cases design decisions have to be made about some components where even broad features of the fluid structure are only vaguely perceived (e.g. the grooves on the inner surface of the outer casings of axial compressors to reduce reverse flow and stall at low flow rates).

For much of industrial and environmental fluid mechanics, fluid-flow design decisions have to be based largely on general concepts and experience of the relevant flows, because calculations can only be very approximate. However, there is a danger that when calculations are deployed they may be little more than cosmetic, if not downright misleading; perhaps because many of those unfamiliar with fluid mechanics nowadays distrust any estimate obtained without an extensive computer calculation, no matter how unreliable the basis of such calculations! Examples of this danger are found in industrial designing (see below) and in environmental fluid flows. But it is also true that speculative calculations to support a design are worth while for two reasons. First, even if they are erroneous, they have to be based on explicit assumptions which can be further investigated, and, second, they provide the basis for reasoned argument, which is particularly valuable in environmental questions (see §4.3).

There may be little connection between any of these design elements and the study of fluid mechanics. But to the extent that there is some connection, it may only amount to referring to the large body of data on fluid flow compiled in handbooks and tables, e.g. *Valve Manufacturers' Handbook* and *Engineering Science Data Unit Tables.* As often as not, for example in the design of internal flow devices such as valves, filters or pipe assemblies, the tables do not provide the information required for a particular flow, especially where a combination of devices is needed. Then the designer, by guesswork, and possibly guided by flow visualization, has to extrapolate from the tables, which can lead to some very misleading calculations, as I have seen! A similar situation often occurs in environmental problems, where, for example, wind forces on complicated structures or atmospheric diffusion over complex terrain may need to be calculated, but where the only well-established rules are for wind forces on simple structures or diffusion over level ground. Then either intuitive generalization from existing data is necessary, or special *ad hoc* experiments have to be mounted, or new research initiated. One of the most important results of fluid mechanics research has been to develop more reliable methods for such *ad hoc* experiments, especially in the field of model testing (e.g. Snyder 1973; Yalin 1971).

In thinking towards the future, one wonders to what extent the design of fluid-flow devices will become a well-posed computational exercise. We are certainly a long way from that position today, because the fluid flows relevant to a particular device are usually only known for a rather restricted range of *geometrical forms*. For example, even a turbomachine could not possibly be designed without implicitly specifying that aerofoil-shaped, nearly rigid blades were used; yet, in principle, the efficiency might be greater if the lifting surfaces had a more complex, even multiply connected geometry (see §3.2).

2.3. *Research and design*

The understanding of fluid mechanics and practical fluid-flow designing have advanced and grown together. Practical fluid-flow designing has been helped by advances in fluid mechanics, some of which have had pure scientific origins, and others have come from research commissioned to solve practical problems. On the other hand, these fluid-flow problems have often then stimulated significant developments in the fundamentals of fluid mechanics.

A nice example of pure research was von Kármán's study of the vortex street, which, he said, was stimulated by this early fascination with an Italian artist's vivid depiction of the vortices round St Christopher's legs. However, he was also anxious to explain Hiemenz' observations of an oscillating cylinder (von Kármán & Edson 1967, p. 62). The exciting work on geo-, astro- and cosmological fluid dynamics is also important pure research which may have considerable use for us on the Earth's crust; for example Durbin found that Hawking & Ellis' (1973) tensor formalism, developed for relativistic problems, provided a useful way of calculating turbulence round bluff obstacles (Durbin & Hunt 1980). (See also §3.8.)

Where fluid mechanics research is commissioned by practical fluid-flow problems, it generally has two stages which ideally are integrated together; first, the analysis (not by any means necessarily mathematical) of the fluid flows involved in the problem, and then the development of a new synthesis, by fluid flow and other techniques, of a design to accommodate to, or to change, the fluid flows. (An important example of both stages is provided by the analysis and rectification of failures in design. In fact, the *pathology* of fluid flows has given rise to some interesting fluid mechanics problems (see §§3.1 and 4.2).)

In the analysis stage, some idealization of the flow is often an essential first step. Assuming the idealized problem can be solved, and preferably tested by idealized experiments, it must then be related back to the complexity of the actual flow. (At this, the hardest point, the practical engineer too often takes over unaided; perhaps because the fluid dynamicist has retreated to write a paper on the idealized problem?) G. I. Taylor's work (Batchelor 1960, 1963, 1971) provided some splendid examples of theoretical and experimental analysis of idealized fundamental problems in the fields of aeronautics, printing, pollutant dispersion and many other areas.

In most analyses of such practically inspired problems, the research worker aims to develop some quantitative analysis, as well as a qualitative description, of the fluid flows involved. However, the latter element is almost always the more essential ingredient in the synthesis of a design solution. In some of the best examples, no quantitative analysis could have been, or was, developed (see for example §§ 3.1, 3.2). This point needs particularly to be mentioned to readers, referees and contributors of this rather mathematical journal who may overestimate the importance of quantitative analysis in a situation where a qualitative understanding of a fluid flow may be of primary importance (a point also made with many excellent examples by Naudasher & Rockwell 1979).

The analytic stage gains most attention from research workers and teachers of fluid mechanics, but the design development stage is equally fascinating and usually much more difficult.

The design solution may or may not require modifying the flow; for example, an engineering component may just require strengthening, in which case no flow modification may be necessary. But, if the flow has to be modified, the engineering designer has to know how to adjust external boundaries or inlet conditions, or perhaps the fluid properties, to achieve the desired flow. The art of such flow manipulations is a surprisingly neglected area in fluid mechanics research, which tends to be heavily concentrated on the analysis of prescribed flows. The manipulation of turbulent flows is a particularly difficult art and has been the especial study of the group at Illinois Institute of Technology (Loehrke & Nagib 1972).

Applied fluid mechanics research is mainly a matter of solving practical fluid-flow problems within a slowly developing set of techniques. But it also plays a vital part in the development of fluid mechanics generally, because so many of the questions raised by practical fluid-flow problems have then raised important basic questions of fluid mechanics – the complementary aspect of the connection between fluid mechanics and practical fluid-flow designing. These questions have the greatest impact on the subject if they arise at a time when they can be solved. The corollary of applied problems raising more basic research problems is that if the latter can be solved, or at least better understood, then as well as the original problem being solved, there may be a number of *quite different* applied research problems whose solutions may benefit from the advances in the basic fluid mechanics.

For example, the discovery of the vortex breakdown phenomenon on delta wings (see the review by Hall 1972), led to a number of basic questions about the stability and nature of possible equilibrium states of swirling flow. The results of research into these problems have been valuable in problems connected with industrial aerodynamics, pump design, etc. (Hall 1972; Leibovich 1978). Another aspect of this chain of reaction between the applications of research is illustrated by the problem for designers of wind-tunnel contractions of understanding and calculating the change in turbulence produced by the contractions, which was solved approximately by Prandtl and G. I. Taylor, and then more accurately by Batchelor & Proudman (1954), and Ribner & Tucker (1953). By extending these ideas and methods, many other distorted turbulent flows have now been better understood and calculated, and from the understanding of these flows, some new aspects of the original contraction problem have recently been elucidated (when the turbulence scale is of the same size as the contraction) (Hunt 1973; Goldstein & Durbin 1980). So in some cases, the original applied problem benefits not only from the first research investigation, but also from ideas and techniques stemming from the generalization of the problem and the wider application of the research. This is the reason why applied fluid mechanics research should not be too narrowly confined to one particular application (see also §4.3).

2.4. *Environmental flows*

Environmental flows are also controlled and exploited by techniques described in §2.1, e.g. technique (i) the rising column of bubbles to reduce waves (the bubble breakwater); technique (ii) cleaning oil spills or reducing waves by adding other fluids; technique (iii) by erecting buildings or shelter belts for weather or wind protection, and technique (iv), using electrostatic precipitators for dust collection.

As with industrial fluid-flow problems, there are two parts of a solution to an environmental problem; analysis and the synthesis of a solution. A special feature of environmental problems is that the synthesis or 'design' may well be a development of codes of practice or sets of rules, e.g. for siting sources of environmental pollution, or it may be a particular design decision, such as deciding on the route of a river. (Although there are standards for industrial fluid-flow designs, it appears that environmental codes of practice, in particular in wind loading and atmospheric pollution, have generated more controversy and the need for research in fluid mechanics.)

The other special feature of an environmental problem is that its solution may require a rapid prediction of the future development of a fluid flow following within a few minutes or hours from the moment it is requested, i.e. 'real time' predictions. Such computations have to be based on inadequate flow measurements at the instant of computation to predict the future development, and are usually based on quite rudimentary models of fluid flow. For example, they may be used for estimating the likely path of an accidentally released cloud of poisonous gas, and then deciding on policies of evacuation of people, or they may be used in conjunction with real-time measurements of pollution concentration for making real-time decisions about pollution emissions. Although the fluid mechanics incorporated into such schemes is inevitably quite simple, there appears to be plenty of scope for ensuring that broadly correct fluid-mechanical principles are applied. The problems of weather forecasting are very similar in this respect (Leith 1978).

3. Industrial exploitation of fluid flows

Over the past 40 years there have been a number of outstanding ways in which *new and old ideas* about fluid flow have been exploited on an industrial scale. In some cases these have had a major impact on the way in which people work, live and travel, all over the world.

It is probably instructive for research workers and teachers of fluid mechanics to attempt to identify some of these successful exploitations of fluid flow. Perhaps students of the subject should, to a greater extent than they are now, be told about such examples to arouse their interest in the applications of fluid mechanics and to encourage them to think about how fluid flows can be controlled and used.

Many more man-hours are spent in the step-by-step improvements of fluid-flow

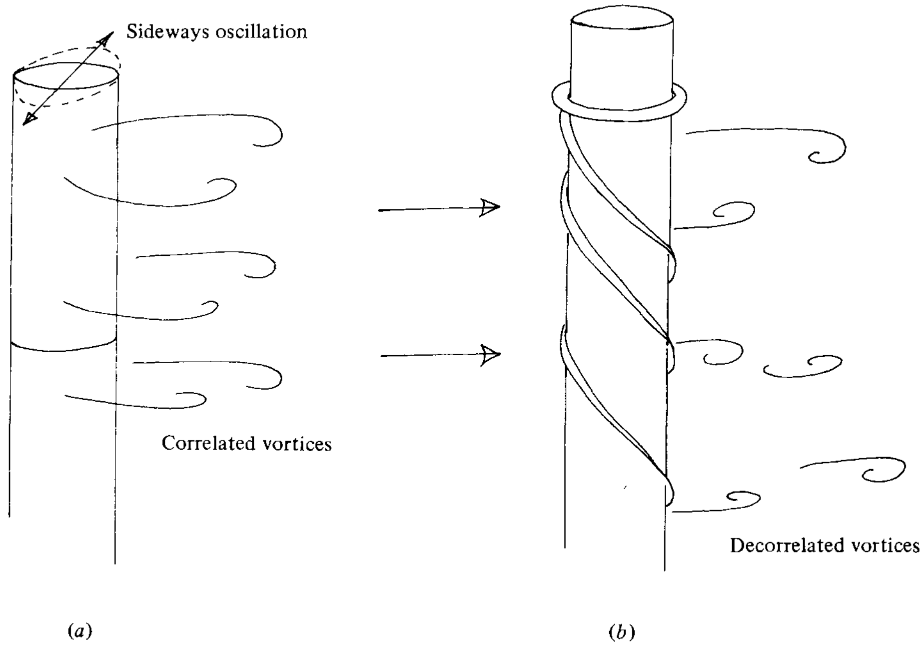

FIGURE 1. Reducing the effects of vortex shedding on a chimney in a cross flow by means of strakes (Scruton 1963). (*a*) No strakes; (*b*) with strakes.

designs, rather than the development of quite new devices or new exploitations of fluid flow. The step-by-step developments may also have quite as great an impact as the new developments; take, for example, the huge impact of the step-by-step development of the jet engine, where the thrust per unit weight has doubled and the specific fuel consumption has halved over the past 30 years (Hawthorne 1978).

But to illustrate how the synthesizing of new designs relates to fluid mechanics, I shall concentrate on describing a few groups of new fluid-flow devices and technology. Inevitably this account is anecdotal and unsystematic. It is based on many conversations with fellow fluid-dynamicists in many countries, and an inadequate amount of time reading about these devices and developments.

3.1. *Vortices and coherent structures in turbulent flows*

Where fluid-flow problems require the analysis of unsteady turbulent flows with a view to synthesizing a new design, a number of important devices have been developed by first identifying (or guessing), in a largely *qualitative* way, the main flow structures or patterns that occur in these flows. (There are other kinds of practical problems (§§4.2, 4.3) where a statistical description, in which the flow structures do not need to be identified, may be more appropriate. A turbulent flow is really only properly understood when both aspects have been fully explained, and if possible related to each other!) Depending on the design, these flow structures may have to be suppressed or amplified, or exploited in some way.

Some useful devices have materialized from fluid mechanics research into these flow structures:

(i) The oscillation of metal chimney stacks and other cylindrical structures in transverse flows is caused by vortex shedding. However, these vortices usually produce damaging deflection of the structure only if (*a*) vortices are well correlated along the cylinder, (*b*) the natural frequency of the structure can be close to that of the vortices, *and* (*c*) the structure has small enough structural damping. Some or all these conditions can be changed depending on the various constraints involved, showing how a design solution to a fluid-flow problem may or may not involve directly altering the flow and how there are a variety of possible solutions to any problem. In this case, various successful fluid-flow solutions have been developed, notably Scruton's (1963) device of three thin helical strakes (figure 1) wrapped around the upper third of the cylinder, which effectively decorrelate the vortices shed at different heights. Structural solutions involving detuning and damping the oscillations are also common; even then the fluid-flow *analysis* may still be necessary in deriving a satisfactory non-fluid-flow design solution.

(ii) A remarkable property of vortex shedding has been exploited to design a new kind of velocity meter. The property is the insensitivity of the wavelength λ, of the vortices to the velocity and inhomogeneity of the approach flows. By measuring the frequency, n, of the vortices, the velocity U is deduced from the product of λ, which had to be previously calibrated, and n (e.g. White, Rodeley & McMurtie 1974).

(iii) The persistence and practical importance of coherent vortices in shear layers is not recognized by all turbulence research workers (see for example chapter 1 of Bradshaw 1976). However, on the basis of visualization studies and calculations of vortices in mixing layers and jets (e.g. Brown & Roshko 1974) it has been suggested that these coherent structures are partly the causes of two practical problems involving such shear layers; the production of aerodynamic noise by jets, such as the exhausts of jet engines, and in the trapping of air bubbles in jets of water plunging into reservoirs. The study of the vortices also provides the clue to the cure: the analysis and the designs for reducing noise in jets has been based on the supposition that such vortices exist (Crow & Champagne 1971) and are reduced in intensity by reducing the shear in the jet, one of the advantages of bypass jet engines. The various ways in which shear layers can be manipulated are reviewed by Rockwell & Naudascher (1979). In the case of the air-entraining water jet, studies by Dr N. Thomas (in preparation) here in Cambridge have shown that bubbles are trapped in the vortices on the edge of the jet. The experiments have suggested that a cure for the problem is to place a grid of bars across the jet to break up the vortices and release the bubbles (figure 2). Such devices are being considered for incorporation in electric power stations (Goldring, Mawer & Thomas 1980).

(iv) Whereas turbulent flows can transport momentum, heat and matter, suitably designed vortices can also do so, usually more effectively and in a required direction with a required scale and intensity. So by either amplifying those vortex motions in the turbulence that have the desired property, or simply adding to them, some remarkable changes to turbulent flow can be effected. For example, adding vortex generators to turbulent boundary layers amplifies longitudinal vortices (Townsend 1976, p. 328), thickens the layer, increases the momentum near the boundary, and improves heat or mass transfer across the layer. These properties have been exploited in various devices, such as (*a*) the fence plus downwind vorticity generators used for the accelerated growth of thick boundary layers in wind tunnels to simulate the atmospheric boundary layer (Armitt & Counihan 1968) (figure 3), and (*b*) vortex

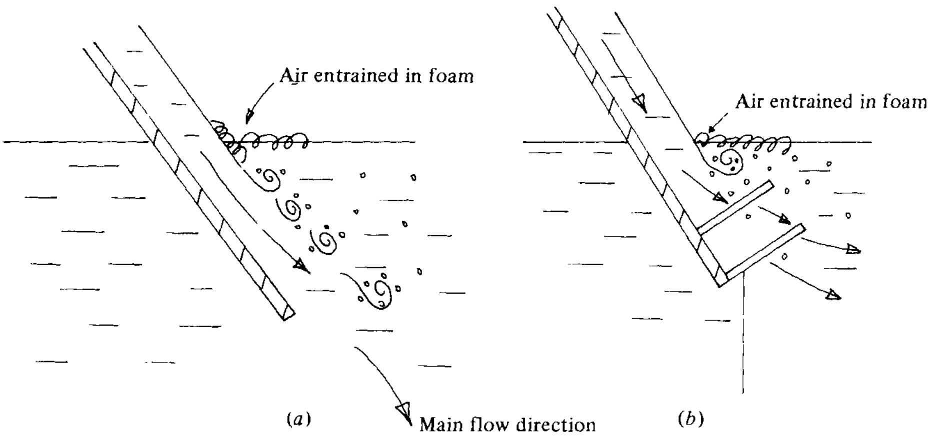

FIGURE 2. Preventing the trapping of bubbles by vortices in plunging water jets by means of a grid bar (Goldring, Mawer & Thomas 1980). (*a*) Vortices in the shear layer trapping bubbles; (*b*) effects of the grid.

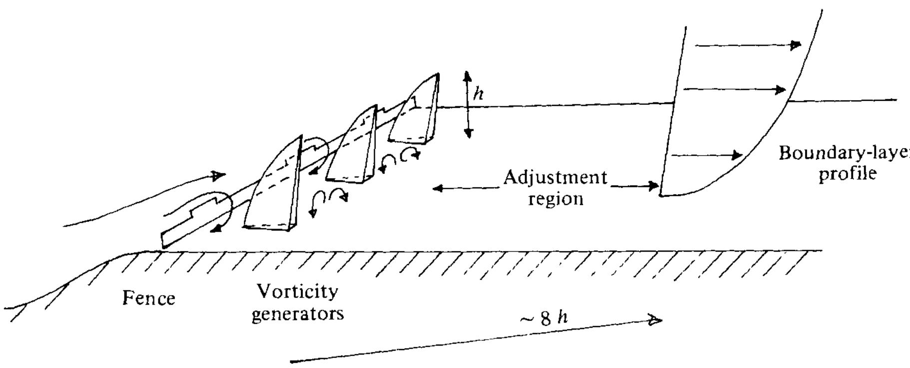

FIGURE 3. Generating vorticity and mixing to produce a thick boundary layer by a fence and vorticity generators (one among many similar devices), originated by Armitt & Counihan (1968).

generators in a cooling air jet flowing over blocks of ice cream in a factory (T.V. Lawson, private communication).

(v) Adding *sound* to turbulent shear layers emanating from a nozzle can markedly amplify (or add to) certain vortices within the layer. One effect of this may be to increase the sound produced, or, as Gutmark, Vaknin & Wolfshtein (1980) have shown, it can increase the heat or mass transfer to a solid surface impinged on by the jet (the jet's mechanical energy for given heat transfer being reduced by a factor of about 2). It appears also (W. C. Reynolds, private communication), that the efficiency of combustion in various flows can also be markedly increased in this way, an idea that may have wide application in future.

3.2. *Solid objects moving through fluids*

(i) *Vehicles*

As the cost of fuel and the size of road vehicles has increased, it has become economic for vehicle operators to reduce aerodynamic drag (which accounts for more than half the energy losses) by investing in attachable devices in the short term, and in basic design improvements in the long term (Sovran, Morel & Mason 1979).

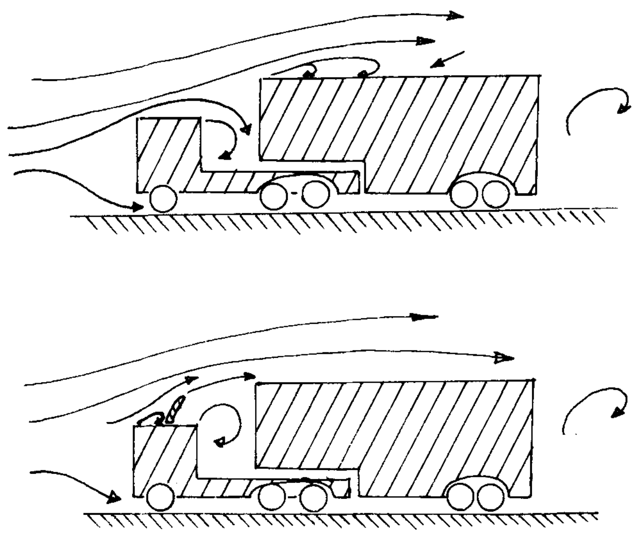

FIGURE 4. Controlling separated flows to reduce the drag of a lorry by means of bluff shields on the lorry cab (after Sovran, Morel & Mason 1978).

A common device takes the form of bluff shields on the roofs of lorry cabs which reduce the vehicle drag by promoting attachment of the separated shear layers onto the sides of the vehicle (figure 4). Other devices, flat aerofoil-like sections parallel to the surface, have been attached to the sloping rear faces of automobiles which also promote reattachment of the shear layer off the roof. Even more complex devices, such as side panels down to within a few centimetres of the road surface, which reduce air flows beneath the chassis, have been attached to racing cars. The development of such devices has been stimulated by the advances in the *qualitative* understanding of bluff body flows. However, their performance can only, as yet, be predicted by wind-tunnel tests, as no reasonably accurate calculations of such complex flows are yet possible. (A 10 % reduction in drag is regarded as desirable; so estimates of this order of accuracy are required.) Even wind-tunnel tests cannot model the considerable effects of atmospheric turbulence.

Where aerodynamic effects have really changed the design of surface vehicles is in the design of trains, where 200 km/h speeds are now common in Europe and Japan (at which speed aerodynamic drag exceeds mechanical resistance). As well as the problems of drag reduction, new fluid-mechanical problems have arisen in predicting the effects of two such trains passing within a metre of each other, tunnel entry, side winds, etc. In this case, theoretical (potential flow and shear flow) calculations, as well as model testing, have been involved in the design, especially in understanding the unsteady loading (for recent papers see Morel & Dalton 1979).

(ii) *New energy extraction and lift devices*

There have been a number of quite new devices proposed for extracting fluid energy and generating lift from fluid motion, whose full exploitation is, I suspect, only just beginning.

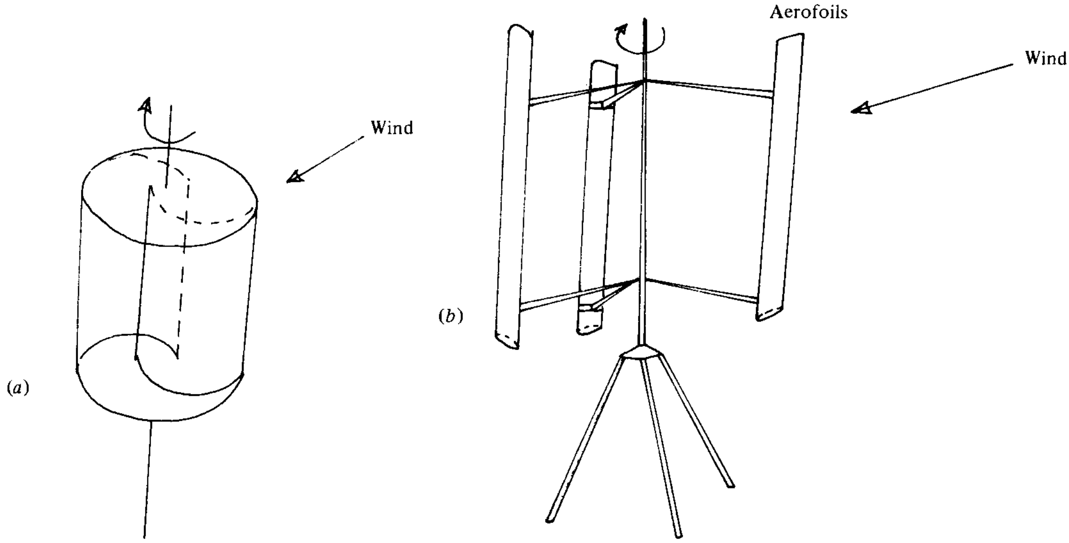

FIGURE 5. New means of harnessing the energy of fluid flow: (*a*) the Savonius rotor; cheap and suitable for air or water, usually of low efficiency; (*b*) Darieus rotor; lighter and higher efficiency.

The Savonius rotor (figure 5*a*) is a simple rotating energy-extraction device exploiting drag, and a little lift, which enables small communities with the minimum of manufacturing and material resources to build their own windmills or water turbines. (These devices, which have even been made out of oil drums, and whose fluid mechanics still require some investigation, exemplify one of Schumacher's 'Small is beautiful' theses (1973, p. 158), that the development of 'intermediate' technology may require at least as great scientific and technical resourcefulness as high technology.) A considerably more efficient and lighter, rotating energy-extraction device is the Darius windmill, which consists of vertical aerofoils at a fixed radius from a vertical axis around which they rotate (or the aerofoils are bent in vertical planes outwards from the top to the bottom of the axis (figure 5*b*)). Such devices are now used in many remote regions of the world (see for example the review in *J. Ind. Aero*, vol. 5, 1980).

One of the most exciting new ideas in fluid mechanics has been the discovery of a new method of lift generation by Weis-Fogh (Lighthill 1973). Weis-Fogh's studies of insect flight showed that their anomalously high lift was generated by clapping their wings together and then flinging them apart so rapidly that they also generated an additional circulation around each wing as the air entered the gap between the separating wings. It is an exciting thought that the principle evolved by insects of generating additional lift by changing the local connectedness of the space around the lifting surfaces may be capable of exploitation, even by humans (a possibility explored in the recent work of Furber & Ffowcs-Williams 1979).

One can hardly leave the topic of a new lifting device without mentioning the game of throwing and spinning saucer-shaped plastic discs, known as 'Frisbees'; a splendid device for familiarizing students with the concepts of lift and the effects of rotation (Danna & Pointer 1978)!

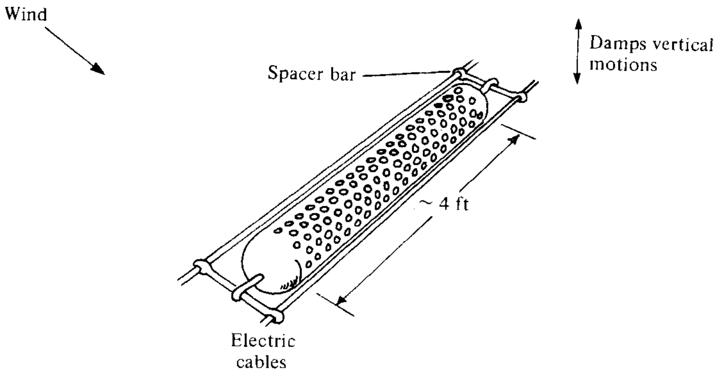

FIGURE 6. Adding aerodynamic drag to overhead electric lines without causing lift (or affecting electrical corona discharge from the wires) (Hunt & Richards 1969).

3.3. *Motion of flexible objects in fluid flow*

(i) *Cables and structures*

Some structures or elements of them can fulfil their function more economically and be adapted to satisfy changing needs or conditions if they are constructed of flexible rather than rigid materials. But this is only practical if their distortion or displacements under the action of fluid forces lie within acceptable bounds.

In the case of overhead high-tension electric cables suspended between pylons, the wind and sometimes the effect of icing, can cause occasional large oscillations – large enough that the cables clash with each other with dire electric consequences, or more frequently, mildly damaging, small-scale high-frequency oscillations. Similar oscillations occur on cables supporting tall towers. Some intriguing devices, mechanical and aerodynamical, have been proposed to reduce such oscillations; some, although justified by questionable calculations, might well make the problem worse in certain conditions (mechanical and aerodynamic cures have side effects, too!). My colleague at the Central Electricity Research Laboratories, Leatherhead, Mr D. J. W. Richards and I had a go at this problem (Hunt & Richards 1970). Richards' devices, three 22 cm diameter, 1·5 m long perforated cylinders per span suspended between clusters of four cables (figure 6), by increasing the aerodynamic drag of the cables, in theory (and it turns out in practice, too) reduce the amplitude of the largest oscillation. We also attempted to justify these devices by calculation because model testing was impossible, and because their effects were likely to be marginal and their criteria of success statistical! The problem was highly nonlinear and poorly determined (because of the twisting of the cables), so the calculation of amplitudes was limited to finding upper-bound estimates – a type of calculation that ought to feature more, in my opinion, in engineering fluid-flow investigation. It may well be better to have such a calculation than none at all, or a misleading attempt at precision. (In a number of other fluid-flow problems, such as heat transfer (Howard 1963), upper bounds have been derived; there are many important practical problems where this general approach is helpful.)

The advent of large buildings, more or less temporary, with flexible roofs and/or walls supported by excess internal pressure or suspended from a rigid frame, is an

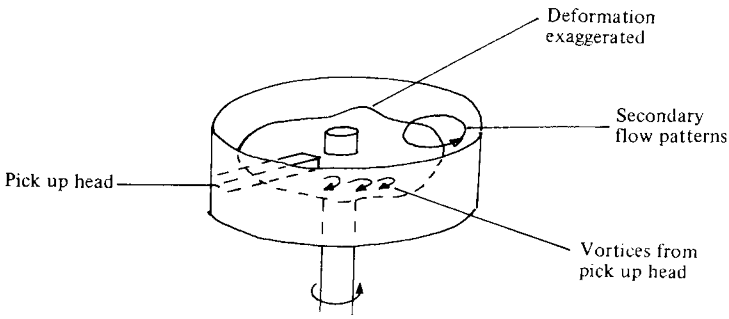

FIGURE 7. Computers can cause fluid-flow problems but cannot always solve them! Air flow around a 'floppy disc' and the fluid/solid instabilities it causes (after Lenneman 1974).

important development in building and materials technology, a vital element of which has been the fluid mechanics investigations into the fluid forces and stability of these structures. Continually larger ones (e.g. 500 m diamter by 150 m high) are being proposed, which raise even more formidable fluid flow and structural problems (for example Trygvason 1980). Wind tunnel models can be used for some of these design problems.

(ii) *Flexible containers*

The size of flexible containers can be much larger if the density of the internal fluid is close to that of the external fluid, for given strength and thickness of the material. But if the container is to *move*, the inertia of the fluid is also a constraint. Thus static flexible air buildings can be larger than flexible containers for carrying liquids in waterways. Hawthorne (1961) has described in delightful detail the development of the serpent-like 'Dracone' – flexible rubber containers for slightly buoyant liquids in water, including the ways of persuading sponsors of the practical and economic viability of an invention. Its development required theoretical estimates of the required strength of the container and natural frequency of the snaking motions (using EDSAC, Cambridge's first computer) and empirical developments of stabilizing fins. These devices are now used, for example, in transporting water along rivers in Nigeria, or removing oil from spills.

(iii) *Moving flexible sheets or laminae*

In a number of devices and processes, sheets of flexible fluid or solid material travel between one or more fluids in the close proximity of rigid surfaces. The range extends in a scale and velocity from the continuous casting of steel (see 3.10), to the rapid motion of tapes and rotating flexible discs ('floppy discs') past recording heads. When the sheet's speed is great enough, and its weight per unit length small enough, fluid flow generated by the sheet produces forces on the sheet that affect the energy required to drive it and can, as with the familiar flapping of a flag in the wind, give rise to instabilities of the sheet.

The development of International Business Machines' 'floppy disc' drive units (see figure 7) has been described in some detail by Lenneman (1974). The investigation was a typical example of experimental development of a fluid-flow device guided by general physical concepts of fluid mechanics, in this case those of flow over rotating discs, the effects of nearby walls, and the transition to turbulence (good examples of 1950s basic fluid mechanics research problems). Of course there were some new problems, such as the effect on the flow of the pick-up head, and the flexibility of the disc. So if the IBM engineers still use fluid-model testing in their development of fluid-flow devices (which should not surprise one given the complexity of the flow involved and the limitations of current mathematical models of unsteady turbulent flows), most of the present methods of fluid-flow development will be with us for at least the next twenty-five years!

3.4. *Lubrication*

Of the many recent developments in fluid lubrication (see Dowson 1979) one of the more notable has been that of gas bearings, an idea that was first demonstrated in 1854, but has only become widely applied in the middle of this century. The different kinds of advantage of these bearings are exemplified by: self-acting gas bearings of inertial gyroscopes (where low frictional losses are essential); gas bearings used in very hot, cryogenic or radioactive conditions (which is why they are used in gas-cooled nuclear reactors); externally pressurized gas bearings for low-speed operation, where the small heat generation and the low thermal distortion may be advantageous; and finally hybrid pressurized and high-speed self-acting bearings have been a vital element in many devices such as the 'ultra-centrifuge' for processing uranium hexafluoride gas, and (a boon for those visiting the dentist) air-turbine driven dentists' drills (which run at 4 to 8 kHz).

As with the other fluid–solid interaction devices, these too are susceptible to instability, because of the high speeds and low relative density and viscosity of the fluid.

At the other end of the Reynolds-number range the most remarkable lubricating device is probably the ball-point pen, developed in the 1940's (Jewkes, Sawers & Stillerman 1958, p. 268). The idea of rolling ink onto a surface is as old as rotary printing, but to use this principle in a hand-held pen, which has to move in *two* directions, also required the concept of the ball in its socket and, it turned out, just the right *fluid* for inside the pen and drying on the paper, in this case the correct proportions of 'glycol' and ink.

3.5. *Jets*

It is usually easier to control a flow by directing it with solid surfaces than by means of its inertia, or by using internal forces such as gravity, electromagnetic or electrohydrodynamics. However, there are flows where the use of solid surfaces is not a practical option, and where expertise in directing fluid flow by other means is great enough that inconvenient solid surfaces can be discarded, or only play a secondary role. The practical uses of jets illustrate this theme.

The second significant contribution of fluid-flow devices to affect the written word is ink jet printing (Sweet 1965), where a thin highspeed stream (18 m s^{-1}) of liquid ink is ejected from a nozzle (figure 8). Because the jet is oscillated at the frequency of the maximum growth rate of the surface tension instability of the jet, the jet breaks up into *regular* droplets (about 60 μm in diameter), at about the wavelength predicted by Rayleigh's linear theory. By giving the droplets an initial charge, the motion of droplets toward their target is controlled by varying an electric field between plates

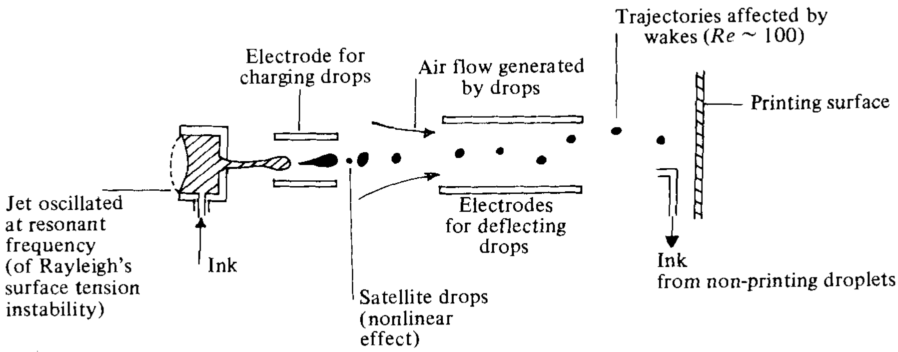

FIGURE 8. The fluid-flow phenomena associated with ink jet printing. (In this case computers can't compute the flow, but can learn by experience how to predict it!)

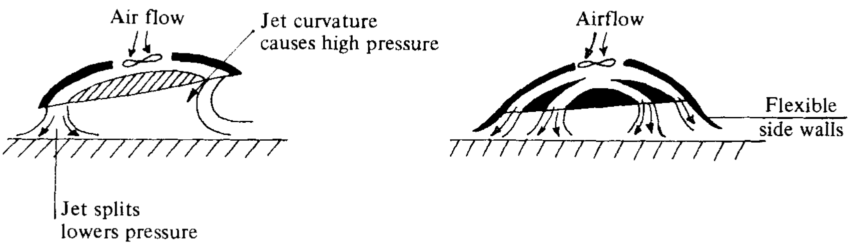

FIGURE 9. The Hovercraft and its stability problems – simple fluid mechanics shows there is a problem but fluid-flow designing expertise largely provided the answers.

either side of the jet. The contribution of modern fluid mechanics has apparently been limited to pointing out that nonlinear effects can produce smaller 'satellite' droplets, but the minimizing of this effect has been strictly empirical.

Another liquid jet device has also become possible only because of non-fluid technology; jet cutting tools first required the development of pumps to produce very high liquid pressures. The resulting thin ($\sim$ 2 mm) jet cuts rock, building materials, cloth, card, with a minimum of dust and noise; a potentially huge contribution to better working conditions, which one would like to see much more widely used. These jets' cutting power can be further increased by adding polymers and/or pellets to the liquid.

Curved air jets have been exploited in a number of ways, most notably in the only new form of mass transport in the last 40 years – a ground effect machine known as the 'Hovercraft' (figure 9) (Earl 1962). The principle was simple enough (as with all the best inventions), but as anyone who has ever tried to build a toy one knows, the problem of stability (again) had to be overcome because, contrary to one's initial expectation, the annular jet does not increase the lift on the side that drops; rather it splits and escapes under the higher edge. So various devices had to be developed, with a good deal of empiricism, to rectify this problem; hence the need for flexible sidewalls, additional jets, splitter plates, etc.

Other large-scale jet devices are the warm air jet curtains sometimes used instead of doors of busy shops, or the air-jet canopy for streets and stadia described by Etkin & Goering (1971).

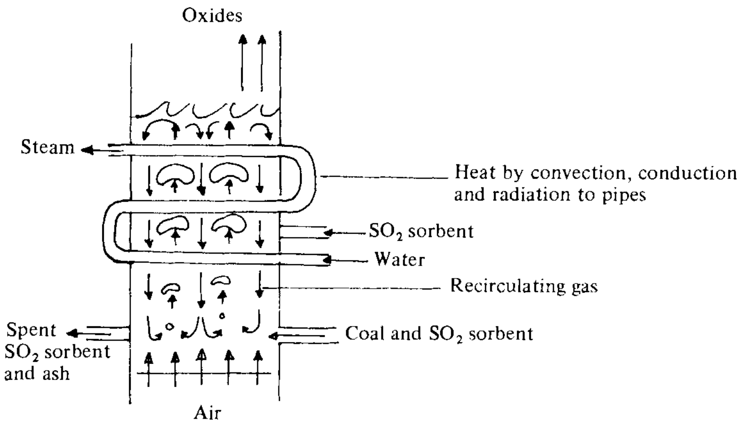

FIGURE 10. Choosing, or in this case inventing, your fluid to solve the problem. Turning the solid fuel (and gas cleaning solids) into a fluid by passing through it the oxidizing air; the process of fluidized-bed combustion.

On a smaller scale, the qualitative understanding of the ability of the small jet to deflect another, and of the property of jets to remain attached to a surface – the Coanda effect (Wille & Fernholz 1965) – has been the basis for the more or less empirical development of many fluid control and fluid logic devices, which have been of particular importance in radioactive or other adverse conditions, where electronics does not function well.

3.6. *Multiphase flows*

In some situations the fluid-flow designer may be able to achieve his goal better by using more than one fluid, or more than one phase of a fluid, and even has the possibility of adding solid particles to the flow. To exercise these new options sensibly, the properties of multiphase flows must be better understood, as well as the technology and economics of producing and, if necessary, separating multiphase fluid mixtures. The need for separating of multiphase flows has given rise to many fluid devices, for example the need for cleaning oil spilt on water (e.g. Wardley Smith 1976), or magnetic separation of ferrous particles from slurries (Watson 1973). Some striking improvements in performance have been achieved by using a second phase in a number of flows.

(i) Very small quantities (e.g. 18 p.p.m.) long-chain polymer molecules can dramatically (e.g. by 33 %) reduce the surface shear stresses produced by turbulent boundary layers – the Toms phenomenon (reviewed by Lumley 1969). Although the process is still not properly understood, it is certainly exploited, for example in fire hoses in the USA, to increase the flow, and as a means of increasing the speed of boats by releasing the solute in small quantities near the bows.

(ii) The rate of transfer of heat and mass between a gas stream and a solid can be improved. For example in the combustion of coal where oxygen passes to the coal and then heat is carried away by the gas, the gas can pass over lumps of coal (very old-fashioned), or the coal can be fed into the gas as a stream of powder (current practice), or the air can bubble up through a mixture of coal particles and inert material. The last is fluidized-bed combustion in which the solid particles act like a fluid and the bubbles are like air bubbles in a liquid (Davidson & Harrison 1963). Because of the thorough mixing this process can considerably improve combustion efficiency, reduce atmospheric pollution and enable inferior fuels to be used – all great benefits from one of the potentially most important fluid-flow devices to have been developed (figure 10).

3.7. *Controlling and exploiting waves*

Of all the fluid devices that have been developed, one of the most puzzling to the layman, and at first to professional fluid-dynamicists, is the bulbous bow on ships. By making the bow wave break further forward, the wave and surface drag are reduced, which significantly reduces the fuel consumption of large ships. (It appears that this device is yet another development in the case of military technology – the ancient ramming bow below the surface – yielding eventually a device of wide civil application.)

While ships lose energy by creating waves, there is in the ocean's own wind-driven waves a huge repository of energy. But to exploit this energy in an ocean environment requires ingenious and robust devices which may be moving or fixed. Starting with intuitive designs for such devices, the modern tools of fluid mechanics analysis have largely† been used to improve and explore the implications of these designs (e.g. Count 1980). For example the analysis has shown how relatively insensitive floating devices are to their particular shape (on the side facing the waves) and the surprising fact that the wave-generated fluctuating pressure in the Vickers static resonant tube device (on the bottom of the sea) is greater than under the wave in the absence of the device (Lighthill 1979). The exploitation of wave energy is certainly now a highly technical business, but its economics is still very uncertain (its cost being typically ten times that of conventional power, for large-scale power generation).

3.8. *Solidifying materials*

The solidification, moulding and transport of molten materials is at the heart of many industrial processes. There have been big changes in the fluid flows involved in this technology in the last 40 years, and these have given rise to some interesting problems in fluid mechanics. I suspect that, as yet, fluid mechanics research has only made a small contribution to improved designs. For example: steel is now cast continuously so that a solidifying stream of metal passes vertically direct from the furnace to the roller, undergoing some distortion or stirring by electromagnetic devices (to reduce the grain size) on its way. Various metals are transported in foundries by electromagnetic pumps. In the Pilkington process glass is now also cast continuously, travelling very slowly on a bath of molten tin.

These new fluid-flow designs and inventions have been largely developed by metallurgists, materials scientists, and electrical engineers; fluid mechanics (including magnetohydrodynamics) research has only subsequently been brought to bear to help analyse and improve these new flows (Moreau 1980). As the requirements become more stringent for greater purity and economy of production, closer analysis of flow processes have become necessary, and this has revealed some new fluid

† An important early theoretical paper by Ogilvie (1963) on the effects of a cylinder on waves lead to the idea of using a rotating cylinder as a wave absorber (Evans 1976).

phenomena. For example, undesirable striations found in growing crystals were partially explained by the effects of a flow oscillation being driven by the steady convective motion in a *horizontal* temperature gradient (Hurle, Jakeman & Johnson 1974). In this case the undesirable fluid motion was not cured, but it was learnt how to *avoid it*, an important part of exploiting a fluid flow, and one where the purely analytical approach may be sufficient. In some current crystal growth problems the results of studies in geophysical fluid dynamics of rotating stratified flow is finding application, a nice example of one application of fluid mechanics helping another.

3.9. *Magnetohydrodynamic devices*

In principle one might think that new magnetohydrodynamic devices would be continually appearing, because in this case the designer has all the other fluid-flow artifices at his disposal with the addition of body forces to control the flow and to extract or inject energy into the flow. (Plasma devices are not included in these remarks.)

In fact, it is hard to think of more than one or two successful and widely used new devices (the electromagnetic pump, induced voltage flowmeter and induction furnace being essentially pre-1940 devices!); one being the induced-magnetic-field flow meter, used in liquid sodium cooling circuits in fast-breeder reactor nuclear power stations (Lehde & Lang 1948). It is much easier to think of MHD devices which have been proposed and have spawned much fluid mechanics research, but which have not been practical or economic successes; among these are devices such as electromagnets in rockets setting up electromagnetic forces in the hot ionized gases around the rocket to deflect away the gas and then reduce the heat transfer, or MHD electric power generators to extract electric power from higher temperature streams of gas than is possible by conventional steam and turbine systems, where the top temperature of the thermodynamic cycle is limited by the materials of the turbine. (One should say, however, that at least one such generator is working in a Moscow power station.) Some bizarre devices appeared in this Journal as theoretical possibilities, mainly I suspect as an excuse to explore their theory, such as lifting aerofoils in fluids of infinite conductivity with aligned magnetic fields!

Despite these and other projects not being developed beyond the experimental stage, magnetohydrodynamics research has, in fact, been applied in practice. It has made contributions to metallurgical processes (Moreau q.v.) and to the conceptual design of systems for the cooling and 'breeding' of tritium in fusion reactors. In the latter case, the MHD problem was not how to design and use an appropriate electromagnetic field more effectively, but how to estimate and circumvent, if possible, the pressure losses along the cooling pipes caused by the imposed magnetic field, which has to be present in the reactor to confine the plasma. The calculated pressure losses turn out to be so great that, even with ingeniously shaped pipes or baffles to obstruct the electric current, the use of liquid metal as a coolant is unlikely to be practical – another MHD project consigned to oblivion! A most interesting by-product of these cooling studies was the discovery of thermoelectric MHD phenomena (Shercliff 1979). In participating in these studies I was most surprised to find that the basic work on laminar MHD pipe flow (see Hunt & Shercliff 1971) could actually be used in practical engineering contexts (the reason being that strong enough magnetic fields suppress turbulence). This example only goes to show how one can never predict when and where (or if) ideal fluid mechanics calculations may turn out to be relevant – also something that editors and referees should keep in mind!

4. Environmental fluid flows

4.1. *Studies of natural flows*

The growth in the scientific, popular and eventually political interests in the environment have had a great impact on the study of fluid mechanics, in that new kinds of problems have had to be studied, new experimental techniques have been developed, huge field experiments have been mounted and fluid mechanics research workers have been involved in many multidisciplinary projects (Hunt 1980). While many industrial fluid-flow designers may only dimly perceive the benefits of fluid-mechanical studies, planners and engineers concerned with environmental questions have to a greater extent realized that many of their practical problems can only be solved by using the existing knowledge of fluid mechanics, and by encouraging further research. This is why an increasing number of research workers in fluid mechanics have become involved in environmental problems (a tendency which Shercliff 1981 suggests is regrettable).

Before considering how any environmental flow can be exploited or can affect human activities, some information about it and, preferably, some understanding of it is required. So special studies have had to be made of those atmospheric and oceanic motions which have not been of particular interest to meteorologists and oceanographers, for example the details of unstratified fluid flow over surface humps, (hills or sand waves) because of the importance of these flows to studies of forces on structures or surface erosion. (A practical consequence of this has been that the financing and directing of much environmental fluid-flow research has come from electric power companies, environmental agencies and other environmental groups.) The importance of understanding the mechanics of environmental flow as opposed to just measuring whatever parameters are needed is that:

(i) this may reduce considerably the amount of measurements needed to describe a given situation;

(ii) it enables simulation or modelling to be performed satisfactorily;

(iii) as with weather forecasting, merely statistical methods are not enough to *predict* future events in environmental flows, especially *extreme* events, and

(iv) it is essential in predicting the effects of deliberate modification of the environment. For example the input for several environmental wind engineering calculations (cf. §§4.2, 4.3) and the basis for generally accepted criteria for accuracy of a wind or water-tunnel modelling of atmospheric boundary-layer flows (Hunt & Fernholz 1975; Snyder 1973) have been derived from field measurements over flat surfaces in the atmospheric boundary layer, the most celebrated perhaps being those near Moscow, in Kansas and in Minnesota (Panofsky 1974). The mean and fluctuating velocity and temperature profile measurements have, with the aid of the kind of similarity and dimensional arguments pioneered by Kolmogorov, Monin and Obukhov, enabled the means, variances, spectra and other statistical quantities to be assembled in forms that have some physical interpretation and considerable generality, at least up to 50–100 m (and higher in convective conditions).

Other more recent field, laboratory, computational and analytic studies of the mean flow and turbulence over changes in surface topography have been stimulated by the need to establish codes for wind loads on structures, or environmental guidelines about dispersion, and by the need to understand what kind of hill location and shape are optimal for the positioning of windmills on them. Such studies may save effort spent on measuring wind speeds on unsuitable hills. Also such studies can suggest the most appropriate shapes of *artificial* hills which have been proposed as a means of exploiting wind energy more effectively in flat areas of the world – a modest example of environmental modification.

Much greater benefits would emerge from a better understanding of the fluid dynamics of tornadoes and hurricanes, and for a consequential ability to predict their paths. Progress on the mechanics of tornadoes has been made through careful and intrepid (!) observation and by model calculations (e.g. Leslie 1971); but understanding is far from complete, and this must rank as one of the major outstanding problems in environmental fluid mechanics.

Coastal estuary and river flows

Coastal and river floods have left even more millions killed and homeless than tornadoes and hurricanes. However, considerable progress has been made in the organization of data, the installation of communication and advanced-warning systems, and new coastal defences have been built in order to prevent the kind of flooding that occurred in 1953 in the Netherlands and Britain. Such remedial measures could be developed with confidence only because of the advances in understanding of large coastal tidal surges, including those connected with high winds and monsoon conditions (e.g. Heaps 1969). In some countries flood protection may not be practicable, but advanced warning based on such fluid-flow computations may help to prevent the fearful loss of life that occurred in Bangladesh and India in 1970 (Johns & Anwar Ali 1980).

While methods of measurement in the atmosphere have developed rapidly (even now, for example, the velocity in a 1 m^3 box below 10^3 m can be measured from the ground by Doppler radar), there has not been the same progress in measuring coastal or estuarine flows, where local probes are still the rule. (Will underwater acoustics eventually change this?) Despite the absence of detailed knowledge of these flows, they have had to be widely exploited, particularly for the dispersion of heat and pollutants, and modified beyond recognition by huge harbours and waterways. These environmental problems have had to be tackled by first estimating the environmental fluid flows on the basis of quite limited field data, and the results of hydraulic models and mathematical models (which of course require the same field data as input). For example, the advances in understanding wave motions over seas with varying depth have been important in the design of harbour works (Battjes 1980) and the theoretical studies of effects of stratification and fluid flow in estuaries are beginning to be of use in interpreting field data of estuaries and in understanding how large natural perturbations, such as droughts, affect their conditions (e.g. Uncles & Radford 1980).

Comments on the calculations of these flows

In both cases just mentioned important simplifications are deployed, in one case linear wave theory, and in the other eddy diffusivity models because of their ease of use and familiarity to engineers. Whether they will be superseded or just corrected by more advanced theory is not clear, such as the nonlinear wave theories being developed for coastal engineering applications by Peregine (1981) and other research workers. It is also worth observing that there are examples of geometrically complex environmental flows, where the geometry so controls the fluid flow that it may be rather insensitive to different assumptions about shear stresses, or mixing, or wave structure (where the change in wave speed is only proportional to the *square* of the wave slope). As another example, the mean velocity profile and diffusion from a point source in a shear flow over a plane surface are sensitive functions of the turbulence assumptions, but are much less so in the perturbed flow over a hump on the surface (Hunt 1980).

4.2. *Unsteady forces on structures*

Over the past 30 years, engineers have realized that unsteady loads on structures subjected to the impact of unsteady environmental flows can be as damaging as mean loads. However the *cri de cœur* of many practising engineers, 'What is the equivalent steady load?', had to be answered, 'There is not one', or, more evasively, 'Well, it all depends on the damping of the structure!' The new fluid-mechanical and structural studies of these problems have now led surprisingly quickly to widely used and new design methods, which like traditional methods may still require *ad hoc* model tests to ascertain some of the parameters.

In the case of the fluctuating loads and pressures caused by a turbulent flow around a structure, these are now described, measured and specified in statistical (including spectral) terms following Davenport (1961), who pioneered the adaptation of these methods from aircraft gust loading context to structural loading context. It is because of the sensitivity of structures to certain frequencies† and scales of loading, that we must know or measure both the spectrum of the incident turbulence and the transfer, or admittance, function that relates the spectra of the incident turbulence to the surface pressure spectra. The major uncertainty in our basic understanding which affects this procedure is the interaction of the incident turbulence with vortices and turbulence in the wake of the structure, which themselves cannot be calculated or computed for even the simplest real structure, such as a truncated cylinder. (This problem is one of a general class of turbulence problems where turbulence of different scales of anisotropy and inhomogeneity interact, but despite its complexity this problem may in some ways be easier than the problem of pure homogeneous turbulence (see Moffatt 1981).)

In the motion around structures of small amplitude water waves, with small particle displacements d, relative to scale D of the structure, the flow does not separate so classical wave diffraction analysis is quite practical, though it may be complicated for anything other than simple structures. For longer particle displace-

† A good example of such oscillations, in this case catastrophic, were observed on the cooling towers at Ferrybridge in 1965 – they were said to resemble the gyrations of a belly dancer, or the effect of a hand moving around inside a bell tent (CEGB 1967).

ments $d \sim D$ the flow can separate, but it is not until d becomes about 30 times D that the flow reverts to a quasi-steady form; over this interval of the ratio d/D, the Keulegan–Carpenter number, where empirical correlations of the fluctuating forces have been used in practice, it is now realized that the unsteady behaviour of the shed vortices largely determines the flow structure and the forces (Maull & Milliner 1978). Computer codes for tracking vortices have now provided an approximate predictive tool for engineers estimating wave forces on off-shore oil platforms.

There are many other aspects of the unsteady loading problem, for example the problem of tornadoes or waves 'slamming' on structures, where there is more empiricism than fluid mechanics. Both in these examples and the previous ones there are many interesting and important fluid mechanics problems to be tackled.

4.3. *Artificial environments*

In most parts of the world the natural environment has to be modified for the very existence of human, animal, and many kinds of plant life. Usually it is more desirable to reduce the natural air flow (but, in hot countries, buildings on stilts are designed to increase it). Although improved by trial and error such environmental modifications have also been influenced by fluid mechanics research over the past 30 years, much helped by the pioneering work on the cold winds of Jutland by Jensen (1954) and also by the publication of special journals, such as *Agricultral Meteorology* and the *Journal of Wind Engineering.*

The successful use of fluid mechanics in the designs of, say, a group of buildings or a football stadium (Poreh 1980) requires a knowledge of what kinds of fluid flow are desirable and/or acceptable. So the *constraints* on the fluid-flow designer in this case are human as well as structural, as I found when advising an architect about the mean winds and gustiness around a proposed building. My aerodynamic advice was useless without knowing how the aerodynamic parameters could be interpreted in terms of people's responses. After discussing this problem with Dr E. C. Poulton of the Applied Psychology Research Unit in Cambridge, we were successful in persuading the Building Research Establishment to finance some experiments into how people perform simple tasks, walk, and subjectively react to the winds which are steady or gusty or have large gradients (e.g. round corners). These conditions were created by three $2{\cdot}7\ \mathrm{m} \times 0{\cdot}7\ \mathrm{m}$ flapping vanes in the old N.P.L. $4\ \mathrm{m} \times 2{\cdot}7\ \mathrm{m}$ wind tunnel. This experiment in 'applied psychoaerodynamics' together with field observations has helped in establishing criteria for acceptable winds round buildings (Isyunov & Davenport 1976), as well as being an interesting applied psychology/ergonomics experiment where subjective responses and objective performance tests correlated rather well (Hunt, Poulton & Mumford 1976)!

The design of artificial wind environments is also an example where fluid flow can only be combined with the other elements of the synthesis if the fluid-flow implication of any variations in the design are comprehensible in direct qualitative terms. Such explanatory handbooks as that of Gandemer & Guyot (1976) and Penwarden & Wise (1975) are valuable outcomes of many years applied fluid mechanics research.

A total different artificial environment study which has presented important fluid mechanics problems is the coalmine, and the studies of these problems have led to significant benefits. Many hundreds of coal miners around the world die each year, and some of these many deaths are caused by accidents involving the explosions of ignitable gases (such as methane) and of coal dust. The important problem of the vertical mixing of these gases stimulated the work of Ellison & Turner (1959) in the third volume of JFM. They showed how a key element in this process was a decrease of the *entrainment* of air into the shear layer between the air and the gas with an increase of the Richardson number (i.e. the ratio of turbulence energy damped by buoyancy to that created by shear). Their concept of entrainment inhibition has been seen to be a good way of explaining mixing in stratified estuaries, and in elevated inversion layers in the atmosphere – a nice example of how the study of one kind of applied fluid problem (stably stratified atmospheric flow) has benefited from the generalization of the concepts used there and from the application to quite another fluid-flow problem. A deeper explanation of Ellison & Turner's findings still awaits, I think, a proper understanding of entrainment.

4.4. *Dispersion*

The beautiful photographs taken in 1969 from the moon of the blue earth sprinkled with white clouds conveyed a dramatic impression of how precious and finite the Earth's environment is. The idea of using this environment as a sink in which contaminants can be dispersed without limit or concern is no longer acceptable. It is, however, inevitable that the fluid environment will be used as a sink for a long time to come, and the best we can do is to make sure it is used as well and as responsibly as possible. The scientific study of dispersion in the fluid environment is likely to play an important part in this; much as it has over the last 40 years.

There have been a number of major developments in policies and practices of air pollution dispersion in which fluid-mechanical ideas have been important:

(i) It was finally realized that there are limits to the ability of the atmosphere to remove low-level pollution, especially when the atmosphere amplifies the concentration by meteorological or photochemical effects. (So London's fireplaces in the 1950s and California's cars in the 1960s had to be cleaned up!) But it also became realized that, although the atmosphere can disperse pollutants from *high* sources and thereby reduce ground-level concentrations in regions near the source (e.g. in the U.K. SO_2 emissions rose by about $\frac{1}{3}$ from 1956 to 1970, but ground-level concentrations were roughly reduced by $\frac{1}{3}$), a policy based on this fact can lead to higher ground-level concentrations further afield (so U.K.'s SO_2 has been detected in Scandinavia). This long-range transport of pollution has raised many fascinating fluid-mechanical questions about the surface deposition of pollutants and about microscopic processes (both of which require understanding of low-Reynolds-number and Brownian motion effects as well as high-Reynolds-number turbulence), and about turbulence and diffusion during the diurnal cycle of the atmosphere. The present inadequate models of these processes have to provide the basis of many politico-environmental decisions.

(ii) The practical benefits and disadvantages of the translation of the results of fluid mechanics research into standard formulae, tables and computer programmes are well illustrated by the standardized methods now used in many countries to predict the diffusion of pollutants emitted into the atmosphere:

Usually the source is a buoyant plume emitted from a chimney of height H which first mixes with the atmosphere under the action of its own thermal and mechanical energy, by the processes of 'entraining' the surrounding fluid (Morton, Taylor & Turner 1956). At some stage this process is overtaken by the diffusing action of the external turbulence and then the pollutant is assumed to diffuse like a passive scalar from a source at greater height ΔH above the original source. This transition process is not really understood at all. The standardized methods for predicting the rate of growth of plumes (pioneered by Pasquill 1961) were developed in the framework of G. I. Taylor's (1921) statistical theory of diffusion in *homogeneous* flow and Monin & Obukhov's (1954) analysis of the diabatic surface layer. Despite the theoretical flaws in such a procedure, it is not so inaccurate that it cannot provide rough guidance. As the research on meteorological dispersion advances, so do these guidelines. This approach is dismissed as useless by Professor Scorer (1980); because nature is too complicated, he says, it cannot be codified. In a sense he is right, but if we are to follow his advice and discuss nature eddy by eddy, how is the government inspector to make his decision and how are others to argue with him? It does seem that, as people become more familiar with, and quite rightly, insist on participation in these scientific questions, there is a clear need to have generally understandable procedures for deciding the scientific aspects of contentious environmental problems. The need is obviously greater in countries where such decisions can be contested; there have been some interesting court cases in the USA whose outcome has depended on delicate fluid-mechanical questions about the diffusion of chimney plumes impinging into hillsides. Such controversies have certainly stimulated research in stratified flow and diffusion (e.g. Hunt & Snyder 1980).

(iii) These standard dispersion procedures also form the basis for 'real-time' emergency procedures, and for control systems where air pollution is monitored, and the sources controlled; such schemes are being used in Belgium and the Netherlands (see, for example, Rasse *et al.* 1976).

Many of the worst problems of water pollution are found in estuaries because the pollutant may travel up and down the estuary several times before reaching the sea; the processes for its removal depend more on turbulent mixing than on simple advection. There has been a much greater revolution in the *ideas* about river and estuarine dispersion than about air pollution dispersion. Consider a river of depth 3 m and typical turbulent velocity of 0·03 m s^{-1}. Whereas estimates of the eddy diffusivity based simply on turbulent motion are of the order of 10^{-2} m^2 s^{-1}, G. I. Taylor's theory (Elder 1959) for the effect of shear on the longitudinal turbulent dispersion showed that the diffusivity K may be of the order of 1 m^2 s^{-1} in straight two-dimensional channels. Later work has shown that, in curved rivers about 200 m wide, K is of the order of 10^3 m^2 s^{-1} (Fischer 1976). The effect of tidal oscillations and stratifications may increase this further. So it is, perhaps, not surprising that the simple water pollution models, in which mixing is assumed to take place rapidly between 'boxes' of water moving up and down the estuary, are often adequate approximations in practice. Such was the basis of the calculation that guided the policies leading to the dramatic cleaning up of many river systems, including the Thames, and have been used to estimate the effect on dispersion of flood barriers (Barrett & Mollowney 1972). As well as perhaps justifying old assumptions, the new methods of turbulence estimation and computation are now used in the designing of flows not previously calculable, e.g. the siting of cooling water outlets and inlets of power stations (McGuirk & Rodi 1979).

To the previous problems of dispersion in shallow water of subsurface soluble or particulate pollutants, there have now been added the two new dispersion problems:

the accidental release of oil, where fluid-dynamic problems are part microhydrodynamic in the break-up and dispersal of oil particles and part large scale in the dispersion by waves, currents, and wind; and, second, the long-term, very slow diffusion of nuclear wastes deposited on the ocean floors.

4.5. *Fluid resources in the ground*

A new speciality of fluid mechanics has developed with the investigation of the extraction of thermal power from the ground, namely thermal convection in porous media, a subject well represented in the *JFM* from the earliest volumes (e.g. Wooding 1957). Whereas the Earth's environment is only mildly disturbed by the injection of water in thermal power extraction processes, it is drastically altered by mining operations where salt is extracted or petroleum is pushed out by the injection of water. The improvement of the latter operation, which can double the yield of an oil well, especially if polymers are added to the water, is a particularly important fluid mechanics research problem as the world's petroleum supplies run low.

5. Conclusion

I have attempted to show some of the ways in which the control and exploitation of fluid flows in industry and the environment have been very considerably helped by the growth in understanding of fluid mechanics, in all its ever increasing number of specialities. There are also, I think, many other ways in which our present knowledge of fluid flow and fluid mechanics could have been used to help in the *analysis* of practical problems, and the synthesis of the results in fluid-flow design.

How will the future developments in fluid mechanics help in developing new users of fluid flow? Clearly the wider-scale use of computers (helped by the development of larger, cheaper computers) will enormously aid some kinds of fluid-flow designing, such as the prediction of environmental disasters, or the step-by-step improvement of fluid-flow designing (e.g. Mr Welbourn of the Cambridge Engineering Department has suggested we should be able to improve greatly the design of most of the basic elements in flow circuits, such as 90° pipe bends, to lower the pressure drop and use less solid material. Computer-controlled manufacturing makes possible designs other than the present simple circular arc bends). Such optimization should become commonplace, even though still based on very heuristic methods for turbulent flows. But the synthesis of quite new methods of fluid-flow designing will in many cases only come with better understanding of the fluid-mechanical processes. For example, one might hope that a better understanding of interactions and instabilities of vortices (Saffman 1981) and of the mixing of scalar contaminants (Moffatt 1981) may revolutionize many fluid-energy devices from combustion devices to heat exhangers, and the dispersion of buoyant plumes in the environment.

Although it is unlikely that there will be a sudden leap forward in the understanding of fluid mechanics as a whole, it being likely to develop step-by-step (with some steps larger than others), there may, with luck, be a jump in the attitude of fluid-mechanics researchers to the problems of synthesizing fluid flows, which, as Shercliff (q.v.) points out, have many challenging theoretical as well as experimental aspects. I certainly hope that *JFM* will have a few more good papers on this subject.

I am very grateful to Professor H. K. Moffatt and Professor J. A. Shercliff for their comments on drafts of this paper.

REFERENCES

ARMITT, J. & COUNIHAN, J. 1968 *Atm. Env.* **2**, 49–71.

BARRETT, M. J. & MOLLOWNEY, B. M. 1972 *Phil. Trans. Roy. Soc.* A **272**, 211.

BATTJES, J. A. 1980 *Proc. 15th Int. Cong. Theor. & Appl. Mech.* North Holland.

BATCHELOR, G. K. 1960, 1963, 1971 *The Scientific Papers of G. I. Taylor*, vols. 2, 3, 4. Cambridge University Press.

BATCHELOR, G. K. & PROUDMAN, I. 1954 *Quart. J. Mech. Appl. Math.* **7**, 83.

BRADSHAW, P. 1976 *Turbulence.* Springer.

BROWN, G. L. & ROSHKO, A. 1974 *J. Fluid Mech.* **64**, 775.

CENTRAL ELECTRICITY GENERATING BOARD 1967 Report of the Committee of Inquiry into the collapse of cooling towers at Ferrybridge, London.

COUNT, B. M. 1980 *Fluid Mechanics in Energy Conversion*, pp. 3–42. S.I.A.M. Philadelphia.

CROW, S. C. & CHAMPAGNE, F. H. C. 1971 *J. Fluid Mech.* **48**, 547.

DANNA, M. & POINTER, D. 1978 *Frisbee Players' Handbook.* Parachuting Publications (Santa Barbara).

DAVENPORT, A. G. 1961 *Proc. Inst. Civil Eng.* **19**, 449.

DAVIDSON, J. F. & HARRISON, D. 1963 *Fluidised particles.* Cambridge University Press.

DOWSON, D. 1979 *History of Tribology.* Longmans.

DURBIN, P. A. & HUNT, J. C. R. 1980 *J. Fluid Mech.* **100**, 161.

EARL, T. D. 1962 *Agardograph* 67.

ELDER, J. W. 1959 *J. Fluid Mech.* **5**, 544.

ELLISON, T. & TURNER, J. S. 1959 *J. Fluid Mech.* **6**, 423.

ETKIN, B. & GOERING, P. L. E. 1971 *Phil. Trans. Roy. Soc.* A **269**, 527.

EVANS, D. V. 1976 *J. Fluid Mech.* **77**, 1.

FISCHER, H. B. 1976 *Ann. Rev. Fluid Mech.* **8**, 107–133.

FURBER, S. B. & FFOWCS-WILLIAMS, J. E. 1979 *J. Fluid Mech.* **94**, 519.

GANDEMER, J. & GUYOT, A. 1976 *Intégration du phénomène vent dans la conception du milieu bâti.* La Documentation Française.

GOLDRING, B. T., MAWER, W. T. & THOMAS, N. H. 1980 *Proc. 3rd Pressure Surge Cong., Brit. Hydromech. Res. Assoc., Cranfield, U.K.*

GOLDSTEIN, M. E. & DURBIN, P. A. 1980 *J. Fluid Mech.* **98**, 473.

GUTMARK, E., VAKNIN, A. & WOLFSHTEIN, M. 1980 Abstracts of *15th Int. Cong. of Theoretical & Applied Mechanics* p. 187. Dept. Mech. Engng, Univ. Toronto.

HALL, M. G. 1972 *Ann. Rev. Fluid Mech.* **4**, 195.

HAWKING, S. W. & ELLIS, G. F. R. 1973 *Large-Scale Structure of Spacetime.* Cambridge University Press.

HAWTHORNE, W. R. 1961 *Proc. Inst. Mech. Eng.* **175**, 52.

HAWTHORNE, W. R. 1978 *Aero. J.*, March p. 93.

HEAPS, N. S. 1969 *Phil. Trans. Roy. Soc.* A **265**, 93.

HOWARD, L. N. 1963 *J. Fluid Mech.* **17**, 405.

HUNT, J. C. R. 1973 *J. Fluid Mech.* **61**, 625.

HUNT, J. C. R. & RICHARDS, D. J. W. 1969 *Proc. Inst. Elec. Eng.* **116**, 1869.

HUNT, J. C. R. & FERNHOLZ, H. H. 1975 *J. Fluid Mech.* **70**, 543.

HUNT, J. C. R., POULTON, E. C. & MUMFORD, J. C. 1976 *J. Fluid Mech.* **11**, 15.

HUNT, J. C. R. & SHERCLIFF, J. A. 1971 *Ann. Rev. Fluid Mech.* **3**, 37.

HUNT, J. C. R. & SNYDER, W. H. 1980 *J. Fluid Mech.* **96**, 671.

HUNT J. C. R. 1980 *Proc. 15th Int. cong. Theor. & Appl. Mech.* North Holland.

HURLE, D. T., JAKEMAN, E. & JOHNSON, C. P. 1974 *J. Fluid Mech.* **64**, 565.

JENSEN, M. 1954 *Shelter Effect.* Copenhagen.

JEWKES, J., SAWERS, D. & STILLERMAN, R. 1958 *The Sources of Invention.* Macmillan.

JOHNS, B. & ANWAR ALI, M. 1980 *Quart. J. Roy. Met. Soc.* **106**, 1.

ISYUMOV, N. & DAVENPORT, A. G. 1976 *Proc. 4th Int. Conf. Wind Effects on Structures.* Cambridge University Press.

KÁRMÁN, T. VON & EDSON, L. 1967 *The Wind and Beyond.* Boston: Little, Brown & Co.

LEHDE, H. & LANG, W. T. 1948 Device for measuring rate of fluid flow. U.S. Pat. 2435043.

LEIBOVICH, S. 1978 *Ann. Rev. Fluid Mech.* **10**, 221.

LEITH, C. E. 1978 *Ann. Rev. Fluid Mech.* **10**, 107–128.

LENNEMAN, E. 1974 *I.B.M. J. Res. Dev.* **18**, 480.

LESLIE, L. M. 1971 *J. Fluid Mech.* **48**, 1.

LIGHTHILL, M. J. 1973 *J. Fluid Mech.* **60**, 1.

LIGHTHILL, M. J. 1979 *J. Fluid Mech.* **91**, 253.

LOEHRKE, R. I. & NAGIB, A. M. 1972 *Agard Rep.* 598.

LUMLEY, J. 1969 *Ann. Rev. Fluid Mech.* **1**, 367.

MCGUIRK, J. J. & RODI, W. 1979 *J. Fluid Mech.* **95**, 609.

MAULL, D. J. & MILLINER, M. G. 1978 *Coastal Engng* **2**, 149.

MAYALL, W. H. 1979 *Principles of Design.* Design Convention, London.

MOFFATT, H. K. 1981 *J. Fluid Mech.* **106**, 27.

MONIN, A. S. & OBUKHOV, A. M. 1954 *Akad. Nauk SSR Leningrad. Geofiz. Inst. Trudy* **151**, 163. Translated in *Aerophysics of Air Pollution* (eds. J. A. Fay & D. P. Hoult), AIAA New York 1969.

MOREAU, R. 1980 *Proc. 15th Int. Cong. Theor. & Appl. Mech.* North Holland.

MORELL, T. & DALTON, C. 1979 *Aerodynamics of Transportation.* A.S.M.E.

MORTON, B. R., TAYLOR, G. I. & TURNER, J. S. 1956 *Proc. Roy. Soc.* A **234**, 1.

OGILVIE, F. T. 1963 *J. Fluid Mech.* **16**, 451.

PANOFSKY, H. A. 1974 *Ann. Rev. Fluid Mech.* **6**, 147.

PASQUILL, F. 1961 *Met. Mag.* **90**, 33.

PENWARDEN, A. D. & WISE, A. F. E. 1975 Wind environment around buildings. *BRE Rep.* London: HMSO.

PEREGRINE, D. H. 1981 *J. Fluid Mech.* **106**, 59.

POREH, M. 1980 *Proc. 5th Int. Conf. on Wind Engineering.* Pergamon.

RASSE, D., LEGRAND, M., DEROUANE, A., VERDUGN, G. 1976 *Proc. Conf. Systems and Models in Air Pollution. Inst. Meas. Control, London,* paper 15.

RIBNER, H. S. & TUCKER, M. 1953 *N.A.C.A. Rep.* 1113.

ROCKWELL, D. & NAUDASCHER, F. 1979 *Ann. Rev. Fluid Mech.* **11**, 67–94.

SAFFMAN, P. G. 1981 *J. Fluid Mech.* **106**, 49.

SCHUMACHER, E. S. 1973 *Small is Beautiful.* London: Sphere.

SCORER, R. S. 1980 *Clean Air* **10**, no. 5.

SCRUTON, C. 1963 *Nat. Phys. Lab. (Teddington U.K.) Aero. Rep.* 1012.

SHERCLIFF, J. A. 1979 *J. Fluid Mech.* **91**, 231.

SHERCLIFF, J. A. 1981 *J. Fluid Mech.* **106**, 349.

SNYDER, W. H. 1973 *Boundary Layer Met.* **3**, 113.

SOVRON, G., MOREL, T. & MASON, W. T. 1979 *Aerodynamic Drag Mechanisms of Bluff Bodies and Road Vehicles.* Plenum.

SWEET, R. G. 1965 *Rev. Sci. Inst.* **36**, 131.

TAYLOR, G. I. 1921 *Proc. Lond. Math. Soc.* **20**, 196.

TOWNSEND, A. A. 1976 *Structure of Turbulent Shear Flow* (2nd edn). Cambridge University Press.

TRYGVASON 1980 *Proc. 5th Int. Wind Eng. Conf.*, p. 1061. Pergamon.

UNCLES, R. J. & RADFORD, P. J. 1980 *J. Fluid Mech.* **98**, 103.

WARDLEY SMITH, J. 1976 *The Control of Oil Pollution.* London: Graham & Trotman.

WATSON, J. H. P. 1973 *J. Appl. Phys.* **14**, 4209.

WHITE, D. F., RODELY, A. E. & MCMURTIE C. L. 1974 In *Flow, its Measurement and Control in Science and Industry*, vol. 1. pt 2. Pittsburgh, Pa. I.S.M.A.

WILLE, R. & FERNHOLZ, H. 1965 *J. Fluid Mech.* **23**, 801.

WOODING, R. A. 1957 *J. Fluid Mech.* **2**, 273.

YALIN, M. S. 1971 *Theory of Hydraulic Models.* Macmillan.