Int. J. Engng Ed. Vol. 14, No. 3, p. 177–185, 1998
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Fluid Mechanics from the Beginning to the Third Millennium*

MOHAMED GAD-EL-HAK
Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA. E-mail: mohamed.gad-el-hak.1@nd.edu

Although the christening of the discipline is a relatively recent undertaking, fluid mechanics goes back to the time of archaic Homo sapiens. The art of fluids in motion was born when quite empirically, unceremoniously and without a hint of what either a fluid or mechanics is, the resourceful inhabitants of the planet Earth discovered that a streamlined object travels farther as compared to a blunt one. Great changes took place during the first half of this century in both the teaching and research of the discipline, and it appears that the subject is set for another upheaval as we approach the third millennium. This paper discusses those past and future evolutions of fluid mechanics.

IN THE BEGINNING

The farther backward you can look, the farther forward you are likely to see. (Sir Winston Leonard Spencer Churchill, 1874–1965)

THIS PAPER is certainly not intended to be a history of the subject, but a few important milestones are recalled in this and the next five sections. The purpose of the exercise is to submit that the discipline of fluid mechanics, as taught in engineering schools and practiced in industry, is perhaps ripe for a major overhaul equal in significance to the changes that took place early in the twentieth century. The different eras to be discussed are seen from the perspective of the history of the universe time line depicted in Fig. 1.

The art of fluid mechanics arguably has its roots in prehistoric times when streamlined spears, sickle-shaped boomerangs and fin-stabilized arrows evolved empirically [1] by the sheer perseverance of archaic *Homo sapiens* who knew nothing about air resistance or aerodynamic principles. Three aerodynamically correct wooden spears were recently excavated in an open-pit coal mine near Hanover, Germany [2]. Archeologists dated the carving of those complete spears to about 400,000 years ago [3] which strongly suggests early Stone Age ancestors possessing resourcefulness and skills once thought to be characteristics that came only with fully-modern *Homo sapiens*.

Modern man also unknowingly yet artfully applied fluid flow principles to achieve certain technological goals. Relatively soon after the dawn of civilization and the establishment of an agriculture way of life 8000 years ago, complex systems of irrigation were built along inhabited river valleys to control the water flow, thus freeing man from the vagaries of the weather. Some resourceful albeit mischievous citizens of the Roman Empire discovered that adding the right kind of diffuser to the calibrated convergent nozzle ordinarily installed at home outlets of the public water main significantly increased the charge of potable water over that granted by the Emperor. For centuries, farmers knew the value of windbreaks to keep top soil in place and to protect fragile crops.

ARCHIMEDES TO LEONARDO

Mechanics is the paradise of the mathematical sciences because by means of it one comes to the fruits of mathematics. (Leonardo da Vinci, 1452–1519)

The Greek mathematician Archimedes (287–212 BC) provided an exact solution to the fluid-at-rest problem and expressions for the buoyant force on various bodies, long before calculus or the modern laws of mechanics were known. The science of hydrostatics was developed at about the same time the Romans were building their water-supply systems. A few centuries of scientific drought followed, only to be re-irrigated by the Renaissance's deluge of art and science. Leonardo da Vinci (1452–1519) correctly deduced the conservation of mass equation for incompressible, one-dimensional flows.

Leonardo also pioneered the flow visualization genre close to 500 years ago. Much of Leonardo's notebooks of engineering and scientific observations were translated into English in a magnificent two-volume book by MacCurdy [4]. Succulent descriptions of the smooth and eddying motions of water alone occupy 121 pages. In there, one can easily discern the Renaissance genius's prophecy of

* Accepted 10 March 1998.

15 billion (years ago)	**Big bang**	
4.6 billion	**Solar system formed**	
1.5 billion	**Life began on Earth**	
250 million	**Dragonfly**	
4 million	***Ancestral hominid***	
2 million	***Homo habilis***	(handy)
1.5 million	***Homo erectus***	
500,000	***Archaic Homo sapiens***	
200,000	***Homo sapiens***	(wise)
10,000	**Agriculture**	(civilization)
5,500	**Plough**	
5,000	**Irrigation systems/Writing**	
4,000	**Biblical Judaism**	(Abraham)
3,500	**Metals**	
1600	**Middle ages**	
600	**Modern age**	(renaissance)
300	**Modern science/Newton's laws**	
150	**Navier-Stokes equations**	
100 (years ago)	**Powered flight/Boundary layer theory/ Science of flow control**	
Present	**What better time to be alive!**	
Future	**Information age**	

Fig. 1. History of the universe time line. All dates are approximate, and the time scale is highly nonlinear.

some of the flow physics to be discovered centuries after his time. Particularly relevant to the modern notion of coherent structures, the words eddies and eddying motions percolate throughout Leonardo's treatise on liquid flows.

Figure 2 is perhaps the world first use of visualization as a scientific tool to study a turbulent flow. Around 1500, Leonardo sketched a free water jet issuing from a square hole into a pool. He wrote 'Observe the motion of the surface of the water, which resembles that of hair, which has two motions, of which one is caused by the weight of the hair, the other by the direction of the curls; thus the water has eddying motions, one part of which is due to the principal current, the other to the random and reverse motion.' Reflecting on this passage, Lumley [5] speculates that Leonardo da Vinci might have prefigured the now famous Reynolds turbulence decomposition nearly 400 years prior to Osborne Reynolds' own flow visualization and analysis!

In describing the swirling water motion behind a bluff body, da Vinci provided the earliest reference to the importance of vortices in fluid motion: 'So moving water strives to maintain the course pursuant to the power which occasions it and, if it finds an obstacle in its path, completes the span of the course it has commenced by a circular and revolving movement.' Leonardo accurately sketched the pair of quasi-stationary, counter-rotating vortices in the midst of the random wake.

Finally, da Vinci's words '. . . the small eddies are almost numberless, and large things are rotated only by large eddies and not by small ones, and small things are turned by both small eddies and large,' presage Richardson's cascade, coherent structures and large-eddy simulations, at least.

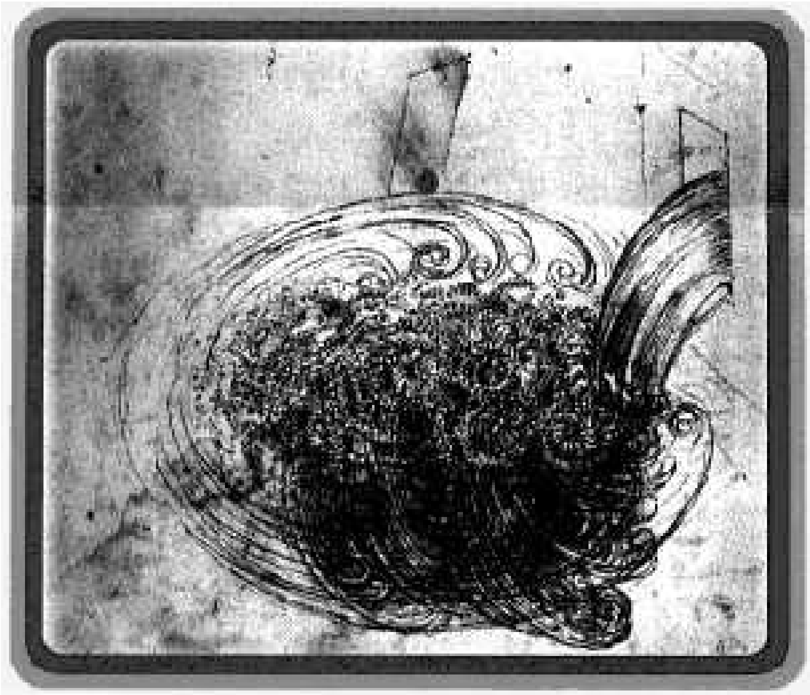

Fig. 2. Leonardo da Vinci's sketch of water exiting from a square hole into a pool; circa 1500.

THE FUNDAMENTAL EQUATIONS

Now I think hydrodynamics is to be the root of all physical science, and is at present second to none in the beauty of its mathematics. (William Thomson (Lord Kelvin), 1824–1907)

Little more than a century and half after the incomparable Newton's *Principia Mathematica* was published in 1687, the first principles of viscous fluid flows were affirmed in the form of the Navier-Stokes equations, with major contributions by Navier in 1823, Cauchy in 1828, Poisson in 1829, Saint Venant in 1843, and Stokes in 1845. With very few exceptions, the Navier-Stokes equations provide an excellent model for both laminar and turbulent flows. The anticipated paradigm shift in fluid mechanics discussed in this paper centers around the ability today as well as tomorrow of computers to numerically integrate those equations. We therefore recall in this section the equations of fluid motion in their entirety.

Each of the fundamental laws of fluid mechanics, conservation of mass, momentum and energy, are listed first in their *raw form*, i.e. assuming only that the speeds involved are non-relativistic and that the fluid is a continuum. The latter assumption implies that the derivatives of all the dependent variables exist in some reasonable sense. In other words, local properties such as density and velocity are defined as averages over elements large compared with the microscopic structure of the fluid but small enough in comparison with the scale of the macroscopic phenomena to permit the use of differential calculus to describe them. The resulting equations therefore cover a very broad range of situations, the exception being flows with spatial scales which are not much larger than the mean distance between the fluid molecules, as for example in the case of rarefied gas dynamics, shock waves that are thin relative to the mean free path, or flows in micro- and nano-devices. Thus at every point in space-time and in Cartesian tensor notations, the three conservation laws read:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_k) = 0 \tag{1}$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_k \frac{\partial u_i}{\partial x_k}\right) = \frac{\partial \sum_{ki}}{\partial x_k} + \rho g_i \tag{2}$$

$$\rho\left(\frac{\partial e}{\partial t} + u_k \frac{\partial e}{\partial x_k}\right) = -\frac{\partial q_k}{\partial x_i} + \textstyle\sum_{ki} \frac{\partial u_i}{\partial x_k} \tag{3}$$

where ρ is the fluid density, u_k is an instantaneous velocity component (u, v, w), $\sum_{ki}$ is the second-order stress tensor (surface force per unit area), g_i is the body force per unit mass, e is internal energy per unit mass, and q_k is the sum of heat flux vectors due to conduction and radiation. The independent variables are time t and the three spatial x_1, x_2 and x_3, or (x, y, z). Finally, the Einstein's summation convention applies to all repeated indices.

CLOSING THE EQUATIONS

You are not educated until you know the Second Law of Thermodynamics. (Charles Percy (Baron) Snow, 1905–1980)

Equations (1), (2) and (3) constitute five differential equations for the 17 unknowns ρ, u_i, $\sum_{ki}$, e and q_k. Absent any body couples, the stress tensor is symmetric having only six independent components, which reduces the number of unknowns to 14. To close the conservation equations, relation between the stress tensor and deformation rate, relation between the heat flux vector and the temperature field, and appropriate equations of state, relating the different thermodynamic properties, are needed. For a Newtonian, isotropic, Fourier, ideal gas, for example, these relations read:

$$\sum\nolimits_{ki} = -p\delta_{ki} + \mu\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right) + \lambda\left(\frac{\partial u_j}{\partial x_j}\right)\delta_{ki} \tag{4}$$

$$q_i = -\kappa\frac{\partial T}{\partial x_i} + \text{Heat flux due to radiation} \tag{5}$$

$$\mathrm{d}e = c_v\,\mathrm{d}T \qquad \text{and} \qquad p = \rho RT \tag{6}$$

where p is the thermodynamic pressure, μ and λ are the first and second coefficients of viscosity, respectively, δ_{ki} is the unit second-order tensor (Kronecker delta), κ is the thermal conductivity, T is the temperature field, c_v is the specific heat at constant volume, and R is the gas constant. (Newtonian implies a linear relation between the stress tensor and the symmetric part of the deformation tensor (rate of strain tensor). The isotropy assumption reduces the 81 constants of proportionality in that linear relation to two constants. Fourier fluid is that for which the conduction part of the heat flux vector is linearly related to the temperature gradient, and again isotropy implies that the constant of proportionality in this relation is a single scalar.)

The Stokes' hypothesis relates the first and second coefficients of viscosity, $\lambda + \frac{2}{3}\mu = 0$, although the validity of this assumption has occasionally been questioned [6]. With the above constitutive relations and neglecting radiative heat transfer, equations (1), (2) and (3) respectively read:

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_k) = 0 \tag{7}$$

$$\begin{aligned}\rho\left(\frac{\partial u_i}{\partial t} + u_k\frac{\partial u_i}{\partial x_k}\right) &= -\frac{\partial p}{\partial x_i} + \rho g_i \\ &+ \frac{\partial}{\partial x_x}\left[\mu\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right) + \delta_{ki}\lambda\frac{\partial u_j}{\partial x_j}\right]\end{aligned} \tag{8}$$

$$\rho c_v\left(\frac{\partial T}{\partial t} + u_k\frac{\partial T}{\partial x_k}\right) = \frac{\partial}{\partial x_k}\left(\kappa\frac{\partial T}{\partial x_k}\right) - p\frac{\partial u_k}{\partial x_k} + \phi \tag{9}$$

The three components of the vector equation (8) are the Navier-Stokes equations expressing the conservation of momentum for a Newtonian fluid. In the thermal energy equation (9), ϕ is the always positive (as required by the Second Law of Thermodynamics) dissipation function expressing the irreversible conversion of mechanical energy to internal energy as a result of the deformation of a fluid element. The second term on the right-hand side of (9) is the reversible work done (per unit time) by the pressure as the volume of a fluid material element changes. For a Newtonian, isotropic fluid, the viscous dissipation rate is given by

$$\phi = \tfrac{1}{2}\mu\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)^2 + \lambda\left(\frac{\partial u_j}{\partial x_j}\right)^2 \tag{10}$$

There are now six unknowns, ρ, u_i, p and T, and the five coupled equations (7), (8) and (9) plus the equation of state relating pressure, density and temperature. These six equations together with sufficient number of initial and boundary conditions constitute a well-posed, albeit formidable, problem. The system of equations (7)–(9) is an excellent model for the laminar or turbulent flow of most fluids such as air and water under most circumstances, including high-speed gas flows for which the shock waves are thick relative to the mean free path of the molecules.

Considerable simplification is achieved if the flow is assumed incompressible, usually a reasonable assumption provided that the characteristic flow speed is less than 0.3 of the speed of sound. The incompressibility assumption is readily satisfied for almost all liquid flows and many gas flows. In such cases, the density is assumed either a constant or a given function of temperature (or species concentration). The governing equations for such flow are:

$$\frac{\partial u_k}{\partial x_k} = 0 \tag{11}$$

$$\begin{aligned}\rho\left(\frac{\partial u_i}{\partial t} + u_k\frac{\partial u_i}{\partial x_k}\right) &= -\frac{\partial p}{\partial x_i} \\ &+ \frac{\partial}{\partial x_x}\left[\mu\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)\right] \\ &+ \rho g_i\end{aligned} \tag{12}$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + u_k\frac{\partial T}{\partial x_k}\right) = \frac{\partial}{\partial x_k}\left(\kappa\frac{\partial T}{\partial x_k}\right) + \phi^* \tag{13}$$

These are five equations for the five dependent variables u_i, p and T. Note that the left-hand side of equation (13) has the specific heat at constant pressure c_p and not c_v. This is the correct incompressible-flow limit—of a compressible fluid—as discussed in detail in Section 10.9 of Panton's book [7]; a subtle point perhaps but one that is frequently missed in textbooks. The system of equations (11)–(13) is coupled if either the viscosity or density depends on temperature, otherwise the energy equation is uncoupled from the continuity and momentum equations and can therefore be solved *after* the velocity and pressure fields are determined from solving (11) and (12).

PRANDTL'S BREAKTHROUGH

There is no greater impediment to progress in the sciences than the desire to see it take place too quickly. (George Christoph Lichtenberg, 1742–1799)

Even with the simplification accorded by the incompressibility assumption, the above system of equations is formidable and has no general solution. Usual further simplifications—applicable only to laminar flows—include geometries for which the nonlinear terms in the (instantaneous) momentum equation are identically zero, low-Reynolds-number creeping flows for which the nonlinear terms are approximately zero, and high-Reynolds-number inviscid flows for which the continuity and momentum equations can be shown to metamorphose into the linear Laplace equation. The latter assumption spawned the great advances in perfect flow theory that took place during the second half of the nineteenth century. However, neglecting viscosity gives the totally erroneous result of zero drag for moving bodies and zero pressure drop in pipes. Moreover, none of those simplifications apply to the rotational, (instantaneously) time-dependent and three-dimensional turbulent flows.

Not surprisingly, hydraulic engineers of the time showed little interest in the elegant theories of hydrodynamics and relied instead on their own collection of totally empirical equations, charts and tables to compute drag, pressure losses and other practically important quantities. Consistent with this pragmatic approach, engineering students then and for many decades to follow were taught the art of hydraulics. The science of hydrodynamics was relegated, if at all, to mathematics and physics curricula.

In lamenting the status of fluid mechanics at the dawn of the twentieth century, the British chemist and Nobel laureate Sir Cyril Norman Hinshelwood (1897–1967) jested that fluid dynamists were divided into hydraulic engineers who observed things that could not be explained and mathematicians who explained things that could not be observed.

In an epoch-making presentation to the third International Congress of Mathematicians held at Heidelberg, the German engineer Ludwig Prandtl resolved, to a large extent, the above dilemma. In 1904, Prandtl [8] introduced the concept of a fluid boundary layer, adjacent to a moving body, where viscous forces are important and outside of which the flow is more or less inviscid. At sufficiently high Reynolds number, the boundary layer is thin relative to the longitudinal length scale and, as a result, velocity derivatives in the streamwise direction are small compared to normal derivatives. That single simplification made it possible for the first time to obtain viscous flow solutions even in the presence of nonlinear terms, at least in the case of laminar flow. Both the momentum and energy equations are parabolic under such circumstances, and are therefore amenable to similarity solutions and marching numerical techniques. From that moment on, viscous flow theory was in vogue for both scientists and engineers. Practical quantities such as skin-friction drag could be computed from first principles even for non-creeping flows. Experiments in wind tunnels and their cousins provided valuable data for problems too complex to submit to analysis.

THE SWITCH FROM ART TO SCIENCE

There is always an easy solution to every human problem—neat, plausible and wrong. (Henry Louis Mencken, 1880–1956)

It took a number of years for the boundary layer theory mentioned in the last section to travel outside the small circle of Prandtl and his students at Göttingen. Prandtl's paper, written in German naturally, contained a wealth of information: the concept of boundary layer, the resulting approximations, the mechanism of separation, and flow control strategies to delay flow separation. Yet, the manuscript was limited by the Congress organizers to 8 pages—difficult reading indeed. The pace, for researchers at least, picked up just prior to and certainly after World War II. But engineering schools for the most part continued to teach hydraulics, with scant attention to the Navier-Stokes equations. Only when those schools, particularly in the United States, decided that a quantum shift from engineering technology to engineering science education was in order, did fluid mechanics replace hydraulics in undergraduate engineering curricula.

The key impetus for that switch was an important report, the Grinter Report, prepared by a committee of the American Society of Engineering Education set to evaluate the future of engineering education in general. In May 1952, ASEE President S. C. Hollister charged that committee 'to recommend the pattern or patterns that engineering education should take in order to keep pace with the rapid developments in science and technology, and to educate men [sic] who will be competent to serve the needs of and provide the leadership for the engineering profession over the next quarter-century'.

The Grinter Report [9], published in September 1955 and named after Linton E. Grinter who chaired the ASEE Committee on Evaluation of Engineering Education, is considered a major work in the development of undergraduate engineering curricula that is used today in the United States. The report outlines specific objectives for both the technical and humanities areas of study necessary for future engineers and was the first time in the development of engineering education that the curricula was divided into four segments:

1. humanities and social sciences;
2. mathematics and basic sciences;
3. engineering science;
4. engineering specialty subjects and electives.

According to Weese and Wolf [10], the Grinter Report lay fallow until it was punctuated by the launching of the Soviet satellite Sputnik in October 1957. The cold war and the space race opened engineering education to the reformations recommended by that report, most importantly the switch to a curriculum based on the fundamentals of engineering science. Readers interested in the pedagogic change from engineering technology to engineering science may consult references [11–15].

So, fluid mechanics as taught today centers around first principles and the art of *rational* approximations: integral methods, inviscid flow, boundary-layer approximation, asymptotic analysis, etc. The wind tunnel continues to validate as well as complements the analytical results. But the digital computer may change all that. Today the full equations can be numerically integrated for almost any laminar flow. Turbulent flows are a different beast of course. Only trivial geometries and very modest Reynolds numbers can be tackled via direct numerical simulations. Few decades from now, however, turbulent flows may be approached as readily as their laminar counterparts. This and the potential for a paradigm shift in fluid mechanics education and practice are argued in the following section.

THE COMPUTER

However far modern science and technics have fallen short of their inherent possibilities, they have taught mankind at least one lesson: Nothing is impossible.
(Lewis Mumford, 1895–1990)

We consider in this section the future of some of the physical sciences which are developed enough for problems to be well-posed mathematically even though, due to their complexity, analytical solutions are not possible. Such problems are typically approached through a combination of physical and numerical experiments, the latter increasing in scope and range as more computing power becomes available. Will they take over the former? Many areas in mechanics, and in particular fluid mechanics, appear to be at this stage. In a letter addressed to George G. Stokes dated 20 December 1857, William Thomson wrote 'Now I think hydrodynamics is to be the root of all physical science, and is at present second to none in the beauty of its mathematics.' Since we do not disagree with Lord Kelvin's assessment of the importance of fluid dynamics and since the present paper concerns the future of this particular area, we focus on this subject as a quintessential example for the rest of this section. However, the arguments presented apply equally to many other disciplines: heat transfer, structural mechanics, etc.

As a teaching and research discipline, will fluid mechanics be around during the twenty-first century and beyond? During the last century, theoretical hydrodynamics flourished but was totally disjoint from the empirical science of hydraulics. The twentieth century witnessed the development of boundary layer theory and the merging of hydraulics and hydrodynamics into a unified science. What will become of fluid mechanics research and teaching during the next century? As we approach the third millennium the art and science of fluid mechanics might be set for dramatic changes. In no small part, rapidly advancing computer technology would be responsible for those changes.

Leaving aside for a moment less conventional, albeit just as important, problems in fluid mechanics such as those involving non-Newtonian fluids, multiphase flows, hypersonic flows and chemically reacting flows, in principle practically any laminar flow problem can presently be solved, at least numerically. Turbulence, in contrast, remains largely an enigma, analytically unapproachable yet practically very important. For a turbulent flow, the dependent variables are random functions of space and time, and no straightforward method exists for analytically obtaining stochastic solutions to the governing nonlinear, partial differential equations. The statistical approach to solving the Navier-Stokes equations always leads to more unknowns than equations (the closure problem), and solutions based on first principles are again not possible. The heuristic modeling used to close the Reynolds-averaged equations has to be validated case-by-case, and does not therefore offer much of an advantage over the old-fashioned empirical approach.

Turbulence, therefore, is a conundrum that appears to yield its secrets only to physical and numerical experiments, provided that the wide band of relevant scales is fully resolved—a far-from-trivial task at high Reynolds numbers [16]. Direct numerical simulations (DNS) of the canonical turbulent boundary layer have so far been carried out, at great cost despite a bit of improvising, up to a very modest momentum-thickness Reynolds number of 1410 [17].

In a turbulent flow, the ratio of the large eddies (at which the energy maintaining the flow is input) to the Kolmogorov micro-scale (the flow smallest length-scale) is proportional to $Re^{(3/4)}$ [18]. Each excited eddy requires at least one grid point to describe it. Therefore, to adequately resolve, via DNS, a three-dimensional flow, the required number of modes would be proportional to $Re^{(3/4)^3}$. In order to describe the motion of small eddies as they are swept around by large ones, the time step must not be larger than the ratio of the Kolmogorov length-scale to the characteristic rms velocity. The large eddies, on the other hand, evolve on a time-scale proportional to their size divided by their root-mean-square velocity. Thus, the number of time steps required is again proportional to $Re^{(3/4)}$. Finally, the computational work requirement is the number of modes $\times$ the number of time steps, which scales with Re^3, i.e. an order of magnitude increase in computer power is needed as the Reynolds number is doubled [19]. Since the computational resource required varies as the cube of the Reynolds number, it may not be possible to simulate very high Reynolds number turbulent flows any time soon.

Despite the bleak assessment above, one wonders whether gigantic computers combined with appropriate software will be available during the twenty-first century to routinely solve, using DNS, practical turbulent flow problems? The black box would prompt its operator for the geometry and flow conditions, and would then spit out a numerical solution to the specific engineering problem. Nobody, except the software developers, needs to know the details of what is going on inside the black box, not even which equations are being solved. This situation is not unlike using a present-day word processor or even hand calculator. A generation of users of the Navier-Stokes computers would quickly lose the aptitude, and the desire, to perform simple analysis based on physical considerations, much the same as the inability of some of today's users of hand calculators to manually carry out long divisions. The need for rational approximations, so prevalent today in fluid mechanics teaching and practice, would gradually wither.

Future computers

During the late 1990s, the supercomputer power approached the teraflop, i.e. 10^{12} floating-point operations per second. This is about right to compute a flow with a characteristic Reynolds number of 10^8, sufficient to simulate the flow around an airfoil via DNS, around a wing via large-eddy simulation, or around an entire commercial aircraft via Reynolds-averaged calculation. An exaflop (10^{18} flops) computer is needed to carry out direct numerical simulation of the complete airplane [19].

Silicon-based computer powers have witnessed spectacular recent advances, something like a factor of 10 000 improvement in speed and capacity during the past 20 years. (Although loosely related, this is consistent with the law named after the co-founder of Intel Corporation, Gordon Moore, who in 1965 predicted that the transistor density on a semiconductor chip would double and its price would halve roughly every 18 months. Incidentally, Moore's Law has been bettered in 1997.) If one is to extrapolate those recent advances to the next fifty years or so, using direct numerical simulations to solve the turbulence problem for realistic geometries and field Reynolds numbers may begin to approach feasibility. Unfortunately, however, silicon microchips are rapidly approaching their physical limits with little room for further growth.

Fortunately this kind of linear thinking may be misleading. Revolutionary computing machines that bear little resemblance to today's silicon-based computers may be developed in the future. A recent article in *Science* [20] discusses five such futuristic computing concepts: quantum dots, quantum computers, holographic association, optical computers, and DNA computers. We focus on the last possibility: the so-called DNA (deoxyribonucleic acid) computing systems, a novel concept introduced and actually demonstrated late in 1994 by Adleman [21], who in turn was inspired by the original Feynman's [22] vision of building even smaller sub-microscopic computers. The idea is already attracting considerable attention from computer scientists as well as microbiologists. In such massively parallel machines, the four basic chemical units of DNA (adenine, thymine, guanine and cytosine, designated A, T, G and C, respectively) would be used as computing symbols, and the system would utilize the genetic material for information storage and computations.

Computer theorists argue that a problem could be set up by synthesizing DNA molecules with a particular sequence that represents numerical information, and by letting the molecules react in a test tube, producing new molecules whose sequence is the answer to the problem. Thus, the same genetic machinery that generates living organisms could be used to solve previously unapproachable mathematical puzzles. Crude estimates indicate that a mere 500 gm of DNA molecules (a human body contains about 300 gm of DNA) suspended in 1000 liters of fluid would have the equivalent memory to all the electronic computers ever made! In such 'primordial, reacting soup', four months of manipulating the DNA molecules would yield an answer to a problem that would have required more operations than all those ever performed on all the conventional computers ever built.

In principle, a super-supercomputer that could integrate the equations of motion for a mainstream turbulence problem could also do the same, perhaps with some additional effort, for the myriad of other important fluid problems. Astrophysical flows, multiphase flows, non-Newtonian fluids, hypersonic problems involving dissociation and rarefied gas effects, combustion problems, etc., whether they involve laminar or turbulent flow, are all extremely difficult to formulate and integrate; but once properly modeled the number crunchers would give the needed answers.

If the above or similar vision materializes, the question is then what will become of fluid mechanics as a subject to be taught to engineering and science majors and as a distinct research discipline. True, engineers will always need to know some basics of fluid engineering in order to interpret the computational results and to design useful products, but would we still need to teach the Navier-Stokes equations and the handful of special problems that can be solved analytically? Or would the discipline exist in a form totally unrecognizable to us today? Certainly the millions of word processor users of today do not need to be taught how to write the essential software; only a few are commissioned to carry out that hard task. Would fluid mechanics journals be even necessary? To some with vested interests, the present author included, the disappearance of fluid mechanics as a discipline would be unfortunate; but to others its replacement by an operational black box would be just what is needed. Our own hope is that practical needs as well as human curiosity keep the field on the forefront of engineering education as well as basic and applied research for many decades (or centuries) to come. Our descendants might eventually be able to compute any flow, but they must also be able to do something meaningful with the results.

THE FUTURE

As for the future, your task is not to foresee, but to enable it. (Antoine de Saint-Exupéry, 1900–1944, in *The Wisdom of the Sands*)

As argued in the previous section, the computer of the future may be able to numerically integrate *any* problem in fluid mechanics that one is likely to encounter. There may be little need for the myriad of rational approximations so prevalent in today's fluid mechanics and other engineering curricula. Gradually but surely, engineering students will have to rely more on prepackaged software and less on analysis to solve the numerous challenging problems they may encounter on the campus or in real life. Therefore, if one day computers could solve *everything*, a paradigm shift in teaching fluid mechanics and perhaps even all of engineering science might be inevitable. This is not something the present author wishes, for as Galileo Galilei has said, 'Thinking is one of the greatest joys of humankind'. And that is certainly a trait which would wither with the ever more powerful computers.

So, where do we go from here? I leave you now with the words of the mathematician Charles Lutwidge Dodgson (1832–1898) who created the two memorable stories about 'Alice' merely to amuse the young daughter of an acquaintance, and whose *nom de plume* was Lewis Carroll.

> *'Cheshire Puss,' she began, rather timidly, as she did not at all know whether it would like the name: however, it only grinned a little wider. 'Come, it's pleased so far,' thought Alice, and she went on, 'Would you tell me, please, which way I ought to walk from here?'.*
> *'That depends a good deal on where you want to get to,' said the Cat.*
> *'I don't much care where——' said Alice.*
> *'Then it doesn't matter which way you walk,' said the Cat.*
> *'——so long as I get* somewhere*,' Alice added as an explanation.*
> *'Oh, you're sure to do that,' said the Cat, 'if you only walk long enough.'*
>
> (From Lewis Carroll's Alice's *Adventures in Wonderland*, 1865)

REFERENCES

1. T. I. Williams, *The History of Invention*, Facts on File Publications, New York (1987).
2. R. Dennell, The world's oldest spears, *Nature*, **385**, 27 February (1997) pp. 767–768.
3. H. Thieme, Lower palaeolithic hunting spears from Germany, *Nature*, **385**, (27 February 1997) p. 807.
4. E. MacCurdy, *The Notebooks of Leonardo da Vinci, Vol. I and II*, Reynal & Hitchcock, New York (1938).
5. J. L. Lumley, Some comments on turbulence, *Phys. Fluids A*, **4** (1992) pp. 203–211.
6. M. Gad-el-Hak, Questions in fluid mechanics: Stokes' hypothesis for a Newtonian, isotropic fluid, *J. Fluids Eng.*, **117** (1995) pp. 3–5.
7. R. L. Panton, *Incompressible Flow*, second edition, Wiley Interscience, New York (1996).
8. L. Prandtl, Über flüssigkeitsbewegung bei sehr kleiner reibung, in *Verhandlungen des dritten internationalen Mathematiker-Kongresses*, Heidelberg, Germany (1904) pp. 484–491.
9. L. E. Grinter, Report of the committee on evaluation of engineering education, *J. Eng. Education*, **44** (September 1955) pp. 25–60.
10. J. Weese and L. J. Wolf, The advance toward distinction in engineering technology, *J. Eng. Education*, **83** (January 1994) pp. 41–46.
11. J. K. Finch, *Trends in Engineering Education: The Columbia Experience*, Columbia University Press, New York (1948).
12. G. A. Hawkins, editor, *Recent Advances in the Engineering Sciences: Their Impact on Engineering Education*, McGraw-Hill, New York (1958).
13. J. R. Killian, Jr., *Education for the Age of Science*, US Government Printing Office, Washington, DC (1959).
14. J. R. Kiely, *Assessment of the Goals of Engineering Education in the United States*, Engineering Joint Council, Washington, DC (1966).

15. J. G. Harris, E. M. DeLoatch, W. R. Grogan, I. C. Peden and J. R. Whinnery, Journal of Engineering Education round table: reflections on the Grinter Report, *J. Eng. Education*, **83** (January 1994) pp. 69–94.
16. M. Gad-el-Hak and P. R. Bandyopadhyay, Reynolds number effects in wall-bounded turbulent flows, *Appl. Mech. Rev.*, **47** (1994) pp. 307–365,.
17. P. R. Spalart, Direct simulation of a turbulent boundary layer up to $R_\theta = 1410$, *J. Fluid Mech.*, **187** (1988) pp. 61–98.
18. H. Tennekes and J. L. Lumley, *A First Course in Turbulence*, MIT Press, Cambridge, Massachusetts (1972).
19. G. E. Karniadakis and S. A. Orszag, Nodes, modes and flow codes, *Phys. Today*, **46** (March 1993) pp. 34–42.
20. J. Glanz, Computer scientists rethink their discipline's foundations, *Science*, **269** (8 September 1995) pp. 1363–1364.
21. L. M. Adleman, Molecular computation of solutions to combinatorial problems, *Science*, **266** (11 November 1994) pp. 1021–1024.
22. R. P. Feynman, There's plenty of room at the bottom, In *Miniaturization*, ed. H. D. Gilbert, Reinhold Publishing, New York (1961) pp. 282–296.

Mohamed Gad-el-Hak received his B.Sc. (summa cum laude) in mechanical engineering from Ain Shams University in 1966 and his Ph.D. in fluid mechanics from the Johns Hopkins University in 1973. He has since taught and conducted research at the University of Southern California, University of Virginia, Institut National Polytechnique de Grenoble and Université de Poitiers, and has lectured extensively at seminars in the United States and overseas. Dr. Gad-el-Hak is currently Professor of Aerospace and Mechanical Engineering at the University of Notre Dame. Prior to that, he was a Senior Research Scientist and Program Manager at Flow Research Company in Seattle, Washington. Dr. Gad-el-Hak has published over 270 articles and presented 165 invited lectures in the basic and applied research areas of isotropic turbulence, boundary layer flows, stratified flows, compliant coatings, unsteady aerodynamics, biological flows, non-Newtonian fluids, hard and soft computing including genetic algorithms, and flow control. He is the author of the book *Topics in Flow Control*, and editor of three Springer-Verlag's books *Frontiers in Experimental Fluid Mechanics, Advances in Fluid Mechanics Measurements*, and *Flow Control: Fundamentals and Practices.* Professor Gad-el-Hak is a fellow of the American Society of Mechanical Engineers, a life member of the American Physical Society, an associate fellow of the American Institute of Aeronautics and Astronautics, a member of the American Chemical Society, and a research fellow of the American Biographical Institute. He has recently been inducted as an eminent engineer in Tau Beta Pi, an honorary member in Sigma Gamma Tau and Pi Tau Sigma, and a member-at-large in Sigma Xi. From 1988 to 1991, Dr. Gad-el-Hak served as Associate Editor for AIAA Journal. He is currently serving as Associate Editor for Applied Mechanics Reviews. In 1998, Professor Gad-el-Hak was named the Fourteenth ASME Freeman Scholar.