FLUID MECHANICS IN THE NEXT CENTURY

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We consider here 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, we focus on this subject as a quintessential example for the rest of this perspective.

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

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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. 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 (Gad-el-Hak and Bandyopadhyay, 1994). 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 (Spalart, 1988). 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 (Karniadakis and Orszag, 1993).

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.

If one is to extrapolate the recent advances in silicon-based computer power (something like a factor of 1000 improvement in speed and capacity during the last 20 years) to the next fifty

years or so, using direct numerical simulations to solve the turbulence problem for realistic geometries and field Reynolds numbers would not be feasible. But although the recent advances are spectacular, silicon microchips are rapidly approaching their physical limits. Fortunately this kind of linear thinking may be misleading. Revolutionary computing machines that bear little resemblance to today's chip-based computers may be developed in the future. A recent article in *Science* (Glanz, 1995) 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 only late in 1994 by Adleman, who in turn was inspired by the original Feynman's (1961) 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 will 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. Will fluid mechanics journals be even necessary? To some with vested interests, the present authors 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 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.

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