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EXECUTIVE SUMMARY

The purpose of this book is to illustrate some of the exciting activities currently underway in various areas of fluid mechanics, and to bring forth the broad range of ideas, challenges and applications which permeate the field. The greater part of the book, the individual chapters on various research topics, is written for specialists in fluid mechanics, including Program Monitors, and concentrates on the scientific questions that determine the research directions. The present section, however, is addressed to the general reader, who is more interested in the ways in which this research may influence public policy, or enhance the economy and US competitiveness in international markets, than in the technical details.

We might begin with a few general statements about fluid mechanics, the study of the motion of 'fluids', meaning liquids and gases, and the effects of such motion. Fluid motions are responsible for most of the transport and mixing (of materials or properties) that take place in the environment, in industrial processes, in vehicles, and in living organisms. Hence, they are responsible for most of the energy required to power aircraft, ships and automobiles, to pump oil through pipelines and so forth. In the environment, fluid motion is responsible for most of the transport of pollutants (thermal, particulate and chemical) from place to place, as well as for making life possible by transporting oxygen and carbon dioxide and heat from the places where they are produced to the places where they will be used or rejected. In industrial processes, it is largely responsible for the rates at which many processes proceed, and for the uniformity of the resulting product. Research in fluid mechanics has as its ultimate goal improvement in our ability to predict and control all of these situations, so as to improve our ability to design devices (for example, aircraft gas turbines, automobile engines) and to regulate (for example, industrial emissions). If fluid motions appear to be ubiquitous, one might recall that the ancient Greek philosophers postulated that there were but four elements, air, earth, fire, and water. Of the four, three are fluid states, and the fourth, Earth, is not only saturated with water in the thin continental skins on which we live, but is mostly liquid metal just below the continents.

It is a good idea to bear in mind that modern fluid mechanics, as a discipline, is comparatively old, having had its roots in the first half of the eighteenth century, although some initial work was done by the Greeks and Romans, beginning in the last few centuries BC. However, even after two hundred and fifty years, (or 2500, depending on the viewpoint) many unsolved problems remain, and our ability to predict many flows is limited.

Many reasons for this are possible. Examination of the record, however, suggests that it was not lack of federal funds or of military or commercial interest that was responsible. Indeed, military and commercial interest in the applications of fluid mechanics has nearly always been intense, beginning with that of Hierȯn the Tyrant of Syracuse (who employed Archimedes, but otherwise gave the title a bad name), who had an intense interest in the development of anti-siege weapons, and continuing to the present day. The slow progress has been due, rather, to the extraordinary difficulty of the subject itself. Many reasons for this, inherent to the subject and not of concern to us here, can be adduced, but the fact remains. Progress is difficult, and is likely to remain so, but the payoff can be considerable.

Let us turn now to specific areas. Compressible flows are those in which the changes in pressure from place to place in the flow are so large that the density of the fluid is changed. The flow around a commercial aircraft is compressible, as is the flow inside the engine. These flows present special difficulties: waves propagate in these flows at the speed of sound, and temperatures are high and non-uniform, causing a number of effects that are difficult to predict. Velocities in these flows are close to, or exceed, the speed of sound (supersonic), perhaps by a great deal (hypersonic). Compressible flows are most common in aeronautical applications involving high speed internal and external flows, but there is also a wide range of non-aeronautical applications such as laser technology, vacuum technology, gas-phase reactors, plasma processing of materials, manufacturing processes involving shock waves, and the rapidly developing field of micro-electronic flow sensors and actuators associated with control. The development of a new generation of high-speed military and civilian aircraft, the development of new aircraft engines using high pressure-ratio compressors and turbines and supersonic combustion ramjets for high altitude air-breathing propulsion, and the development of new helicopter concepts all require research on compressible flows. Applications involving high altitude flight or operation in earth orbit or space entail hypersonic flows. Some new materials (such as diamond films) are synthesized from gases so hot that many molecules come unstuck into their component atoms, and the atoms are stripped of many electrons; a fluid in this state is called a plasma. This is a compressible flow too, but a particularly difficult one. In this plasma synthesis, as well as in the development of high-power gas-dynamic lasers, things change so much and so rapidly that the fluid's internal state is always lagging seriously behind its surroundings, creating special problems of prediction. Models of processes occurring in nature such as solar convection, dynamics of cosmic gas clouds, interstellar jets, galactic evolution, and so forth, also involve compressible flows.

All these flows, as well as their lower-speed, relatively incompressible counterparts, can and must be calculated numerically, as part of the design

process. This procedure is called computational fluid dynamics, or computational aerodynamics, with their subsets: direct and large eddy simulation of turbulence. The ability to calculate these various flows has in part replaced experiment, and has become an essential part of the design process, allowing rapid evaluation of changes in design parameters. This substantially shortens design cycle time, which results in corresponding reductions in the cost of new designs.

Most of these flows are turbulent, that is, unsteady and chaotic, not repeating in detail. The turbulent state is opposed to the laminar state, which is smoothly varying, organized, and not chaotic. The difference is significant, since the chaotic motions of the turbulent flow produce 1000 times the drag or heat transfer of the corresponding laminar flow. Turbulence is the last great unsolved problem of classical physics; there is no comprehensive theory of turbulence, although much partial qualitative understanding has been achieved. Even in the absence of complete understanding, we have been forced to develop (necessarily not completely satisfactory) ways of computing turbulent flows for design purposes. The inadequacy of the models used is the factor limiting further development of computational fluid dynamics. The use of dynamical systems theory and approaches such as fractal and multifractal measures (separate chapters of this book are devoted to these topics, where definitions can be found) are attempts to build models of various aspects of turbulent flows that will permit us to make more accurate calculations.

The possible payoffs are many, and we will mention only a few: reduction of drag (relative to lift) of aircraft, or increase of propulsive efficiency, would result in a commercial aircraft fleet with much reduced specific fuel consumption, and lower costs per passenger mile, improving competitiveness, and reducing dependence on foreign oil. More generally, development of aircraft having a broader performance envelope (higher altitude, longer range, higher speed, greater payload) would improve competitiveness. In that, as in many other areas, we currently face stiff competition from Europe and perhaps soon from the Pacific Rim. NASA feels that in order to remain competitive in the next two decades, we will have to improve our lift/drag ratio by a factor of two, and improve propulsive efficiency, all this by flow control of various sorts, reducing drag or increasing mixing, on the wings, fuselage and inside the engine.

Flow control is in its infancy. What is envisioned are, surfaces covered with micro-devices that can sense the state of the flow, and actuators that can influence the flow, introducing disturbances at just the right time to increase or reduce the mixing of high- and low-speed fluid, (making the flow follow the contour of a wing, for example, or increasing the rate at which combustion takes place in an engine) or reducing the drag. One of the most important aspects of this process is the interpretation of the sensor input, and the decisions regarding what disturbance to introduce, when and where (known as the control algorithm). This requires an acute understanding of the structure of the flow; such an understanding is obtained by the use of dynamical systems theory, which allows the construction of relatively simple (though still complicated) models of the flows.

We may mention here noise pollution and abatement or control of fluid mechanically-induced sources. There are two principal applications: the first is aircraft and aircraft engine noise. For example, noise abatement or control is a key to the feasibility of any future supersonic transport. Without special treatment, the engines of a supersonic transport are so noisy that current regulations prohibit its operation from US airports. To meet the regulations, the noise level must be very substantially reduced; to bring this about, we need some way to greatly increase the mixing of the heated jet from the engine with the surrounding air, to cause the jet to expand much faster, and slow down considerably. Exotic nozzle shapes have been tried without much success, and current efforts are considering active control of the flow, in the manner described above. The second application concerns ships and hydromachinery. Here, fluid-mechanical noise production is not only a major source of noise pollution, affecting passengers and workers, but a major source of damage as well. Much of the noise produced in liquids is associated with cavitation, the local vaporization of the liquid in regions of reduced pressure, and the subsequent collapse of the vapor bubble as it is carried into regions of higher pressure; the collapse of the bubble on a surface generates pressures high enough to damage steel. Marine propellors typically fail because of cavitation damage. Detection of submarines and torpedoes is usually by their acoustic signature; in this case, the vessels are usually designed to avoid cavitation, which is extremely noisy; however, the turbulent boundary layers excite structural vibrations which can radiate noise to great distances. The turbulent boundary layer also generates pressure fluctuations (known as self-noise) which confuse the vessel's own listening apparatus. A great deal of research goes on in an attempt to reduce these effects. We can also mention here naturally occurring sound in oceans and lakes, which is of interest partly because it obscures sonar detection, and partly because the sound produced by falling rain, for example, can provide a useful route to remote monitoring of weather.

Many natural and technological flows are vortex-dominated, and such flows are a subject of special study. A vortex is a tube of fluid which is strongly rotating; a tornado is a dramatic example. Other high-energy and large-scale vortices are hurricanes and the polar vortex (the ozone hole). In supporting the weight of an aircraft, the wing generates a vortex, which trails behind the aircraft from the wingtips. The intensity of these vortices is proportional to the weight of the aircraft. These vortices close behind very large

aircraft are strong enough to flip a light plane over, and are the reason for the required separation between take-offs at airports. Additional vortices are shed from maneuvering aircraft. To understand this we have to consider how fluid moves over a surface. Since fluid adheres to any surface with which it is in contact, in order to move past the surface the fluid must roll forward. This rolling is called vorticity. A vortex is concentrated vorticity. When the aircraft maneuvers, the flow sometimes leaves the surface, and it carries with it the vorticity that was generated next to the surface, which is rolled up by the flow into a vortex. The generation, interaction and dispersal or mixing of vorticity plays a profound role in a wide class of applied, geophysical and fundamental fluid flows. A better ability to predict and control flows will arise from a deep understanding of the processes leading to the formation (cyclogenesis), evolution, and persistence of coherent vortex structures in flows in which distributed vorticity is present. Such an understanding would make possible data assimilation in prediction codes and signal feedback for control of aircraft, ship and chemical process performance. Imagine forecasting meteorological or oceanographic events in which local environmental measurements and remote (e.g. satellite) observations are fed back into local space-time regions of the computer simulation code. This has the potential for reducing errors and improving the reliability of predictions. Similarly for man-made flows, we may have sensors located within the flow which provide feedback signals to force the flow in a stable manner.

As we have suggested, in most devices, and especially land, sea, and air vehicles, drag and fluid resistance take place in a very thin layer of fluid near the moving solid object. This is known as the boundary layer. In addition to being the source of drag, the processes in this thin region are subject to dramatic alterations that cause phenomena like the sudden loss of lift — or stall — in airplanes, and a concurrent sudden increase in drag. This is usually due to a massive change in the airflow near the wings in which the flow no longer smoothly follows the contour of the object but is violently torn away from it in a process called boundary layer separation, a process we have already mentioned. Much progress has been made in understanding this state of affairs and how to prevent it. It is an issue of major concern not only for economic reasons, but also for reasons of aircraft safety near airports and in flight, especially while manuevering. Instability of the boundary layer is the proximate cause for the transition of flow from laminar to turbulent, with consequent alteration of behavior. Similar issues of separation and instability of boundary layers arise in a vast variety of other flows, including internal flows in internal combustion, jet, and rocket engines, in medical equipment such as heart-lung machines, in manufacturing processes involving materials in a liquid or molten state, and so on. In most cases, these phenomena have major consequences on the performance and safety of these devices, and the prediction of motions in the boundary layer is a critical issue to the success of the associated technology.

The bulk of international commerce, both in raw materials and manufactured goods, is transported by sea. Seagoing vessels of all kinds face harsh and dangerous conditions, especially because of the power of ocean waves. Improvements in design of such vessels, and also important fixed ocean structures like offshore oil platforms, require understanding and predicting the interaction between the structure and waves. Water waves also are a major source of drag on ships, and this is a major factor limiting the speed and setting the cost of ocean transportation. Understanding of some aspects of this wave resistance has led to important design improvements, such as the bulbous bow now universally used to reduce wave drag on cargo vessels. Much more needs to be done to produce better designs for ships and fixed station platforms, to understand the effects of waves when ships are maneuvering both in open water and in harbor areas, and to deal with extreme wave states that threaten the survival of the ships, platforms, and, of course, their passengers and crews.

Coastal areas are densely populated, and of economic importance because they provide access to sealanes and shipping, to fisheries and the other resources of the oceans, and recreation. Coastlines are moveable, slowly, by waves, currents and tides. The interaction of waves with coastal installations and harbors, and the movement of sediment in the turbulent, wave-buffeted surf zone that causes the coastline to change its shape, are among the concerns of coastal engineers. Waves and their effects are difficult to predict, especially when the waves are high, and the consequent effects most impressive. Important progress has been made in understanding the origin, growth, and propagation paths of waves in the deep ocean but many critical issues in this process remain unknown. This is even more so as waves enter the shallower water near the coasts, where they are strongly affected, and help to drive strong currents, and where they are subject to the turning effects of decreasing depth. While some effects of wave and current action are relatively slow, like the reshaping of the shoreline, others are sudden and catastrophic, like tidal waves (tsunamis). The destruction of property and life following tsunami impact often has been devastating. Now, understanding of how tidal waves are born and grow has reached a level that permits tracking of these waves and early warning of populations in their paths. Prediction of damage requires understanding of the waves at their largest amplitudes, and this remains a challenging open problem.

Accurate prediction of the weather is an everyday concern, with enormous ramifications for most human activity and economic impacts too massive to tally. This is the realm of meteorology, which has always posed some of the most fascinating and difficult of fluid mechanical problems. The oceans play

a key role in this process; "el Niño" has become a household name. The fluid mechanics and concomitant heat transport in the ocean are the realm of the physical oceanographer, and so it is the coupled ocean-atmosphere fluid system that controls the weather, and its long term trend, the climate. The fluid mechanics of these processes share many common features, and these fields, and related fluid processes in the Earth sciences, are now often collectively termed "geophysical fluid dynamics." The related areas involve fluid mechanics in stars and the giant gaseous planets, in other astrophysical fluid dynamics questions, and in fluid mechanics of the Earth's interior, which shape the distribution and drift motion of the continents, volcanic activity, and the generation of the magnetic field of our planet by the dynamo motions of its molten iron interior. Processes such as the breaking of wind waves in the ocean and in lakes cause bubbles of gas from the atmosphere to be mixed into the surface layers, where the gas enters into solution in the water. These processes are vital; for example, the oxygen levels and therefore the biological productivity of the seas and lakes are determined by this exchange of gas between the atmosphere and the surface waters. Similarly, the levels of greenhouse gases in the atmosphere are strongly influenced by the transfer of these gases to the ocean, which has an enormous capacity to absorb them; in this way, gas transfer plays a significant role in the important debate on global warming.

Understanding of fluid processes is key to a wide spectrum of environmental questions. Here one is concerned with siting of power plants and other installations that are sources of toxic chemicals or require large flows of water for cooling and other purposes, the river or lake source of which may be degraded in the bargain. Other concerns include protection against and prediction of spills of liquid pollutants (such as the Exxon Valdez catastrophe) or heavier-than-air gases (such as the Bhopal catastrophe). Ecologically sensitive coastal areas and river estuaries are often heavily used, and the prediction of flows in these systems is critical to planners concerned with avoiding their contamination. Groundwater and its motion and quality are major public health matters. The surface impacts of volcanism raise extremely difficult issues that need to be understood. These problems, and many other problems of environmental fluid mechanics are novel, complex, often poorly understood and inadequately studied. They are central to planning a complex society, and to anticipating the consequences of, and preparing for, the natural and manmade disasters that continually visit us.

Combustion of fossil fuels powers most aircraft, ship, and automobile engines, and produces much of our electrical power and home and industrial heating. Improvements of these combustion processes reduce fuel consumption and pollutant generation. Some notable examples of fluid mechanical research have contributed to this end, with massive economic benefit. For example, it was found that imparting swirl to the air in jet engine combustors improved fuel economy substantially. This innovation has found its way into the design of new, high efficiency home oil burners, extending the economic benefit considerably. Many other examples of innovative engine design based on an understanding of the fluid mechanics underlying the engine can be cited. Combustion research involves experimental measurements in an environment that tries to melt the instruments, and requires expertise in chemically reacting, heat releasing, variable density particle-laden flows; the scientific and engineering challenges are formidable.

It can be a happy, or a disastrous, circumstance when small changes produce large effects. This is the case with fluid motions, which tend to be very sensitive and responsive, sometimes even to minute alterations of flow rates, boundary shapes, boundary temperatures; in fact, to virtually all conditions of the motion. This sensitivity is due to the tendency of fluid motion states to be unstable. From a practical standpoint, it affords an opportunity to fine-tune designs and industrial processes to achieve a desired result with small alterations. Thus, for example, processes which produce sheets of material (metals, plastics, or other materials) typically pull the sheets rapidly from a molten state, and the surface quality of the sheets and films so produced, or the rates at which they can be produced, is affected by instabilities in the liquid sheet before solidification occurs. Similarly, crystal manufacture, such as silicon used in computers and most modern electronic equipment, is achieved through crystallization from a crucible of moving liquid, and the fluid instabilities affect production rates and product quality. The general problem of transition from laminar to turbulent motion, with all of the ramifications associated with transition, is a long-standing problem of fluid instability. The instability of a fluid motion can have positive or negative effects, depending on whether the result of the instability produces or destroys a desired property of the flow. Thus, for example, one may wish to avoid or delay transition to turbulence to reduce vehicle drag, or one may wish to promote it to enhance mixing in combustion processes in engines. While the economic benefits of understanding and controlling fluid instabilities are well known in the industries mentioned, an awareness of their potential for improving production quality and rates is virtually nonexistent in others. The introduction of this area of fluid mechanical science to many industrial sectors where it is not known could have valuable consequences. In the following paragraph, which broaches another topic, several examples relevant to this paragraph will nevertheless be found.

Magnetohydrodynamics (MHD), which deals with the combined effects of fluid mechanical and electromagnetic forces, is an exciting but, at the moment, only moderately active area of research and development that has not been exploited to nearly its full potential. This relatively low level of present

activity is regrettable considering that a large variety of flow phenomena can be modified in a dramatic way through the controlled application of electromagnetic forces. Well-known examples include the damping, modification and even suppression of turbulence in a variety of flows; also, the use of electromagnetic stirrers in a bath of molten metal, as in steel casting, which provides the only non-intrusive method (that is, not requiring the introduction to the bath of a device, which would likely melt) currently available for keeping the contents of the bath well-mixed. Currently, the most promising area of MHD application appears to be in the materials processing industry where, for instance, a magnetic field can be used to modify the flow patterns which occur naturally in the production of single crystals of semiconductors, thereby insuring that the composition of the product (that contains trace amounts of other elements to make it electrically active) is uniform.

The naturally occurring flow patterns referred to above arise because the flowing material is from place to place lighter (tending to rise) or heavier (tending to sink), because the temperature and composition are not uniform. A flow produced by these effects is called buoyant convection. Buoyant convection occurs in many environmental flows. Examples include: convection in room fires, in energy storage systems, and in atmospheric and oceanic systems. In view of their frequent occurrence, these flows deserve special attention. The forces which drive convective flows can also be used as controls to optimize the operation of various processes involving, for example, crystal growth or chemical vapor deposition, and, depending on the application, either to enhance or to suppress flow instabilities within the system.

The production of high performance structural materials and coatings (such as the carbon fiber reinforced plastic used in golf clubs, tennis rackets and bicycle frames) also involves complicated phenomena where the discrete molecular nature of the gas cannot be ignored, especially in the manufacture of microelectromechanical devices. These phenomena are complicated because conditions in the gas are so extreme, and changes so rapid, that the internal state of the gas never catches up to its surroundings. As a result of the importance of these phenomena in such production, there has been a resurgence of interest in the field of rarefied gas dynamics which was associated traditionally with the flight of aircraft and missiles at high altitudes. In fact, the design of tiny machines having dimensions of the order of microns requires the implementation and modification of rarefied gas dynamical computational techniques which were originally developed for a completely different application.

Many of the computational techniques referred to above aim to construct solutions to more or less exact equations describing the flow of gases under rarefied conditions. In recent years, however, important advances have been made using the method of molecular dynamics (MD), which applies to liquids as well as to gases. Here the behavior of a fluid under particular circumstances is determined by computing simultaneously the motion of all the individual interacting molecules. This, of course, is possible only on the largest computers. Important insights have thereby been obtained into situations in which flow dimensions are of the order of inter-molecular dimensions, for example the rupture of a thin liquid film, as occurs when a gas bubble approaches a liquid-vapor interface, or the dynamics of the moving edge of a liquid drop spreading across a solid substrate. Such calculations provide extremely useful information concerning the point at which we must abandon the usual image of a fluid as a seamless continuum, and must consider it instead as a collection of molecules. We have noted before that fluid usually sticks to any solid surface. This is an excellent approximation so long as the fluid flows over the surface like sand over a beach-ball—that is, so long as the inter-molecular dimensions are small relative to the dimensions of the surface. As the two become comparable, however, like sand flowing past a pin-head, the simple condition at the surface no longer works, and more sophisticated conditions must be applied; MD can help to determine what those are. Similarly, MD offers an opportunity for studying flows that involve two fluids that mix a little on a molecular level, so that they are not separated where they meet by a sharp interface, but are diffusing into each other while they are flowing. Situations like this occur in many industrial chemical processes and in the kitchen; imagine mixing molasses and cream. MD also allows us to investigate phenomena involving an interface between two fluids, one that is strongly influenced by surface impurities, another situation that occurs frequently in industrial processes. All of these flows are much too complicated to compute from equations, and this type of molecule-by-molecule simulation is the only way to find out what is happening.

Those flows involving two (or more) fluids that do not mix, or may mix a little, are called two-phase (or multi-phase) flows. Another two-phase material which plays a key role in a variety of natural and industrial processes is a suspension of solid particles in a liquid. Examples include coal slurries, biological suspensions, high-energy composite fuels for space propulsion and colloidal suspensions for making films as well as coatings for electronic applications, in addition to fluids containing suspended particles that can be influenced by imposed electric fields, so that the nature of the flow can be changed by applying an external electric field. In particulate flows one wishes to predict the bulk behavior of the suspensions from a knowledge of the fine structure or, conversely, to construct suspensions having prescribed flow behavior (called rheology). This requires that the many factors which contribute to the rheology of such systems, i.e. the influence of one particle on a neighbor through the motion of the fluid around it, the forces due to bombardment of the particles by the surrounding molecules, the surface

forces on the particles, etc., be properly accounted for. Furthermore, particles tend to wander, from regions of large particle concentration to regions of low, but also from regions in which the layers of fluid are moving rapidly relative to one another to regions in which this is not true. This has been shown to play a key role in these flows, since the flow causes the particle concentration to change, and this changes the properties of the fluid, causing marked changes in the flow. This kind of interaction makes the flow exceedingly difficult to compute. Newly developed experimental techniques as well as more sophisticated numerical simulations have provided new insight on how particles in suspension rearrange themselves under flow conditions to produce the observed phenomena.

All of the discussion above, with the exception of multi-phase flows, concerns problems involving gases or liquids that contain small molecules, like water, where the bulk properties of the fluid (like density and viscosity) are independent of the flow conditions. Another large and important branch of fluid mechanics is concerned with liquids that are often referred to as "complex," in recognition of the fact that these materials exhibit much more complicated behavior. Examples of complex fluids can be found in any kitchen, bathroom, playroom or garage, and include egg white, cake batter, silly putty, proprietary oil additives, blood, mucous and many, many others. Most of these fluids either consist entirely of large molecules, or have large molecules floating in them, as well as particles or droplets. Most plastics in their liquid state fall in this category. This branch of fluid mechanics is often called non-Newtonian to distinguish it from the classical work on small-molecule (or Newtonian) fluids. Although this class of fluids is common in nature, in a variety of technologies, and as the liquid-state precursors of many important types of advanced materials, the status of our understanding of their behavior and our ability to predict their motions, is at a very early stage of development. In general terms, the difference between complex fluids, and the single component, Newtonian fluids, is that in the latter case, the mathematical formulation is known but the macroscopic physical processes are complex and often not well understood, especially for turbulent flow conditions; for complex fluid, even the appropriate governing equations and conditions at the boundaries (do these fluid stick to solids or is it more complicated?) are still not well understood. To compound the difficulty, the model equations that have been proposed are extremely difficult to solve; and standard methods of computational fluid dynamics generally do not work for this class of problems.

This paucity of understanding extracts a substantial economic penalty. The production and processing steps leading to a finished product employing advanced materials are most often carried out via deformation (stretching, squeezing) and flow in the liquid state. Although largely empirical procedures have historically been used in the design of new processes, future economic competition, as well as requirements for improved product quality, reproducibility and precision, all demand the development of a deductive basis for process design and control. For example, the inability to predict the behavior of polymer liquids in an extrusion molding process precludes prediction of the final shape of the solidified product — thus the design of each mold must be done by a trial and error process costing tens to hundreds of thousands of dollars, and much time, for each new part, and limiting our ability to produce precision parts. Since thousands of new injection molding processes are developed each year, the cost of our ignorance amounts to hundreds of millions of dollars for this one technological application.

Qualitative phenomena observed in non-Newtonian flow experiments are often dramatically different from expectations based on similar observations for small-molecule liquids (e.g., a finger dipped in many of these fluids will spin a thread when withdrawn, and the forces involved are quite different from those produced when the fluid is rubbed between the palms).

Development of new experimental techniques are needed to provide much more comprehensive characterization of the rheological behavior of complex fluids, and for characterizing the microstructural state of a non-Newtonian liquid undergoing a flow, since this determines the properties of any product which results from the flow process.

If we succeed in answering these fundamental questions, the potential pay-offs in the area of advanced materials processing are many-fold. (1) They will form a basis for computer-aided design of processing systems for manufactured parts eliminating time-consuming and costly trial-and-error development. (2) Major increases in production rates in manufacture of fibers may be possible. Instabilities of the bulk flow (leading to unsteadiness and fiber non-uniformity), and apparent breakdowns in boundary conditions, etc., currently constitute the major limitations of both production rates and product quality, but no one knows how to minimize or eliminate these instabilities, or even whether it is possible. (3) One critical feature of complex fluids is that their microstructural state, and thus their macroscopic properties, can be altered when they undergo a flow. Thus, there is the possibility of developing products from a complex fluid with properties that can be predetermined or optimized by modification of the processing flow conditions, e.g., polymers may yield very light weight and moldable electrical conductors, but only if we can understand how to process them into highly oriented and stretched configurations. Although the potential economic pay-off is enormous in terms of light weight materials of high strength, high conductivity, etc., the technology is today largely empirical and extremely limited in scope. (4) Finally, a key route to new materials with specified properties, which is generally much less expensive than chemical synthesis, is by

mechanical blending of two (or more) fluid or fluid and solid components. Given a set of constituent materials, and their properties, there is clearly a major economic incentive to develop the ability to predict the outcome of a blending process, as well as to predict how to modify the process to achieve a desired morphology. Beyond the applications of complex fluids as precursors of new materials, or materials-based products, there are many additional technological applications for suspensions, emulsions and multiphase (gas-liquid) fluid flows. Among these one may mention multiphase flows in oil reservoirs, or in groundwater percolation processes; cavitation phenomena which lead to noise production, and to many well-known and expensive structural failures ranging from propellors on ships to dam spillways, due to cavitation damage, and in thin, viscous films to lubrication breakdown in hydromachinery; the use of multiphase fluids in heat transfer processes that are intimately connected to the cooling processes in nuclear power plants, and pipeline transport processes involving slurries. One common feature in some of these applications is still the overall macroscopic flow properties, but in other applications it is important to understand the details of motion at the microscale. For example, in an oil reservoir, it is important to be able to predict overall pumping costs of any secondary or tertiary recovery process, but control of the morphology of the boundaries separating oil and water is also critical to the production of oil rather than water. As another example, the details of the interfacial regions in multiphase boiling heat transfer determine success, or failure via the development of local hot spots due to "dryout" of the solid heated boundary.

Finally, the intersection of fluid mechanics and biology in the area of biofluid mechanics offers the opportunity for many important applications, both in better understanding of normal biological processes (for example, cell, tissue, cartilage or even bone growth in response to fluid stresses, transport processes, etc.), but also in the development of therapeutic medical procedures. Among a long list of biofluids research with clear medical implications, we may cite: (a) fluid mechanics' role in the growth of atherosclerotic tissues in the circulatory system, and an understanding of mechanisms for localization of atherosclerotic lesions, based upon the response of the biological system at the cellular level to fluid stresses; (b) heart and heart valve function and the design and performance evaluation of artificial replacements (prosthetic cardiac valves); (c) cardiovascular flow measurement methods: although much current development is directed toward research applications, there is clearly a major medical pay-off in improved diagnosis of vascular disease and in the design and evaluation of therapeutic interventions; (d) pulmonary flows — interesting fluid-structure interaction problems in understanding physiological phenomena such as "wheezing" — possibly leading to better treatment methods for asthmatic conditions, etc. Also the role of fluid films, surfactants and airflow in such pathologies as "Sudden Infant Death Syndrome" or "Crib Death." It is clear that this is a field at early stages of impact. The problems are (often) more microscopic, at the level of cells or micropores, than is characteristic of other areas of fluid research. The fluids, apart from water and air, are often more complex.

The editors hope that the general summary given above has at least suggested the vitality of the field of fluid mechanics and that the reader with some scientific background will be motivated to gain further insight by studying the chapters which follow.