RESEARCH IN FLUID DYNAMICS: Meeting National Needs

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The science of fluid dynamics describes the motion of liquids and gases and their interaction with solid bodies. It is a broad, interdisciplinary field that touches almost every aspect of our daily lives, and it is central to much of science and engineering. ***Fluid dynamics impacts defense, homeland security, transportation, manufacturing, medicine, biology, energy and the environment.*** Predicting the flow of blood in the human body, the behavior of microfluidic devices, the aerodynamic performance of airplanes, cars, and ships, the cooling of electronic components, or the hazards of weather and climate, all require a detailed understanding of fluid dynamics, and therefore substantial research.

Fluid dynamics is one of the most challenging and exciting fields of scientific activity simply because of the complexity of the subject and the breadth of the applications. The quest for deeper understanding has inspired numerous advances in applied mathematics, computational physics, and experimental techniques. A central problem is that the governing equations (the Navier-Stokes equations) have no general analytical solution, and computational solutions are challenging. Fluid dynamics is exciting and fruitful today in part because newly available diagnostic methods for experiments and parallel computers for simulations and analysis allow researchers to probe the full complexity of fluid dynamics in all its rich detail.

The outcomes from this future research will have enormous impact. For instance, they will lead to improved predictions of hurricane landfall and strength by understanding the mechanisms that govern their formation, growth, and interaction with the global weather system. They will speed the development of fusion power by helping to understand and control the instabilities that currently limit the energy densities that are achieved. They will lead to more efficient vehicles, by reducing the friction between the vehicle surface and the surrounding air. They will lead to a new generation of micro-scale devices that will include combustors to replace batteries, advanced flow control devices to cool electronic systems, and labs-on-a-chip to manipulate and interrogate DNA. Already, the number of channels in micro-fluidic devices is growing at a rate faster than the exponential growth in electronic data storage density.

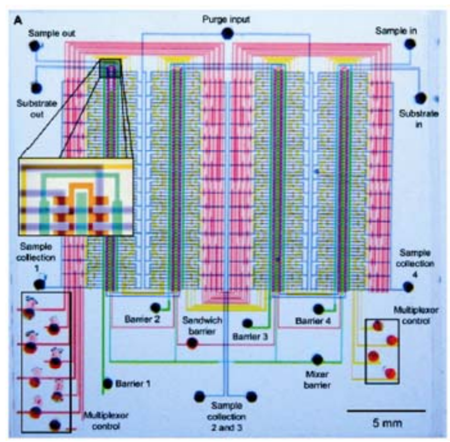

Figure 1: Microfluidic device containing 2056 integrated channels (Thorsen et al., Science, 2002). Such devices are revolutionizing biomedical science.

We illustrate the importance of fluid dynamics research by considering five particular areas of study: nano- and micro-scale fluid dynamics, environmental flows, turbulence, flow control, and biological and biomedical fluid dynamics. Each of these topics illustrates how improved scientific knowledge of fluid dynamics can significantly enhance the Nation's future.

Nano and Micro-Scale Fluid Dynamics

Many of the recent advances in science and technology are aimed at making devices small. The electronics industry provides the best example of the gains in productivity, efficiency, scale and even new culture-changing products that result from designing and controlling small devices. Similar advances and applications in fluid dynamics are occurring at a rapid pace; the resulting technology is called *microfluidics* when the typical sizes of the fluid-carrying channels are smaller than 1 millimeter[1] and *nanofluidics* when the typical sizes are smaller than 1 micron (for reference, the thickness of a human hair is about 100 microns). The ability to control fluids in channels of such small dimensions is leading to advances in basic research and technological innovations in biology, chemistry, engineering, and physics. The advances are most significant in research focusing on new materials, new fabrication methods, cooling of electronic devices, multiphase flows in labs-on-a-chip, and efforts to understand basic processes in individual biological cells.

Micro- and nanofluidic methods will lead to novel technological applications and scientific insights because smaller systems allow flow and reactions to be analyzed more rapidly, facilitate manipulation of medically relevant blood cells, and can be mass produced. Microfluidic systems minimize the use of expensive and hard-to-obtain samples. Finally, they allow "combinatoric" studies in which many possibilities are investigated simultaneously, as is often required for chemical analysis, synthesis, and drug development.

Understanding fluid dynamics of small devices will be crucial to advances in science and engineering. For example, scientists have learned how to integrate thousands of small channels with hundreds of individually controlled valves into a single "lab-on-a-chip," thus pointing the way to the kind of large-scale integration that transformed electrical circuit design and led to the computer revolution. A photograph of such an integrated microfluidic device is shown in Figure 1 (note the scale bar). Future devices will integrate many distinct microfluidic components.

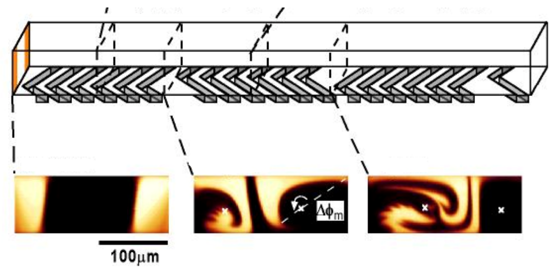

Figure 2: Pressure-driven flow in a microchannel with small amplitude "herring-bone" grooves on one side leads to a swirling motion and rapid mixing, a precondition for effective use of this technology (Stroock et al., Science, 2002).

In small devices where fluids are manipulated and reacted, it is necessary to mix fluids efficiently, which is made difficult by the natural tendency of the fluid to maintain laminar flow. Achieving good mixing is essential for next generation genetic studies such as those involving reactions that amplify a small quantity of DNA. Figure 2 shows one method of achieving mixing in a small device, by adding ridges to a channel to stir the fluid. However, other methods are still needed.

Recent work on microfluidics seeks to design sensors for individual molecules and to manipulate single molecules of DNA. In addition, it is possible to probe biological, chemical and mechanical processes at the scale of individual cells (Figure 3); such studies can yield detailed knowledge of shape changes during flow and of the mechanical properties of the cell membrane, or interactions of the membrane with electrically charged or protein-coated walls. This knowledge can be used to control or eliminate some diseases.

Many fundamental research questions arise at these smaller scales such as how to include electrostatic forces, and how to understand flow in and around nanosize building blocks. Future developments in micro- and nanofluidic science and engineering will have a wide impact on the U.S. and world-wide economies and are important to the competitive advantage of U.S. research and industry. They will

[1] There are 1000 millimeters in one meter, one thousand microns in one millimeter, and so one million microns in one meter.

benefit nearly every industrial, consumer and research sector.

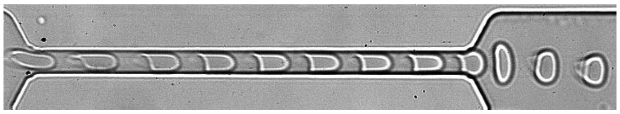

Figure 3: Time-lapse photo showing a red blood cell squeezing through a microchannel of comparable size (about 5 microns), which is typical of flow in the microcirculation (Stone et al., Harvard University).

Environmental Flows

The study of fluid mechanics allows many environmental flows to be understood, modeled, and predicted, with important consequences for engineering, planning, and policy-making. These flows include atmospheric, oceanic, riverine, lake, and subsurface flows. An intriguing aspect of natural flows is their wide range of scales – some ten orders of magnitude in space and time. At the large (global) end of the scale are huge weather systems and the oceanic conveyor belt, both tens of thousands of kilometers (km) in size. Lower in the hierarchy are thunderstorms and ocean gyres of 1000-km scale; hurricanes and atmospheric (e.g., polar) vortices about 100 km across; and ocean eddies, atmospheric waves caused by mountains, and flows in urban basins about 10 km in size. Severe storms bring much death and destruction, which could be mitigated with better forecasting and environmental sensing.

These motions are influenced by the rotation of the Earth and density stratification, which lead to a fascinating set of geophysical phenomena. Smaller scale motions are especially evident; for example, pollution-laden air streaming through the street canyons of cities and seeping into buildings; ocean waves; turbulent wind gusts; and airflow into lungs that impacts human health. The millimeter-sized whirling motions that dissipate energy are the smallest motions, and they help suspend micro- and nano-scale particles (e.g., aerosols, pollutants, and biota). Interactions involving many scales maintain the Earth's environmental parameters in the narrow range conducive to life. Natural flows also distribute nutrients to species, habitats, and ecosystems, thus maintaining biodiversity.

The societal contributions of environmental fluid mechanics have been pervasive. Only 15 years ago, great leaps in the accuracy of hurricane track forecasts were made, with a 50% reduction in prediction error. Similarly, fluid dynamics provides the basis for computer forecasting models, some of which have made major strides in recent years: improved predictions related to El Niño, the ozone hole, and tsunami propagation; pollution transport; hydrologic forecasting; jet stream tracking for air traffic routing; and airborne laser defense. The looming specter of bio-chemical terrorism has heightened the need for emergency evacuation planning, which relies heavily on transport models for toxic substances based on fluid-dynamics principles.

Perhaps no other issue is more important in environmental forecasting than the so-called sub-grid scale parameterizations -- mathematical representations of processes occurring within the computational grid boxes of predictive models. These processes (turbulence, mixing, eddies, waves, convection, and diffusion) are understood qualitatively, but not quantitatively or collectively, due to the nonlinearity of natural phenomena. Motions at different scales, as well as interactions between scales, continue to be a fertile ground for cutting-edge research. Opportunities are plentiful for studying real life-size flow configurations.

Many traditional problems in hydraulics have evolved into grand challenges. These include sustainable water supply and drainage; control of sediment transport; sediment-water-pollution exchange; subsurface seepage, storage, and recharge (aquifer dynamics); river restoration; flow over vegetation, wetlands and plant canopies; bank stability (e.g., levees) and exchanges between rivers and floodplains; and fish ladders and habitats. All of these have substantial economic implications.

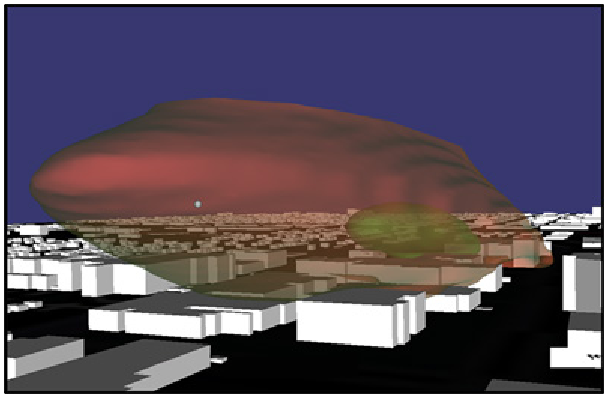

Figure 4: Nested model simulation of a toxic vapor plume in Oklahoma City. Large-scale, medium-scale and city-scale (computational fluid dynamics) models are shown together. (Displayed in Arizona State University's Decision Theater – a learning and decision space where complex social, economic and natural processes are visualized.)

The difficulty of resolving a wide range of length scales has led to "nested modeling," where scale-specific models are integrated (Figure 4). Selecting initial conditions for nested models remains problematic, however, as is the interfacing of critical components of the climate system (e.g. atmosphere, oceans, and ice). The new area of sensor-model fusion, where modeling, data gathering, processing, and incorporation of data into models occur simultaneously, offers great potential for improved environmental predictions at lower cost. Fundamental advances in sensor placement, data acquisition, high-performance computing, and automated recognition of physical processes are in progress.

Better forecasting requires improved data, often obtained by remote sensing, that can be used to test the flow models. Major social benefits can be anticipated from research-based knowledge of environmental flows.

Turbulent Flows

Most matter in the universe is fluid, predominantly in a state of turbulent motion. Billowing smoke stacks, cumulus clouds and waterfalls are visible everyday examples of turbulent flows. Though less visible, turbulent flows are ubiquitous in our transportation systems, process industries and natural environment (the atmosphere, oceans, rivers and even stars). In contrast to laminar flows (exemplified by honey pouring from a jar) turbulent flows are chaotic, three-dimensional, and unsteady over a large range of scales. A bumpy aircraft flight may be caused by eddies of atmospheric turbulence which are larger than the aircraft, whereas the drag on the wing and fuselage are caused by turbulent eddies smaller than a millimeter.

Turbulent flows are capable of efficient transport and are characterized by high mixing rates. In the mixing of fuel and air in all types of engines (e.g., in cars, aircraft and ships), turbulent flow is essential, and devising means of enhancing the turbulent mixing rates would yield significant benefits in fuel economy and reduced pollutant emissions. On the other hand, the drag on these vehicles is largely due to the effectiveness of turbulent flows in transporting momentum, which is unwanted in this context. Similarly, the cost of pumping oil and gas through pipelines is directly proportional to the frictional losses due to turbulence. In these examples, devising ways to reduce turbulent friction and drag has very significant economic pay-off. In yet other cases, the goal is to suppress deleterious instabilities and the ensuing turbulence. Inertial-confinement fusion is an example whose success relies on the control of the Rayleigh-Taylor instability. In hypersonic flight, delaying the transition to turbulence can make the difference between successful reentry from space and the loss of a mission.

From a scientific viewpoint, turbulence is a notoriously difficult subject. An impressive list of Nobel Laureates confronted the turbulence problem but made more valuable contributions elsewhere. The fundamental difficulties stem from the three-dimensional unsteady chaotic nature of turbulent flows, and from the non-linear interactions that take place between motions of vastly different sizes.

The intrinsic difficulties of turbulence are now yielding to research using modern technologies–primarily laser diagnostics, in the laboratory, and simulations using high-performance computing. Techniques such as digital particle image velocimetry (DPIV) can be used to determine the three-dimensional fluctuating velocity fields. Such experimental investigations provide invaluable information on the interacting processes involved in turbulent flows.

In all fields of engineering, computer modeling is playing an increasingly important role in addressing questions such as: If we build a device to a particular design, how will it perform? Or, how should we design a device to produce the best performance at the least cost? Computer modeling can be used to answer these questions only to the extent that the underlying physics is sufficiently well understood for the model to be reliable, accurate and computationally tractable. An important advance in turbulence research is the development of the technique of large-eddy simulation (LES). In this approach, illustrated in Figures 5 and 6, the large-scale motions are explicitly represented while the influence of the unrepresented small scales is modeled approximately. In the U.S., heavy trucks, such as the one shown in Figure 5, consume about 30 billion gallons of diesel fuel annually. Research on the complicated flow patterns behind trucks can guide improved designs, leading to reduced drag and improved fuel economy.

Figure 5: Computer simulation of the turbulent wake behind a truck (Fluent, Inc.).

The advent of LES has placed a research emphasis on important small-scale processes that cannot be represented directly in LES, but instead have to be modeled. Such an important small-scale process is the interaction between the turbulent flow and small suspended particles, droplets or bubbles. Examples are the formation of rain droplets in warm clouds; the dispersion of dust, pollen, spores and biological agents; and fuel sprays in gasoline, diesel and aircraft gas-turbine engines. Figure 6 illustrates a large-eddy simulation of the combustor of a Pratt & Whitney aircraft engine in which the fuel enters as a spray (shown in green). Further research on these processes is essential in order for LES to be a reliable and accurate design tool for such applications, and hence to realize the potential benefits in fuel economy and reduced pollution.

An unwanted by-product of turbulent flow can be acoustic noise. Aircraft noise is responsible for much of the community reluctance to increase airport capacity and currently restricts operations at many airports. As a consequence, turbulence-generated noise is a growing concern in the aviation industry for both fixed-wing aircraft and rotorcraft. The key challenge to the aeroacoustic engineering community is the development of noise abatement technologies that do not sacrifice system performance. Unsteady aerodynamics and turbulence generated by rotorcraft blades and aircraft engine turbomachinery and jet exhaust form the key noise sources. Understanding and predicting the impact of abatement technologies is a critical capability required to bring quieter products to market. The detailed structure of the turbulent flow is a critical element of the noise generation process, and must, therefore, be modeled accurately.

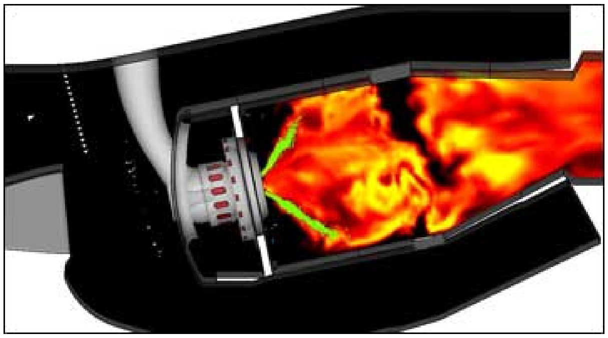

Figure 6: Computer simulation of a gas-turbine combustor, showing the fuel spray (green) (Stanford University).

In summary, turbulent flows are ubiquitous in major sectors of the economy, in transportation and the chemical process industry, and in the environment. They present a formidable research challenge in the physical sciences, but this research is becoming increasingly fruitful due to modern techniques such as laser diagnostics and high performance computing. There is great potential pay-off for research in this area, with likely benefits including improved energy security and reduced chemical and noise pollution.

Flow Control

"Flow control" denotes a collection of methods to manipulate a fluid flow into a state with desired properties. Successful flow control can lead to enhancement of mixing, augmentation of heat transfer, reduction of noise and pollution, increased lift and maneuverability, and reduction of drag. The ability to control flows has great consequences in many science and engineering applications, and plays a key role in maintaining U.S. leadership in technology.

Dimples on a golf ball present an intriguing example as to what flow control can do to achieve a desired goal. The airflow over a dimpled golf ball separates from the surface much farther back than that on a smooth ball, thus dramatically reducing the drag. As a result, a skilled golfer can drive a dimpled golf ball 300 yards, nearly three times the distance of a smooth one. Analogous advances affecting vehicle performance are anticipated.

Worldwide ocean shipping consumes about 2.1 billion barrels of oil per year. A control scheme that reduces skin-friction drag by even 10% could save $10 billion per year (at $50 per barrel) for shipping industries. The consequent reduction of pollutants in ship emissions would be equally impressive. A similar projection can be made for airline industries, which consume about 1.5 billion barrels of jet fuel per year. Reduced drag can also provide faster speed where that is important.

Agility and maneuverability for aircraft and weapons can be significantly improved through flow control, which affords the opportunity to achieve improved performance far beyond that which conventional methods can offer (Figure 7). In addition, flow control through miniaturized fluidic nozzles is particularly attractive for small unmanned aerial vehicles (UAVs) and smart weapons.

Heat transfer augmentation or suppression is of pivotal importance in many engineering applications. A case in point is cooling for computer chips, which is controlled by the imposed air flow. As the number of transistors in an electronic chip continues to increase with advances in chip-manufacturing technology, inefficient cooling is often the limiting constraint. Massively parallel supercomputers, which are essential in keeping the U.S. at the forefront of cutting-edge research, can benefit from efficient cooling of chips tightly packed together. Successful flow control can provide a significant improvement in heat transfer, thereby allowing further miniaturization.

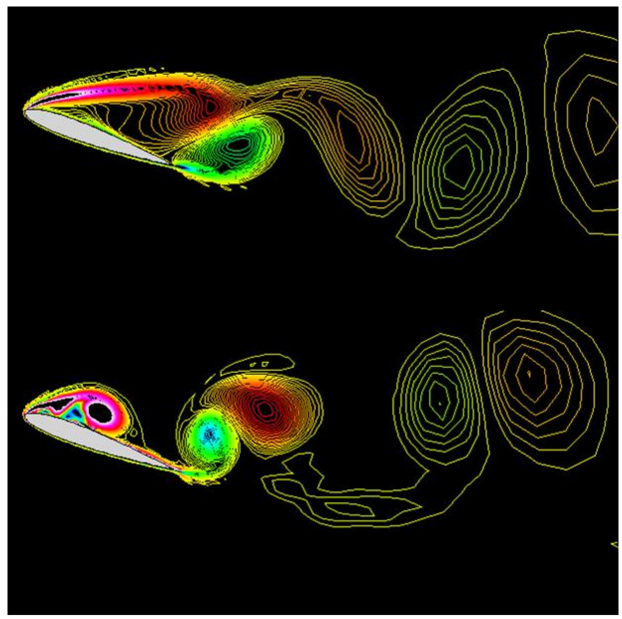

Figure 7: Flow separation on an airfoil at a high angle of attack can be delayed by periodic blowing and suction through small holes, to reduce drag. Top, uncontrolled; bottom, controlled (S.-C. Huang and J. Kim, UCLA).

Flow control improves the efficiency of combustion in jet engines, internal combustion engines in land and sea vehicles, and power plants. In addition to reduced fuel consumption, improved combustion reduces pollution, noise, and wear. Similar improvements are possible in manufacturing, chemical processing, and bio-medical applications of fluid flow. These examples illustrate the pivotal importance of flow control in breaking technological barriers. The immediate and potential benefits–economic, environmental and military–are enormous, and opportunities are abundant.

Successful flow control requires a thorough understanding of the underlying physics of the flow under consideration, efficient control algorithms, and robust sensors and actuators, all of which can be dramatically improved. Great strides have been made through advances in computational fluid dynamics, control theories, and micro- and nanofabrication technology. Better knowledge of the role of organized structures in boundary layers has led to new approaches for controlling these flows, while better understanding of instability of free shear flows has resulted in large control effects with minimal input power. The ability to manufacture a large number of sensors and actuators affords a new opportunity for controlling turbulence, which has previously proven difficult.

The modern approach to flow control provides new opportunities and challenges. In contrast to traditional approaches, in which the control intervention is designed on a trial-and-error basis or is based on the designer's physical insight, one can now use theory to design optimal control systems. Many challenging issues must be addressed before these approaches can be applied to the practical control of complex flow systems.

In summary, flow control is an enabling technology that will lead to many technological improvements wherever fluid flow is important. Research on flow control can help to maintain U.S. leadership in technology. However, realizing this potential requires continued progress in basic fluid dynamics research and control theory.

Biological Fluid Dynamics

Biological fluid flows are present in every aspect of living organisms. The basic functions of life—reproduction, growth, feeding, metabolism, and locomotion—are all sustained by the flow of fluids. The proper function of many organs such as the brain, eye, lungs, heart, liver and kidneys depends critically on fluid transport processes that provide rapid exchange of molecules between tissues and blood. Any disruption or deficiency in biofluid transport at the nano (sub-cellular), micro (cellular), or macro (vessel/organ) scale can result in major vascular diseases (e.g., atherosclerosis and aneurism), heart failure, stroke, hydrocephalus, and glaucoma, each with devastating effects on health. A comprehensive understanding of biological flows may lead to the development of better diagnostics and cost effective treatments.

One of the most common problems related to biological fluid flow in the human body is cardiovascular disease. According to the American Heart Association, cardiovascular diseases remain the number one cause of death in the United States. The annual cost of cardiovascular diseases alone to the U.S. economy is $300 billion. This figure increases substantially when other diseases related to biological flows are included. Furthermore, projections suggest that these costs will increase dramatically as the aging "baby boom" generation becomes more susceptible to diseases of biological fluid flow.

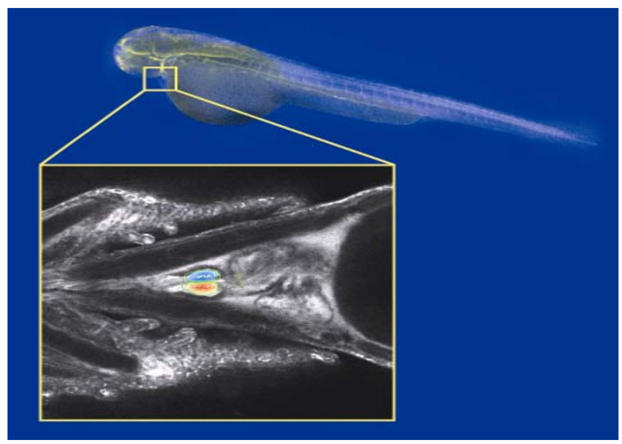

Figure 8: An embryonic Zebrafish, and its heart (inset). The circulatory flow field that is shown in red and blue indicates the presence of strong shear stress downstream of the aortic heart valve (Hove et al, Nature 2003). These stresses are implicated in cardiac disease.

Bio-fluid mechanics poses some of the most difficult basic science and engineering problems to the experimental and computational mechanics communities as well as to the medical device industry. These difficulties arise from the wide range of size scales involved (from cell to organ), the compliant nature of boundaries in the fluid (moving vessel walls and deformable cells), and the inherent complexity of biological fluids (e.g. blood) that are involved in even the simplest bio-fluid mechanical problem.

A classic example of these complexities can be found in the role of blood flow in atherosclerosis and vascular remodeling. Development of better treatment strategies for these diseases requires much better knowledge of the relationship between variables such as wall shear stress leading to plaque formation, and the resulting endothelial cell response and tissue growth. Where progress has been made, it has been stimulated by the availability of novel biological and medical imaging technologies as well as powerful computational and modeling tools. Here, we give a few examples.

Using fast confocal microscopy to map the velocity field inside of an embryonic zebrafish heart (Figure 8) has allowed scientists to study the response of cardiac wall tissues to flow-induced forces. Such studies are needed in order to understand the heart wall's response to altered flow patterns due to artificial valve implants.

Impressive progress has been made in the field of medical imaging, which has allowed accurate observations of the major and minor vessels of the human body. Availability of such data in combination with powerful computational fluid dynamics tools has made it possible to develop patient-based flow modeling to predict the outcome of surgical cardiovascular intervention. In Figure 9, we show one such simulation where global wall forces caused by blood flow have been mapped. Such mappings allow clinicians to predict the potential sites for plaque formation or predict the flow alteration that may arise from surgical interventions.

The field of bio-fluid mechanics also extends beyond medical applications by using biological models to design fluid transport systems that are vital to national defense in the post-9/11 era. Novel designs of unmanned aerial and underwater vehicles can be traced to basic science research on locomotion of flying and swimming animals. Applications such as aerial surveillance, underwater mine detection, and the inspection of hazardous sites may result. These potential applications, along with the likely medical advances that can be anticipated, provide a rich variety of potential benefits from research in biological fluid dynamics.

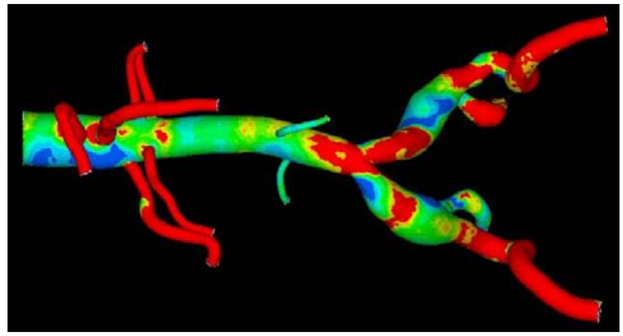

Figure 9: Patient-based computer mapping of wall shear stress in the human aorta (Charles Taylor, Stanford University).

Summary

Research in fluid dynamics is expected to have major impacts on important national needs. ***These include improvements in transportation and energy efficiency, prediction and mitigation of environmental problems, development of novel technologies based on microfluidics, improvements to security and defense, and major contributions to health. Finally, fluid dynamics research makes a large contribution to the training of future engineers and scientists.***

Acknowledgements

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