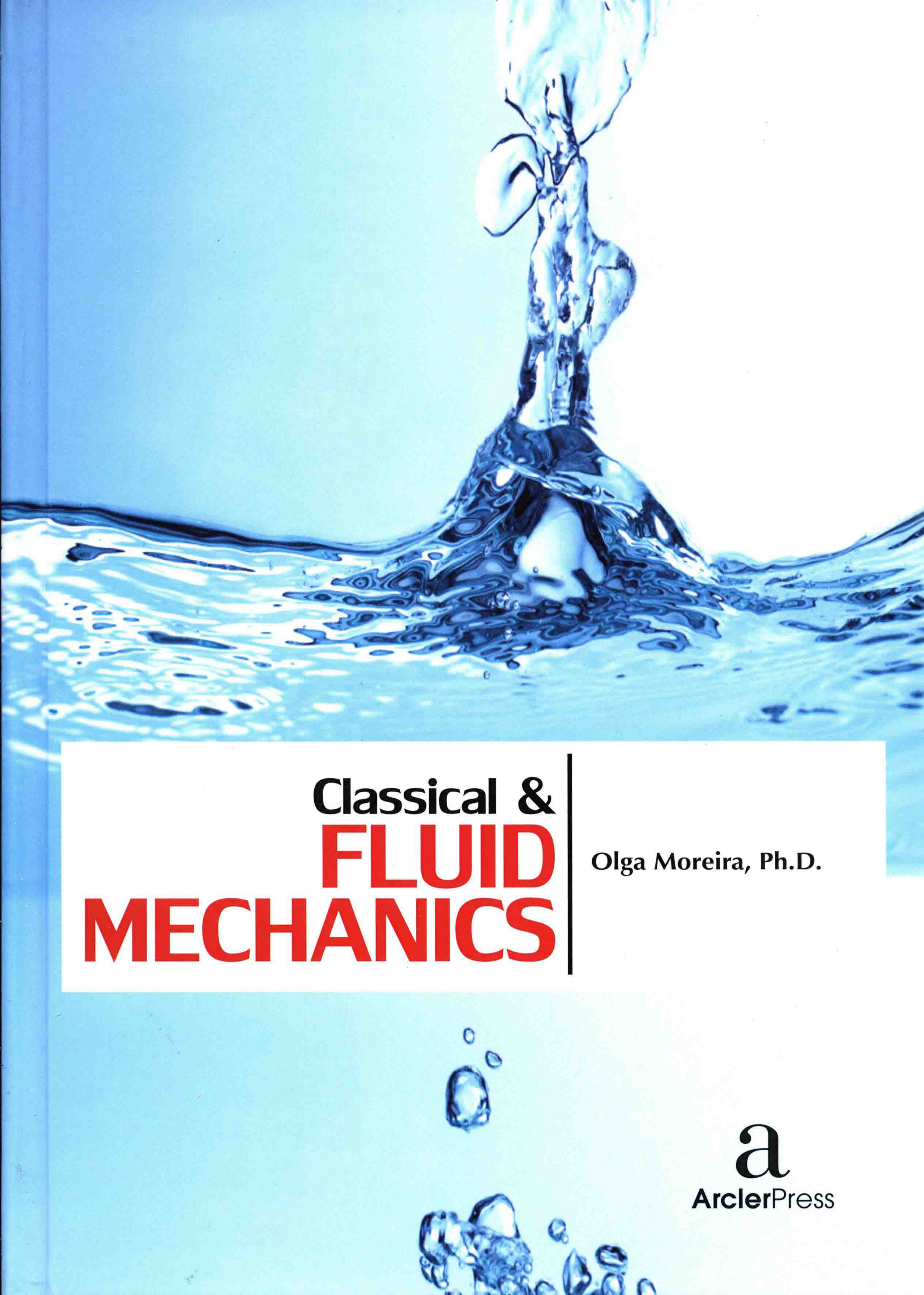

Classical & FLUID MECHANICS

Olga Moreira, Ph.D.

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Olga Moreira obtained her Ph.D. in Astrophysics from the University of Liege (Belgium) in 2010, her BSc. in Physics and Applied Mathematics from the University of Porto (Portugal). Her post-graduate travels and international collaborations with the European Space Agency (ESA) and European Southern Observatory (ESO) led to great personal and professional growth as a scientist. Currently, she is working as an independent researcher, technical writer, and editor in the fields of Mathematics, Physics, Astronomy and Astrophysics.

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Preface

Classical mechanics (a.k.a. Newtonian Mechanics) was one of the first pillars of modern physics providing the first unification of the laws of motion and universal gravitation. Although classical mechanics has been surpassed by the relativity theory and quantum mechanics, it still provides an accurate description of macroscopic objects motion as long as their velocities are far below the speed of light.

This book is a collection of research, which the main purpose is to offer a broad glimpse of the advances of Classical & Fluid Mechanics in several areas (e.g. oscillatory motion, celestial & orbital mechanics, fluid dynamics). The first part (chapters 1 - 5) overviews modern mathematical tools and techniques used to solve and construct differential equations associated with the equation of motion and modeling of oscillatory systems (e.g. Furuta's pendulum, harmonic oscillator). The second part (chapters 6- 12) focuses on the dynamics of multi-body systems (N-body problem), planetary and orbital mechanics, including some applications to study of moons orbits, satellite motion, and Earth's rotation problem. The third includes two examples Newtonian approach to the study of stellar structure (chapters 13 - 14). The remaining chapters are dedicated to advanced topics of fluid mechanics. This includes the description of compressible and incompressible fluid dynamics (chapters: 15 - 16) as well as the modeling of Newtonian (chapters 17-18) and non-Newtonian fluids (Chapters 19-20).

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INTRODUCTION

Fluid mechanics is a branch of physics which concerns the study of fluids and the ways in which they interact with forces. Both liquids and gases are considered to be fluids for the purposes of this branch of science. Often, the field of fluid mechanics is divided into two more specific fields of study. These are fluid statics and fluid dynamics, which concern fluids at rest and fluids in motion, respectively. Fluid mechanics can involve highly complex mathematics, and the aid of modern computers has enhanced this science significantly.

The chronological roots of fluid mechanics go all the way back to at least the ancient Greeks. The Greek physicist and inventor Archimedes was the author of some of the first studies we know of which concern fluid statics, including the property of buoyancy. Persian philosophers in the medieval time period coupled these ancient works with their own studies of fluid dynamics that acted as an early precursor to modern fluid dynamics. Such well-known historical figures as Leonardo da Vinci and Sir Isaac Newton, as well as others, made notable contributions to our understanding of fluid mechanics.

Every type of science starts out with basic, fundamental assumptions that govern the course of their study. Fluid mechanics is typically defined as having three basic premises or assumptions at its root. The first is the conservation of mass, which means that mass can neither be spontaneously created nor destroyed, although it may change forms. The second assumption, the conservation of momentum, is somewhat similar. This law states that the total momentum in a closed system is constant, and cannot spontaneously appear or disappear.

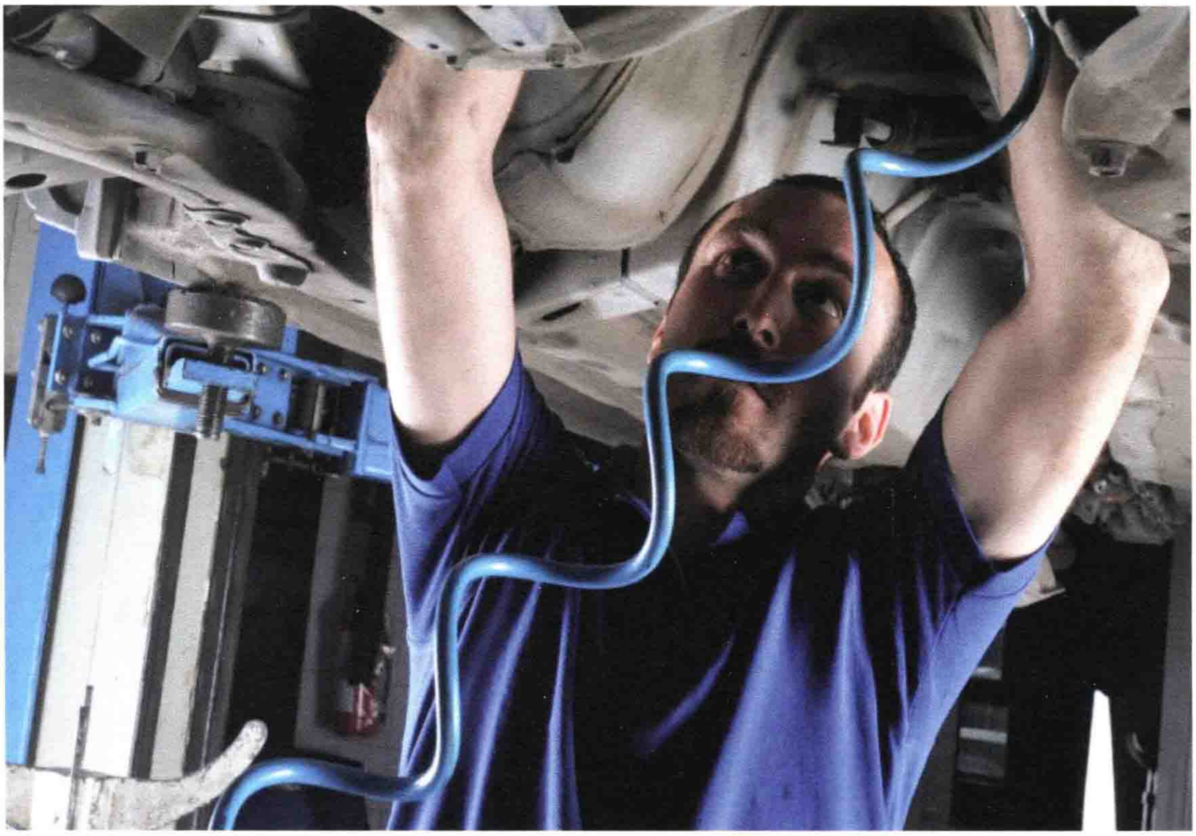
The third basic assumption governing fluid mechanics is what is known as the continuum hypothesis. This is a way of seeing fluids that does not take into account the presence of discrete molecules. Instead, a fluid's properties are assumed to vary in a continuous way from one point to the next.

Because it ignores the actual nature of small particles of matter, the continuum hypothesis is only an approximation used as a tool in calculations. It can result in a slightly inaccurate solution, but also in solutions that are very accurate under ideal circumstances. Other, more exact methods exist, but this hypothesis is often quite useful as a preliminary assumption. Many times, it can also be assumed that a given fluid is incompressible, meaning it cannot be compressed. This is only actually true of liquids, however, and not gases.

What is Fluidics?

The application of the physical properties of liquids and gases as a fluid to perform logic operations that control other mechanical systems is called fluidics. Hydraulics and pneumatics, respectively, starting from the Industrial Revolution that began around the late 1700s, provided a foundation. Subsequent study on the dynamics of fluids — liquids in particular — developed into a theoretical model of predictive behavior. This gave engineers a framework from which to conceive switches and other logic circuits which became the forerunners of modern electronics. Although digital circuits dominate the world today, fluidic processors remain in critical use.

Fluidics is not to be confused with the compression or expansion of liquids and gases as a hydraulic or pneumatic power source. Instead, the flow of a fluid is conceived as a medium capable of changing its character, carrying this information and transmitting it to other flows. The core functioning of a fluidic device has no moving parts.



The first set of assumptions about fluid dynamics is the Newtonian physics of classical mechanics. To this is added the variables of velocity, pressure, density and temperature as functions of space and time. An additional law is especially important — the "continuum assumption," that the flow characteristics of a fluid can be described without accounting for the known fact that fluids are composed of discreet molecular particles. Both theoretical and empirical physicists continue to expand computational understanding of viscosity, turbulence and other peculiar features of a fluid in motion. Engineers have followed with increasingly sophisticated fluidic devices.

Fluidics technology did not have a full opportunity to mature. The first logic circuits, including an amplifier and a diode, were invented in the early 1960s. Concurrently, the same concepts of signal amplification and transmission were realized employing a flow of electrons, and the invention of the solid state transistor ushered in a digital revolution.

The physical flow of a fluid, of course, cannot match the speed of an electron. A fluidic signal processor typically has an operating speed of just a few kilohertz. Unlike an electron, however, the mass flow of a liquid or gas is unaffected by electromagnetic or ionic interferences. Fluidics therefore remain necessary for the control of some failure-intolerant systems, such as military avionics. Fluidics have also developed into effective processors of analog data because of the nature of fluids to flow as a wave.

One of the major challenges of fluidics is that the principles of fluid dynamics are apparently different according to scale. To be sure, climatologists have yet to fully understand how massively large bodies of water or currents of air behave. Likewise, scientists have discovered that fluids behave very differently when studied at the scale of nanotechnology. Future study and application of the latter, called nano-fluidics, pose the possibility of significantly faster and more complex circuitry, including multiple gate arrays for parallel processing.

What is Fluid Dynamics?

Fluid dynamics refers to a subcategory of the science of fluid mechanics, with the other subcategory being fluid statics. While fluid statics deals with fluids that are at rest, fluid dynamics is concerned with fluids that are in motion. Any matter in a gas or liquid state can be considered a fluid. Fluid dynamics is a discipline with many relevant applications in our modern world, most notably because it contains the study of aerodynamics, and also because it comprises part of weather prediction. A typical fluid dynamics problem may include such variables as velocity, temperature, and density.

All of the physical sciences, including fluid dynamics, are governed first and foremost by the laws of conservation. These state that the total amounts of energy, mass, and linear momentum in a closed system remain constant, and that energy and mass can neither be created nor destroyed. That they may change forms, it is true, but they cannot disappear or come from nothing. These laws constitute some of the most basic assumptions in science.

Another governing principle of fluid dynamics is the continuum assumption, also called the continuum hypothesis. While fluids are known to be composed of microscopic, discreet particles, this hypothesis states that they are continuous, and that their properties vary evenly throughout. This often serves as a helpful mathematical approximation, even though it technically ignores one of the basic characteristics of fluids.

Before the invention of powered flight and aircraft in the 20th century, the term hydrodynamics was often used interchangeably with fluid dynamics, because most of fluid mechanics was devoted to studying liquids in motion, rather than gases in motion. When traveling by aircraft became more common, the need developed for these machines to be more efficient at creating and maintaining lift, with a minimum of drag. The branch of study known as aerodynamics made leaps and bounds because of the new technology, which has also come to be applied to automobiles, to some extent, with the goal of increased fuel efficiency.

One of the more important figures in modern aerodynamics was Octave Chanute. In addition to compiling a comprehensive volume of the study of aerodynamics in the late 1800s, he personally assisted the Wright brothers in building their famous aircraft, which accomplished the first manned, powered flight in 1903. It was likely due to this help that they accomplished their goal just ahead of the next closest contender, Samuel Pierpont Langley.

What Do Fluid Engineers Do?

Fluid engineers design and maintain fluid-based mechanical systems. They rely heavily on principles of fluid mechanics, engineering, and the natural sciences as they work with mechanical, hydraulic, and pumping systems. A fluid engineer may work in the design field as an engineer or architect. He may also find employment in the drilling field, where he installs and repairs equipment used to extract water, oil, and natural gas from the earth. These professionals may also maintain and repair the equipment used in mining, construction, and similar operations.

In the design field, fluid engineers may find employment in an engineering firm, power production facility, or manufacturing plant. In these types of jobs, fluid engineers design the hydraulic systems used in major industrial equipment, buildings or power production. For example, a fluid engineering professional employed by an equipment manufacturer may be responsible for designing new equipment, or creating more effective hydraulic and fluid-based operating systems. He may design cranes, excavators and large-scale pumps, relying on his knowledge of fluid mechanics to determine how much fluid is needed and what type will produce the best performance. Fluid design engineers also develop power production systems in hydroelectric plants and similar facilities.

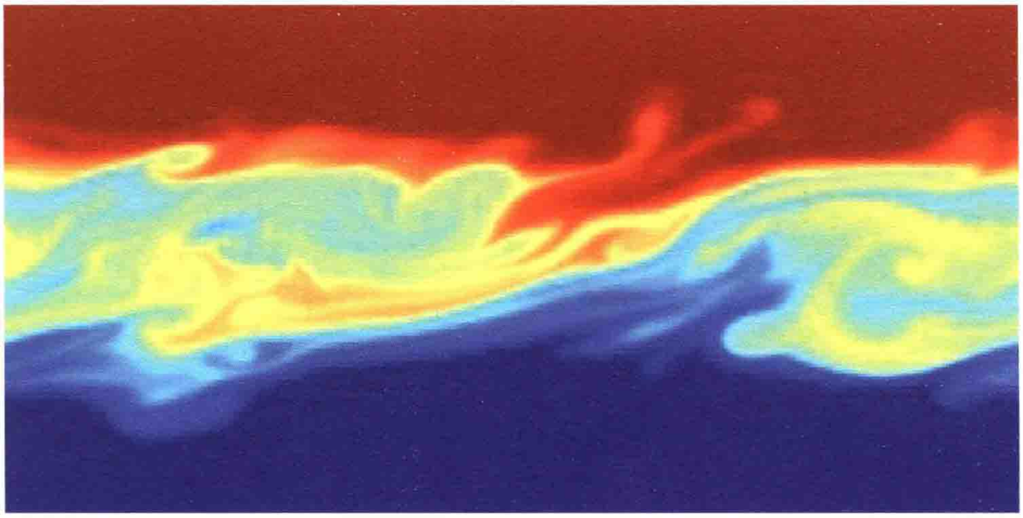
In the drilling arena, fluid or mud engineers set up the drilling systems used to remove oil and natural gas from the earth. Drilling fluid plays a major role in this type of operation, and is used to clear the way for the powerful drill bits as it removes cuttings and waste materials from the earth. In this setting, fluid engineers not only set up and install equipment, but also teach other members of the team how to operate and maintain these systems. They track the how fluid impacts pressure and performance deep underground, and take charge of cleaning and maintaining equipment so that it will produce maximize results.

Fluid engineers may also manage the repair and maintenance of large equipment on mining and construction sites. These professionals may be responsible for keeping washing stations or excavators operating at a gold mine, or maintaining cranes, bulldozers and other equipment used in construction and land clearing operations. In this type of position, fluid engineers perform routine maintenance like checking fluid levels and topping off the fluid as needed. They also perform major repairs and diagnostics when equipment malfunctions, which may include something as simple as replacing a damaged hose or gasket to a job as complex as rebuilding an entire hydraulic operating system.

Fluid dynamics

In physics, fluid dynamics is a sub discipline of fluid mechanics that deals with fluid flow—the science of fluids (liquids and gases) in motion. It has several sub disciplines itself, including aerodynamics (the study of air and other gases in motion) and hydrodynamics (the study of liquids in motion). Fluid dynamics has a wide range of applications, including calculating forces and moments on aircraft, determining the mass flow rate of petroleum through pipelines, predicting weather patterns, understanding nebulae in interstellar space and modelling fission weapon detonation. Some of its principles are even used in traffic engineering, where traffic is treated as a continuous fluid, and crowd dynamics.

Fluid dynamics offers a systematic structure—which underlies these practical disciplines—that embraces empirical and semi-empirical laws derived from flow measurement and used to solve practical problems. The solution to a fluid dynamics problem typically involves calculating various properties of the fluid, such as flow velocity, pressure, density, and temperature, as functions of space and time.



Equations of fluid dynamics

The foundational axioms of fluid dynamics are the conservation laws, specifically, conservation of mass, conservation of linear momentum (also known as Newton's Second Law of Motion), and conservation of energy (also known as First Law of Thermodynamics). These are based on classical mechanics and are modified in quantum mechanics and general relativity. They are expressed using the Reynolds Transport Theorem.

In addition to the above, fluids are assumed to obey the continuum assumption. Fluids are composed of molecules that collide with one another and solid objects. However, the continuum assumption considers fluids as continuous, rather than discrete. Consequently, properties such as density, pressure, temperature, and flow velocity are assumed well-defined at infinitesimally small points, and are assumed to vary continuously from one point to another. The fact that the fluid is made up of discrete molecules is ignored.

For fluids that are sufficiently dense to be a continuum, do not contain ionized species, and have flow velocities small in relation to the speed of light, the momentum equations for Newtonian fluids are the Navier–Stokes equations—which is a non-linear set of differential equations that describes the flow of a fluid whose stress depends linearly on flow velocity gradients and pressure. The simplified equations do not have a general closed-form solution, so they are primarily of use in Computational Fluid Dynamics. The equations can be simplified in a number of ways, all of which make them easier to solve. Some of them allow appropriate fluid dynamics problems be solved in closed form

Classical fluid mechanics

Classical fluid mechanics is a branch of continuum mechanics; that is, it proceeds on the assumption that a fluid is practically continuous and homogeneous in structure. The fundamental property which distinguishes a fluid to from other continuous media is that it cannot be in equilibrium in a state of stress such that the mutual action between two adjacent parts is oblique to the common surface. Though this property is the basis of hydrostatics and hydrodynamics, it is by itself insufficient for the description of fluid motion. In order to characterize the physical behavior of a fluid the property must be extended, given suitable analytical form, and introduced into the equations of motion of a general continuous medium, this leading ultimately to a system of differential equations which are to be satisfied by the velocity, density, pressure, etc. of an arbitrary fluid motion. In this article we shall consider these differential equations, their derivation from fundamental axioms, and the various forms which they take when more or less special assumptions concerning the fluid or the fluid motion are made. Our intent, then, is to present in a mathematically correct way, in concise form, and with more than passing attention to the foundations, the principles of classical fluid mechanics. The work includes the body of exact theoretical knowledge which accompanies the fundamental equations, and at the same time excludes relativistic and quantum effects, most of the kinetic theory, special fields such as turbulence, and all numerical or approximate work.

Vectors and tensors

The mathematical notation used in this article is that of ordinary Cartesian or Gibbsian vector analysis. This notation leads to the utmost conciseness of expression, and at the same time illuminates the physical meaning of the phenomena represented. Most of the vector operations which we use are standard, but occasionally an expression is needed which may appear unusual or ambiguous. For this reason it is convenient to define all operations in terms of vector components: then the meaning of an equation can always be made clear simply by rewriting it in component form. Another advantage accrues to this method, namely that any equation admits an immediate tensorial interpretation if so desired.

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