高等院校卓越计划系列丛书

Fundamentals of Fluid Mechanics

工程流体力学

邵卫云 编著

中国建筑工业出版社

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本教材是高等院校卓越计划系列丛书中浙江大学建筑工程学院卓越计划系列丛书之一，主要根据教育部高等学校力学基础课程教学指导委员会流体力学及水力学课程教学指导小组编制的土建类专业的流体力学教学大纲编写。内容包括流体的物理特性、流体静力学、流体运动学、恒定总流基本方程、相似原理与量纲分析、流体阻力与能量损失、孔口与管嘴出流、管流、明渠流、堰流、渗流及可压缩一元流等。教材内容侧重于基本概念与原理的阐述及其在日常生活与工程中的应用。

本教材是普通高等学校土木、水利、海洋、市政工程等专业的专业基础课程流体力学的双语教学教材，也可作为环境、机械、能源工程等专业的流体力学课程双语教学用书，亦可供有兴趣了解流体力学英文术语词汇及其日常应用的学生与专业人员的参考。

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浙江大学建筑工程学院卓越计划系列教材

丛 书 序 言

随着时代进步，国家大力提倡绿色节能建筑，推进城镇化建设和建筑产业现代化，我国基础设施建设得到快速发展。在新型建筑材料、信息技术、制造技术、大型施工装备等新材料、新技术、新工艺广泛应用新的形势下，建筑工程无论在建筑结构体系、设计理论和方法以及施工与管理等各个方面都需要不断创新和知识更新。简而言之，建筑业正迎来新的机遇和挑战。

为了紧跟建筑行业的发展步伐，为了呈现更多的新知识、新技术，为了启发更多学生的创新能力，同时，也能更好地推动教材建设，适应建筑工程技术的发展和落实卓越工程师计划的实施，浙江大学建筑工程学院与中国建筑工程出版社诚意合作，精心组织、共同编纂了“高等院校卓越计划系列丛书”之“浙江大学建筑工程学院卓越计划系列教材”。

本丛书编写的指导思想是：理论联系实际，编写上强调系统性、实用性，符合现行行业规范。同时，推动基于问题、基于项目、基于案例多种研究性学习方法，加强理论知识与工程实践紧密结合，重视实训实习，实现工程实践能力、工程设计能力与工程创新能力的提升。

丛书凝聚着浙江大学建筑工程学院教师们长期的教学积累、科研实践和教学改革与探索，具有了鲜明的特色：

（1）重视理论与工程的结合，充实大量实际工程案例，注重基本概念的阐述和基本原理的工程实际应用，充分体现了专业性、指导性和实用性；

（2）重视教学与科研的结合，融进各位教师长期研究积累和科研成果，使学生及时了解最新的工程技术知识，紧跟时代，反映了科技进步和创新；

（3）重视编写的逻辑性、系统性，图文相映，相得益彰，强调动手作图和做题能力，培养学生的空间想象能力、思考能力、解决问题能力，形成以工科思维为主体并融合部分人性化思想的特色和风格。

本丛书目前计划列入的有：《土力学》、《基础工程》、《结构力学》、《混凝土结构设计原理》、《混凝土结构设计》、《钢结构原理》、《钢结构设计》、《工程流体力学》、《结构力学》、《土木工程设计导论》、《土木工程试验与检测》、《土木工程制图》、《画法几何》等。丛书分册列入是开放的，今后将根据情况，做出调整和补充。

本丛书面向土木、水利、建筑、园林、道路、市政等专业学生，同时也可以作为土木工程注册工程师考试及土建类其他相关专业教学的参考资料。

浙江大学建筑工程学院卓越计划系列教材编委会

2014.10

前　言

本教材是普通高等学校土木、水利、海洋、市政工程等专业的专业基础课程流体力学的双语教学教材，也可作为环境、机械、能源工程等专业的流体力学课程双语教学用书，亦可供有兴趣了解流体力学英文术语词汇及其日常应用的学生与专业人员的参考。

本教材的编写依据是全国高等学校土建类专业的《流体力学课程教学基本要求》，沿用国内中文流体力学课程教材的内容体系和符号系统，在一定程度上做了拓展，主要表现为：

1. 在有关章节中简单概述了常用的实验室及工程中的流体力学最新测量方法。流速（流场）与流量的测量是流体力学在工程实践中的一个重要环节。而在国内流体力学教材中，除了静水力学中的测压计、毕托管、文丘里流量计、明渠流量的堰流测量有所阐述外，其他的甚少涉及。为此，本教材除了在2.3.3节阐述了测压计、第10章阐述了明渠堰流测量原理外，在6.8.4节简单介绍了风洞与水洞的结构与应用，在8.7节介绍了管道中的点流速（热膜流速计、电磁流速计、LDV等）、流场（PIV）、流量（机械类如涡轮流量计，水头类如文丘里、孔板与管嘴流量计）测量技术，在9.9节介绍了明渠中的流速测量仪器（旋桨流速仪、电磁流速仪、多普勒流速仪ADV和ADCP、光学流速仪）与流量测量方法（水工结构法如堰、Parshall量水槽和Palmer-Bowlus量水槽；流速面积法；底坡面积法；示踪剂法）。

2. 在例题与习题的选择上尽可能选用贴近生活与工程的题目，如例3-9的龙卷风、例4-8的计算机散热、例4-10的射流泵、例8-1的马桶冲水对淋浴头出水的影响等。同时精选思考题、习题，并对所有习题附有答案，利于学生自学。

3. 每章开篇附有相关的流体力学照片与导读，以引导学生；每章最后对本章内容做了详尽的概括，便于学生复习。

4. 书后附有流体力学学术词汇索引，本书中出现的流体力学专家索引与符号表。

本书编写过程中得到了浙江大学市政工程研究所、浙江大学建筑工程学院、中国建筑工业出版社的大力支持，同时顾建农教授提供了水洞原理图与照片、浙江大学市政工程研究所提供了管网、PIV、ADCP等照片、浙江大学土木水利实验室提供了风洞照片、姜利杰博士绘制了书中图的CAD原图，在此一并表示衷心的感谢。另外，对参考文献作者、引用的网上相关照片的作者与网站表示衷心感谢，是你们为我提供了诸多宝贵的素材。最后，特别感谢我的先生和女儿，在我编写的过程中，始终给予我支持与鼓励。

限于作者水平，书中不妥之处敬请读者批评指正。

邵卫云

2014年12月于浙江大学

Contents

1 Introduction

CHAPTER OPENING PHOTO: Water is a transparent fluid which forms the world's streams, lakes, oceans and rain, and covers 71% of the Earth's surface. On Earth, 96.5% of the planet's water is founded in seas and oceans, only 2.5% is freshwater, whereas 98.8% of which is in ice and groundwater, and less than 0.3% is in rivers, lakes, and the atmosphere. In civil, hydraulic and ocean engineering, water has the massive effects on the water related structures. We begin from its physical properties as in the present chapter. (© *2013 For Wallpaper. com*)

In this introductory chapter, we start this chapter with a concept of fluid and continuum, the study methods and a brief history of the development of fluid mechanics. It follows the definition of surface and mass forces acting on the fluid that will be used in the fluid mechanics. Finally, we discuss properties that are encountered in the analysis of fluid flow: the density and specific gravity; the viscosity playing a dominant role in most aspects of fluid flow and the no-slip condition at solid-fluid interfaces; the coefficient of compressibility; the vapor pressure; and the surface tension determining the capillary rise under static equilibrium conditions.

1.1 Brief Look at Fluid Mechanics

1.1.1 The Concept of a Fluid

Fluid mechanics is the study of fluids either in motion (*fluid dynamics*) or at rest (*fluid statics*) and the subsequent effects of fluid upon the boundaries, which may be either solid surfaces or interfaces with other fluids. Fluid mechanics is one of the most important of all areas of physics. Its field varies from the study of blood flow in the capillaries (which are only a few microns in diameter) to the flow of the Three Gorges hydropower plant with a dam of 181m-high, i. e., breathing, blood flow, swimming, pumps, fans, turbines, airplanes, ships, rivers, windmills, pipes, missiles, icebergs, engines, filters, and sprinklers. Fluid mechanics principles are needed to explain the phenomena in this area, i. e., why airplanes are made streamlined with smooth surfaces for the most efficient flight, whereas golf balls are made with rough surfaces (dimpled) to increase their efficiency (see Section 6. 8. 3).

A *fluid* is any substance that deforms continuously when subjected to a shear stress, no matter how small. Thus, from the point of view of fluid mechanics, all matter can be classified as two states, *fluid* and *solid*. Their difference in reaction to an applied shear or tangential stress is perfectly obvious. A solid can resist a shear stress by a static deformation without flow; a fluid cannot. The fluid moves and deforms continuously as long as the shear stress is applied, whereas a fluid at rest must be in a state of zero shear stress.

Given the definition of a fluid above, both *liquids* and *gases* are classified as fluids. The technical distinction lies in the effect of cohesive forces. A *liquid*, being composed of relatively close-packed molecules with strong cohesive forces, tends to retain its volume and will form a free surface in a gravitational field if it is unconfined from above (Fig. 1-1a). A *gas*, being composed of widely spaced molecules with negligible cohesive forces, is free to expand to fill the entire available space and has no definite volume and free surface (Fig. 1-1b).

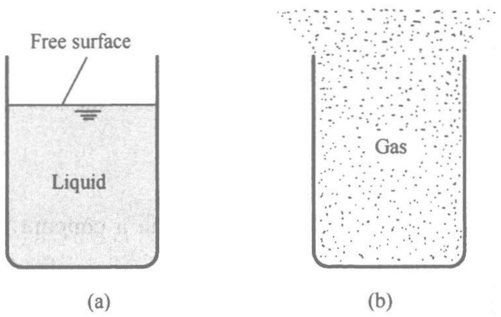

Fig. 1-1 (a) Liquid with a free surface and a definite volume;
(b) Gas which expands freely with no free surface

1.1.2 The Fluid as a Continuum

As far as we know, fluids are aggregations of molecules, widely spaced for a gas, closely spaced for a liquid. The distance between molecules is very large compared with the molecular diameter. For example, 1cm^3 of water at standard conditions (at 1atm and 20℃) contains approximately 3.3×10^{22} molecules, the distance between molecules is approximate 3×10^{-8}cm; 1cm^3 of air at standard conditions contains approximately 2.7×10^{19} molecules, the distance between molecules is approximate 3×10^{-7}cm. Thus, there must be many molecules even in a rather small volume of fluid, the statistical mean characteristics of flow could be obtained. The fluid properties of a fluid, such as pressure, velocity or density, can be assumed to be varied continually in space, that is, the variation in properties is so smooth that the differential calculus can be used to analyze the substance. For a fluid in such a case is called a *continuum*. The assumption is called the *continuum hypothesis*, the most fundamental idea for solving fluid mechanics problem.

Consider for example the density at a specific point in a fluid. It is defined as the ratio of the mass of molecules in a small volume surrounding that point to this given volume. However, the size of this small volume, δV, has to meet with certain criteria. It must be smaller than the physical dimensions of the region under consideration like the wing of an aircraft or the pipe in a hydraulic system. At the same time it must be sufficiently large to accommodate a large number of molecules to make the density meaningful. Too small a δV, the value of calculated density fluctuates because the number of molecules within δV is varying significantly with time. Too big a δV might mean that density itself is varying significantly within the region of interest. It is clear that there is a limit δV_0 below which molecular variations assume importance and above which one finds a macroscopic variation of density within the region. Therefore, the *density* ρ of a fluid is best defined as

$$\rho = \lim_{\delta V \to \delta V_0} \frac{\delta m}{\delta V} \tag{1.1}$$

where δm is the molecular mass within the given volume δV.

Equation1. 1 is plotted in Fig. 1-2. The limiting volume δV_0 is about $10^{-9}\,mm^3$ for all liquids and for gases at atmospheric pressure. For example, $10^{-9}\,mm^3$ of air at standard conditions contains approximately 3×10^7 molecules, which is sufficient to define a nearly constant density according to Eq. 1. 1. In engineering practice, most problems are concerned with physical dimensions much larger than this limiting volume. Thus, *continuum hypothesis* is valid for most engineering problems.

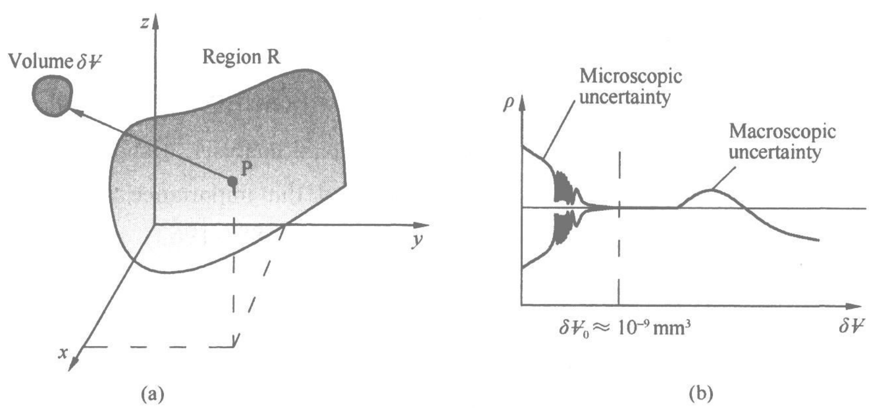

Fig. 1-2 The definition of continuum fluid density: (a) an elemental volume in a fluid region; (b) calculated density versus size of the elemental volume

1.1.3 Study Approaches

It should be noted that the basic practical understanding of the behavior of fluids dates back to the ancient civilizations, at least by the time of the ancient Egyptians. Through necessity there was a practical concern about the manner in which spears and arrows could be propelled through the air, in the development of water supply and irrigation systems, and in the design of boats and ships. In fact, the homes of well-to-do Romans had flushing toilets not very different from those in modern 21st-Century houses, and the Roman aqueducts are still considered a tremendous engineering feature. Some of the earliest writings that pertain to modern fluid mechanics are those of Archimedes (287-212 B. C.), a Greek mathematician and inventor who first expressed the principles of hydrostatics and flotation. Then, little has been added to further understanding of fluid in the next 1000 years behavior till about fifteenth century. Beginning with the Renaissance period, continuous series of contributions began to form the basis of fluid mechanics. Leonardo da Vinci (1452-1519) derived the equation of conservation of mass in one-dimensional steady flow and experimented with waves, jets, hydraulic jumps, eddy formation, etc. Galileo Galilei (1564-1642) marked the beginning of experimental mechanics, and Edme Mariotte (1620-1684), a Frenchman, built the first wind tunnel and tested models in it. Problems involving the momentum of fluids could finally be analyzed after Isaac Newton (1642-1727) postulating his laws of motion and the law of viscosity of the linear fluids now called Newtonian.

Following the numerous significant contributions of the theoretical and mathematical advances have been made, the theoretical and mathematical study of idealized, frictionless fluid behavior was termed *hydrodynamics* contributed by the eighteenth-century mathematicians (Daniel Bernoulli, Leonhard Euler, Jean d'Alembert, Joseph-Louis Lagrange, and Pierre-Simon Laplace). Among them, Leonhard Euler (1707-1783) developed both the differential equations of motion and their integral form, now called *Bernoulli equation*.

The applied or experimental aspects of real fluid behavior, particularly the behavior of water relying almost entirely on experiment, was termed *hydraulics* contributed by the experimentalists (Chézy, Pitot, Borda, Weber, Francis, Hagen, Poiseuille, Darcy, Manning, Bazin, and Weisbach) on a variety of flows such as open channels, ship resistance, pipe flows, waves, and turbines. William Froude (1810-1879) and his son Robert (1846-1924) developed laws of model testing and Lord Rayleigh (1842-1919) proposed dimensional analysis. Osborne Reynolds (1842-1912) published the classic pipe experiment and showed the importance of the dimensionless *Reynolds number*, named after him. Theodore von Kármán (1881-1963) analyzed what is now known as the *von Kármán vortex street*. Geoffrey Ingram Taylor (1886-1975) advanced statistical theory of turbulence and the Taylor microscale.

For the theoretical aspects of real fluid, the general differential equations of viscous flow theory, *Navier-Stokes equations*, named after Lowis Navier (1785-1836) and George Gabriel Stokes (1819-1903), was available but unexploited from nineteen century. Then, in 1904, a German engineer, Ludwig Prandtl (1875-1953) pointed out that fluid flows with small viscosity, e. g., water flows and air flows, can be divided into a thin *viscous layer*, or *boundary layer*, near solid surfaces and interfaces, patched onto a nearly inviscid outer layer, where the Euler and Bernoulli equations apply. The concept of "fluid boundary layer" laid the foundation for the unification of the theoretical and experimental aspects of fluid mechanics. Thus, Prandtl is generally accepted as the founder of modern fluid mechanics.

Besides the theoretical and experimental methods, today, because of the power of modern digital computers, there is yet a third way to study fluid dynamics: *computational fluid dynamics*, or *CFD* for short. In modern industrial practice CFD is used more for fluid flow analyses than either theory or experiment. But it is also important to understand that in order to do CFD one must have a fundamental understanding of fluid flow itself, from both the theoretical, mathematical side and from the practical, sometimes experimental, side. We will provide a brief introduction to each of these ways of studying fluid dynamics in the following subsections.

THE THEORETICAL APPROACH

For the theoretical approach, we employ the mathematical equations that govern the flow and try to capture the fluid behavior within a closed form solution i. e., formulas that can be readily used. Theoretical/analytical studies of fluid dynamics generally require considerable simplifications of the equations of fluid motion, the Navier-Stokes equations. This is perhaps the simplest of the approaches, but its scope is somewhat limited. Not every fluid flow renders itself to such an approach. The resulting equations may be too complicated to be solved easily.

In most practical engineering applications, various assumptions and simplifications need to be made to enable the analytical solution of the differential equations representing the physical situation. This at one hand limits the applicability of the methods to simple type problems, or limits the validity of the solutions if too many assumptions and simplifications are made.

Despite that, analytical methods played significant role in the past and they still play an important role. They have helped engineers and scientists in the understanding of the fundamental rules controlling the behavior of many engineering systems. In addition, they are used to help understand and interpret experimental results. Furthermore, they can be used as a first stage in the validation of CFD models.

THE EXPERIMENTAL APPROACH

Experimental approach is the oldest approach, perhaps also employed by Archimedes when he was to investigate a fraud. It is a very popular approach by which you will make measurements with a wind tunnel or a similar equipment. But this is a costly venture and is becoming costlier day by day.

Rather obviously, fluid experiments performed today in first class fluids laboratories are far more sophisticated. Nevertheless, until only very recently the outcomes of most fluid experiments were mainly a qualitative (and not quantitative) understanding of fluid motion. An indication of this is provided by the adjacent pictures of wind tunnel experiments. In each of these we are able to discern quite detailed qualitative aspects of the flow over different prolate spheroids. Basic flow patterns are evident from colored streaks, even to the point of indications of flow "separation" and transition to turbulence. However, such diagnostics provide no information on actual flow velocity or pressure—the main quantities appearing in the theoretical equations, and needed for engineering analyses.

There have methods for measuring pressure in a flow field for a long time, and these could be used simultaneously with the flow visualization to gain some quantitative data. On the other hand, it is till recently to be possible to accurately measure flow velocity simultaneously over large areas of a flow field. If point measurements are sufficient, *hot-wire anemometry* (HWA) or *laser-doppler velocimetry* (LDV) can be used; but for field measurements it is necessary to employ some form of *particle image velocimetry* (PIV). It is clear that the quantitative detail by PIV is far superior to the simple visualizations in the experiments, and as a consequence PIV is rapidly becoming the preferred diagnostic in many flow situations.

THE COMPUTATIONAL APPROACH

Computational Fluid Dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical methods and algorithms to solve the mathematical equations which govern the processes of fluid flow, heat transfer, mass transfer, chemical reactions, and related phenomena and analyze these problems that involve fluid flows. The fundamental basis of almost all CFD problems are the Navier-Stokes equations, which define any single-phase (gas or liquid, but not both) fluid flow. These equations can be simplified by removing terms describing viscous actions to yield the Euler equations. Further simplification, by removing terms describing vorticity yields the full potential equations. Finally, for small perturbations in subsonic and supersonic flows (not transonic or hypersonic) these equations can be linearized to yield the linearized potential equations.

CFD analysis complementing testing and experimentation can reduce the total effort required in the laboratory. In recent years with the development of computer technology, CFD has played an ever-increasing role in many areas of sports and athletics: from study and design of Olympic swimware to the design of a new type of golf ball providing significantly longer flight times, and thus driving distance (and currently banned by the PGA). The example of a race car also reflects current heavy use of CFD in numerous areas of automobile production ranging from the design of modern internal combustion engines exhibiting improved efficiency and reduced emissions to various aspects of the manufacturing process including, for example, spray painting of the completed vehicles.

It is essential to recognize that it is the CFD computer code that solves the Navier-Stokes equations. The user of such codes must understand the mathematics of these equations sufficiently well to be able to supply all required auxiliary data for any given problem, and he/she must have sufficient grasp of the basic physics of fluid flow to be able to assess the outcome of a calculation and determine, among other things, whether it is "physically reasonable", and if not, decide what to do next, or how to validate the outcome with scaled laboratory experiments.

1.1.4 Fluid Mechanics in Civil Engineering

As what discussed above fluid dynamics is one of the most important of all areas of physics.

The applications in fluid engineering are enormous. When you think about it, almost everything on this planet either is a fluid or moves within or near a fluid.

For the fluid mechanics on a Civil Engineering course, the provisions of adequate water services such as the potable water supply, drainage and sewerage are essential for the development of industrial society. It is these services civil engineers provide.

Fluid mechanics is involved in nearly all areas of Civil Engineering either directly or indirectly. Some examples of direct involvement are those where we are concerned with manipulating the fluid: sea and river (flood) defenses; water distribution/sewerage (sanitation) networks; hydraulic design of water/sewage treatment works; dams; pumps and turbines; water retaining structures. For other examples where the primary object is construction the analysis of fluid mechanics is essential: flow of air in/around buildings; bridge piers in rivers and ground-water flow.

Notice how nearly all of these involve water. The following course, although introducing general fluid flow ideas and principles, will demonstrate many of these principles through examples where the fluid is water.

1.2 Forces Acting on Fluid

The forces acting on a fluid element drawn from the fluid field usually can be classified as: surface force and mass force.

1.2.1 Surface Force

Surface force, designated by $\mathbf{F}_s$, is the force acting directly on the internal or external surface of the fluid element in a fluid field, which has a unit of N. Surface forces are due to only two sources: (a) the pressure distribution acting on the surface, imposed by the outside fluid surrounding the fluid element, and (b) the shear and normal stress distributions acting on the surface, also imposed by the outside fluid 'tugging' or 'pushing' on the surface by means of friction. Thus, surface force is directly proportional to the area of the surface with which fluid is in contact.

In Fig. 1-3 fluids exert both normal and tangential forces on surfaces with which they are in contact (e. g., surfaces of containers and 'surfaces' of adjacent fluid elements). Both of those two perpendicular forces, normal and tangential forces, are the components of surface force acting on the finite area, ΔA.

Shear stress, designated by τ, is the tangential force per unit area on the surface of fluid and defined as

$$\bar{\tau} = \frac{\Delta F_\tau}{\Delta A} \tag{1.2}$$

where ΔF_τ is the tangential component of the surface force ΔF_s applied on the finite area ΔA.

Equation 1.2 indicates that it is the averaged shear stress acting on the finite area ΔA. The shear stress at point D is somewhat different from this averaged shear stress, which could be ob-

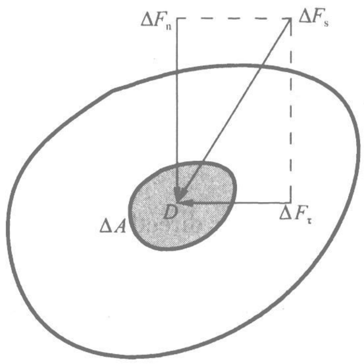

Fig. 1-3 Forces on the surface of a fluid element

tained while finite area ΔA tends to a limit, an infinitesimal limit which is sufficiently small to be negligible in comparison with macroscopic length scales squared, but still sufficiently large to contain enough molecules to permit calculation of averaged properties and 'construction' of fluid parcels. In mathematic expression this limit is replaced by zero, thus the shear stress at a point is defined as

$$\tau = \lim_{\Delta A \to 0} \frac{\Delta F_\tau}{\Delta A} \tag{1.3}$$

The shear stress has units of Pa, $1\text{Pa} = 1\text{N/m}^2$.

Pressure, designated by p, is the normal force per unit area on the surface of fluid. As we have done with the shear stress, we can define average pressure acting on a finite area ΔA as

$$\bar{p} = \frac{\Delta F_n}{\Delta A} \tag{1.4}$$

where ΔF_n is the normal component of the surface force ΔF_s applied over the finite area ΔA. Then the pressure at a point is given as

$$p = \lim_{\Delta A \to 0} \frac{\Delta F_n}{\Delta A} \tag{1.5}$$

where, as usual, the limit process is viewed within the confines of the *continuum hypothesis*. The pressure also has units of Pa.

1.2.2 Mass Force

Mass force, designated by $\mathbf{F_b}$, is the force acting directly on the volumetric mass of the fluid element such as gravitational, electric and magnetic forces. The value of mass force is directly proportional to the mass of fluid body. For homogeneous fluid, it is also directly proportional to the fluid volume, which gets it another name, *body force*. Mass force has units of N.

Unit mass force, designated by $\mathbf{f}$, is the mass force per unit mass of a fluid and defined as

$$\mathbf{f} = \frac{\mathbf{F_b}}{m} = f_x\mathbf{i} + f_y\mathbf{j} + f_z\mathbf{k} \tag{1.6}$$

where f_x, f_y and f_z are the components of the unit mass force in the x-, y-and z-direction, m is the mass of the fluid.

The unit mass force has units of m/s^2, same as the units of acceleration.

For a fluid at rest under gravity, the unit mass forces are $f_x = f_y = 0$, $f_z = -g$ (z- coordinate is upwards), and for a freely falling fluid, $f_x = f_y = f_z = 0$.