Case Studies in Fluid Mechanics with Sensitivities to Governing Variables

M. Kemal Atesmen

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Series Preface

The Wiley-ASME Press Series in Mechanical Engineering brings together two established leaders in mechanical engineering publishing to deliver high-quality, peer-reviewed books covering topics of current interest to engineers and researchers worldwide. The series publishes across the breadth of mechanical engineering, comprising research, design and development, and manufacturing. It includes monographs, references, and course texts. Prospective topics include emerging and advanced technologies in engineering design, computer-aided design, energy conversion and resources, heat transfer, manufacturing and processing, systems and devices, renewable energy, robotics, and biotechnology.

Preface

I have been fascinated by thermo-science fields from childhood on. Simple observations such as the motions of a flying kite, bubbles rising in a boiling kettle, a leaf floating on the surface of a lake, the force you need to get the ketchup out of its bottle, and so on encouraged me to strive to understand the science behind these and many more natural phenomena that are governed by fluid mechanics, heat transfer, and mass transfer. In college and in real engineering life, I learned that knowing only the governing equations in these vast scientific fields, and studying how they evolved and learning by heart their dependent and independent variables, was only the starting point in solving the engineering problems.

Making correct assumptions while using governing equations, using the correct thermophysical properties, and applying the right experimental results to different physical conditions are crucial in approaching the solution of problems in fluid mechanics, heat transfer, and mass transfer. I gained experience in these fields as I tackled more and more problems. Even with today's high-speed computational solutions to intricate, coupled, and non-linear partial differential equations, you have to be experienced in the assumptions you make for governing equations and their boundary conditions, the thermo-physical properties you can use, and the experimental data you apply.

In this book I will provide sensitivity analyses to well-known everyday fluid mechanics, heat transfer, and mass transfer problems. Sensitivity analyses of dependent variables on independent variables provide an engineer with understanding of the crucial variables that have to be focused on during the design process and the uncertainty that has to be quantified in simulation results. The present book is an expanded version of the book I published in 2009, which only covered case studies in heat transfer [1].

In this book a wide range of 24 practical fluid mechanics, heat transfer, and mass transfer problems are investigated. The approach to problem solution starts with the applicable basic laws of fluid mechanics, heat transfer, and mass transfer. These basic laws are the conservation of matter, the conservation of momentum, the conservation of energy, and the second law of thermodynamics. Each problem solution starts with simplifying engineering assumptions and identifies the

governing equations and dependent and independent variables. In some cases, where solutions to basic equations are not possible, historical experimental studies are utilized. Another critical area is the determination of the appropriate thermophysical properties of the fluid under investigation. Then, the solutions to the governing equations, alongside experimental studies, are presented graphically. These analyses are extended to the sensitivities of the dependent variables to the independent variables within the boundaries of interest. These sensitivity analyses narrow the field and range of independent variables that should be focused on during the engineering design process.

Acknowledgments

About the Author

M. Kemal Atesmen completed his high school studies at Robert Academy in Istanbul, Turkey in 1961. He received his BSc degree from Case Western Reserve University, his MSc degree from Stanford University, and his PhD from Colorado State University, all in mechanical engineering. He is a life member of ASME. He initially pursued an academic and an industrial career in parallel, and became an associate professor in mechanical engineering before dedicating his professional life to international engineering management and engineering project management for 33 years. He helped many young engineers in the international arena to bridge the gap between college and professional life in the automotive, computer component, data communication, and offshore oil industries.

He has published seven books, 16 technical papers, and four patents. His books are: *Global Engineering Project Management* (CRC Press, 2008); *Everyday Heat Transfer Problems – Sensitivities to Governing Variables* (ASME Press, 2009); *Understanding the World Around through Simple Mathematics* (Infinity Publishing, 2011); *A Journey Through Life* (Wilson Printing, 2013); *Project Management Case Studies and Lessons Learned* (CRC Press, 2015); *Process Control Techniques for High Volume Production* (CRC Press, 2016); and *Engineering Management in a Global Environment: Guidelines and Procedures* (CRC Press, 2017).

Introduction

In this book a wide range of 24 practical fluid mechanics problems that include heat transfer and mass transfer are investigated. The approach to problem solutions starts with the applicable basic laws of fluid mechanics, heat transfer, and mass transfer. These basic laws are the conservation of matter, the conservation of momentum, the conservation of energy, and the second law of thermodynamics. Each problem solution starts with the simplifying engineering assumptions and identifies the governing equations and dependent and independent variables. In some cases, where solutions to basic equations are not possible, historical experimental studies are utilized. Another critical area is the determination of the appropriate thermophysical properties of the fluid under investigation. Then, the solutions to the governing equations, alongside experimental studies, are presented graphically. These analyses are extended to the sensitivities of dependent variables to independent variables within the boundaries of interest. These sensitivity analyses narrow the field and range of independent variables that should be focused on during the design process.

The development of fluid mechanics started with the well-known law of Archimedes regarding the buoyancy of submerged bodies in the third century BC. After Newton's laws of motion were introduced, Bernoulli introduced his fluid flow equations for frictionless flow under gravity forces during the eighteenth century. Fluid flow equations, including shear forces due to viscosity, were introduced in the nineteenth century by Navier–Stokes. During the same century, Reynolds differentiated between laminar and turbulent flow regimes. Reynolds named the most important dimensionless group in fluid mechanics: the Reynolds number, the ratio of inertia forces to viscous forces. At the beginning of the twentieth century, Prandtl observed the changes in flow close to a solid boundary, namely the boundary layer. Many engineers, physicists, and mathematicians tried to solve the Navier–Stokes boundary layer equations in laminar and turbulent flow regimes under every conceivable condition for internal and external flows, and tried to verify these solutions with experiments. As computers' speed and memory capacity advanced, so did the solutions to the Navier–Stokes equations and the field took a new name: "computational fluid mechanics."

Another significant portion of fluid mechanics is the thermophysical properties of fluids, such as density, viscosity, surface tension, and so on under different temperatures and pressures. Historically, these thermophysical properties for different fluids were determined experimentally as the need arose.

I chose a wide variety of simple and fun problems in this book in order to give readers an insight into different approaches to a solution in fluid mechanics, heat transfer, and mass transfer. The sensitivities of the dependent variables to the governing independent variables are investigated under appropriate physical conditions.

Chapter 1 is about draining fluid from a tank, which uses Bernoulli's equation, namely the conservation of mechanical energy along a streamline in a steady flow, along with the experimentally determined discharge velocity coefficient from the discharge hole.

Chapter 2 treats the vertical rise of a weather balloon. Several assumptions are made by neglecting the effects of wind, humidity, clouds, thermals, reduction in gravity, Coriolis forces, and so on, in order to simplify the problem. Then, Archimedes' buoyancy law is used, along with the ideal gas law, all the way through the upper stratosphere.

Chapter 3 treats the stability of a right circular cone-shaped object floating in water. Again, Archimedes' buoyancy law is used to find the tipping conditions for the cone. Similar applications can be formulated for any object floating on the surface of a fluid.

In Chapter 4 the wind drag forces acting on a person are investigated. All or some of the wind's kinetic energy is converted into pressure energy as a person tries to stagnate the oncoming wind. The Bernoulli equation is applied to determine the wind drag forces on people with different frontal areas. The well-known Du Bois body surface area formula is utilized as a function of the person's height. Also, for human beings, an approximate experimental drag coefficient of unity is used.

Chapter 5 investigates a limiting case for the Navier–Stokes equations, namely creeping flow past a sphere for different viscosity fluids. During the nineteenth century, Stokes found an exact solution for the Navier–Stokes partial differential equations for a steady, incompressible, and creeping flow past a sphere. Here I expand his work to the sensitivities of the dependent variables, such as the sphere's fall velocity and its diameter, to the governing independent variables.

In Chapter 6 the Venturi meters that are used in pipes as flow meters for incompressible fluids are analyzed. In this analysis, a steady, non-viscous and irrotational flow is assumed and again the Bernoulli principle is utilized, along with the conservation of volume flow rate. Venturi meters have been used for water and for waste water volume flow rate measurements for centuries. These gages use a converging and diverging nozzle connected in-line with a pipe. For measurement of the pressure drop in the converging nozzle, the ends of a U-tube partly filled with a measurement fluid of known density higher than that of water are attached to

the upstream of the converging nozzle and to the throat area of the nozzle. There is always a correction factor, called the coefficient of discharge, between the theory and the real flow rate through the Venturi meter. The coefficient of discharge depends on the size, shape, and friction encountered in the Venturi meter.

Chapter 7 analyzes the surface shape of a fluid in a rotating cylindrical tank. In this analysis, the surface tension at the fluid's free surface and the viscous forces between the fluid and the walls of the tank are neglected. Only two forces acting on a fluid's surface particle are considered, namely the gravity force which draws the particle in the downward direction and the centrifugal force which draws the particle away from the center of rotation. Also, the spillover rotational speed is determined.

Chapter 8 investigates a pin floating on the surface of a liquid due to surface tension. Cohesive forces among the liquid molecules close to the surface of a liquid cause the surface tension phenomenon. The surface molecules of a liquid do not have similar molecules above them. As a result, these surface molecules exert greater cohesive forces on the same molecules below the surface, and those next to them on the surface. These excessive cohesive forces of the surface molecules have a tendency to contract to form a membrane-like surface and minimize their excess surface energy. The maximum pin diameters that surface tension forces will hold on different liquid surfaces were determined.

Chapter 9 tackles the steady-state behavior of small raindrops or drizzles. Mist and wind effects are neglected. Only raindrops of spherical shape are considered. For a small raindrop with diameter less than 2 mm, the gravity force balances the drag force, while neglecting the atmospheric air's buoyancy force as the raindrops fall to the Earth's surface. Experimental data is used for the drag coefficient of spherical liquid particles falling in air.

In Chapter 10 I investigate one of the most important performance parameters for different aircraft, namely their range, using Brequet's range formula. In this analysis I do not consider an aircraft's takeoff, climb, descent, and landing conditions. For aircraft with turbofan jet engines, I detail Airbus A380 and Boeing 737-800 cruising conditions. For a propeller-driven aircraft, I analyze the flight of the *Spirit of St. Louis*.

Chapter 11 treats the design of a water clock. To measure time, quite a variety of water clocks have been designed and used by humans for more than 6000 years. In this problem I analyze two water clock designs that have water flowing out of a drain hole at the bottom center of a vessel. In the first case a circular vessel's radius varies linearly with respect to time. In the second case the vessel radius is constant (i.e. a cylindrical vessel).

Water's potential energy stored behind a dam in a reservoir has been used very effectively for many decades for a spin water turbine that activates a generator to produce electricity. In Chapter 12 I apply the first law of thermodynamics for open systems, mostly identified as the modified Bernoulli equation, to sensitivities of design parameters for a water turbine system. The hydraulic diameter concept is

utilized for non-circular internal flows. Friction factors are obtained from a Moody diagram, including the water tunnel's wall surface roughness.

Centrifugal acceleration forces have been used very effectively to separate solid particles from fluids or to separate different density fluids. In Chapter 13 I investigate the separation of particles in a fluid flow by centrifugal forces in a centrifuge shaped like a concentric cylinder. The fluid, along with spherical particles of different diameters, enters the centrifuge at the bottom of the centrifuge and high centrifugal forces due to a rotating inner cylinder will separate out the particles from the fluid. All particles with diameters greater than a critical diameter will adhere to the walls of the stationary outer cylinder while the fluid exits the centrifuge at the top. The exiting fluid will contain only particles with diameters smaller than the critical diameter. In this problem I use the drag forces applied to the spherical particles in a creeping flow, namely I have to make sure that the inertial forces acting on a spherical particle are much smaller than the viscous forces.

Chapter 14 deals with the analysis of a simple carburetor. The first law of thermodynamics for a perfect gas in a steady, one-dimensional and compressible flow is used to simulate the air flow in a simple carburetor. The fuel entering the throat area of the carburetor is treated as an incompressible fluid using Bernoulli's equation. The carburetor's most important dependent variable (the air–fuel ratio)'s sensitivity to independent variables is determined.

Chapter 15 analyzes properties such as the temperature, pressure, and density of an ideal gas flowing through nozzles and diffusers. Analyzing the flow of compressible fluids such as air requires use of the first and second laws of thermodynamics. The mass flow rate of an ideal gas is determined as a function of the Mach number, while assuming constant specific heats and an isentropic flow process.

Chapter 16 investigates the head loss sensitivities due to friction to the governing independent variables such as pipe diameter, fluid kinematic viscosity, and volume flow rate for steady, incompressible, and fully developed laminar flows through a straight pipe of constant cross-section. Simplified Navier–Stokes equations in cylindrical coordinates are used, by assuming that the velocity components in the tangential and radial directions are zero. The only velocity component of the fluid flowing in the pipe is in the axial direction, and it is a constant; this velocity component only varies in the radial direction. Also, the pressure gradient along the axial direction of the pipe is a constant.

Chapter 17 determines the power input requirements for a water supply line from a lake to a factory for different volume flow rates and different pipe internal diameters using the first law of thermodynamics. Friction factors are extracted from Moody diagrams for turbulent pipe flows for different Reynolds numbers and different pipe wall roughness. The head losses due to bends, valves, couplings, elbows, water entrance and exit are obtained from the manufacturer for each component. These head losses are obtained experimentally and the results depend on the Reynolds number and the component's diameter.