Fluid Mechanics Theory and Applications

Authors:
Muhammad Noor Afiq Witri Muhammad Yazid[1], Ummikalsom Abidin[2], Fazila Mohd Zawawi[3], Mohamad Nur Hidayat Mat[4], Zulhanafi Paiman[5]
Email:
mnafiqwitri@utm.edu.my[1], ummi@utm.edu.my[2], fazilamz@utm.edu.my[3], mn.hidayat@utm.edu.my[4], zulhanafi.paiman@utm.edu.my[5]

Abstract: Fluid mechanics is a fundamental branch of physics and engineering that plays a crucial role in various industries. Understanding the behavior of fluids is essential for the design and operation of countless system and technologies; from the efficient transport of water through pipelines to the aerodynamics that propel aircraft through the skies.

It is with great pleasure that we introduce "Fluid Mechanics: Theory and Applications," a comprehensive textbook writen to provide you with a deep understanding of the fascinating world of fluid mechanics. With this textbook, our aim is to bridge tha gap between theory and practical applications, making this complex subject accessible and engaging. In addition, this book has been born out of a desire to offer a valuable resource to students, researchers and professionals seeking to master the principles of fluid mechanics.

This book is based on experience in teaching and researching fluid mechanics by the authors in the past at Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM) as well as other institute of higher learning. Our passion for this subject have driven us to find innovative ways to convey its concepts to learners. This book is the culmination of that journey, and we hope it serve as your guiding light.

Keywords: Eulerian, jet velocity, lagrangian, pump, runner

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Authors: Muhammad Noor Afiq Witri Muhammad Yazid, Ummikalsom Abidin, Fazila Mohd Zawawi, Mohamad Nur Hidayat Mat, Zulhanafi Paiman

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PREFACE

Background

Fluid mechanics is a fundamental branch of physics and engineering that plays a crucial role in various industries. Understanding the behavior of fluids is essential for the design and operation of countless systems and technologies; from the efficient transport of water through pipelines to the aerodynamics that propel aircraft through the skies.

It is with great pleasure that we introduce "Fluid Mechanics: Theory and Applications," a comprehensive textbook designed to provide you with a deep understanding of the fascinating world of fluid mechanics. With this textbook, our aim is to bridge the gap between theory and practical applications, making this complex subject accessible and engaging. In addition, this book has been born out of a desire to offer a valuable resource to students, researchers, and professionals seeking to master the principles of fluid mechanics.

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Organization

Our exploration of fluid mechanics begins with Chapter 1, which provides a basic introduction to fluids, units and fluid properties. In Chapter 2, we explore the equilibrium of fluids at rest, unraveling the forces and pressures that shape their behavior. Chapter 3 introduces the dynamic behavior of fluids, setting the stage for understanding flow phenomena. Chapters 4 and 5 address the governing equations of fluid flow, equipping you with the tools to analyze and solve real-world fluid dynamic problems. We move on to practical applications in Chapters 6, where we unveil the secrets of fluid transport in pipelines. Chapter 7 introduces the Buckingham Pi theorem for dimensional analysis and the art of making meaningful comparisons between different fluid systems. Chapter 8 explores the thin layer of fluid adjacent to surfaces, a crucial concept for understanding drag while Chapter 9 covers two-dimensional potential flows and provides introductory concept for understanding lift. Chapters 10 is devoted to the fascinating world of fluid machinery where we explore the functioning of pumps and turbines. Finally, we journey into the realm of high-speed gases in Chapter 11, exploring the intricacies of compressible fluids, such as those found in rocket engines and supersonic aircraft.

Authors posing in front of a wind turbine at Kampung Sungai Melayu, Johor

CHAPTER 1

FLUID PROPERTIES

At the end of the chapter, you will be introduced to:

- the basic concepts of fluid mechanics,
- the different phase of matters,
- relevant units and dimensions commonly used in fluid mechanics,
- the concept of continuum,
- the concept of viscosity, Newtonian, and non-Newtonian fluid, and
- the concept of density, compressibility, and surface tension.

1.1 Fluid Mechanics

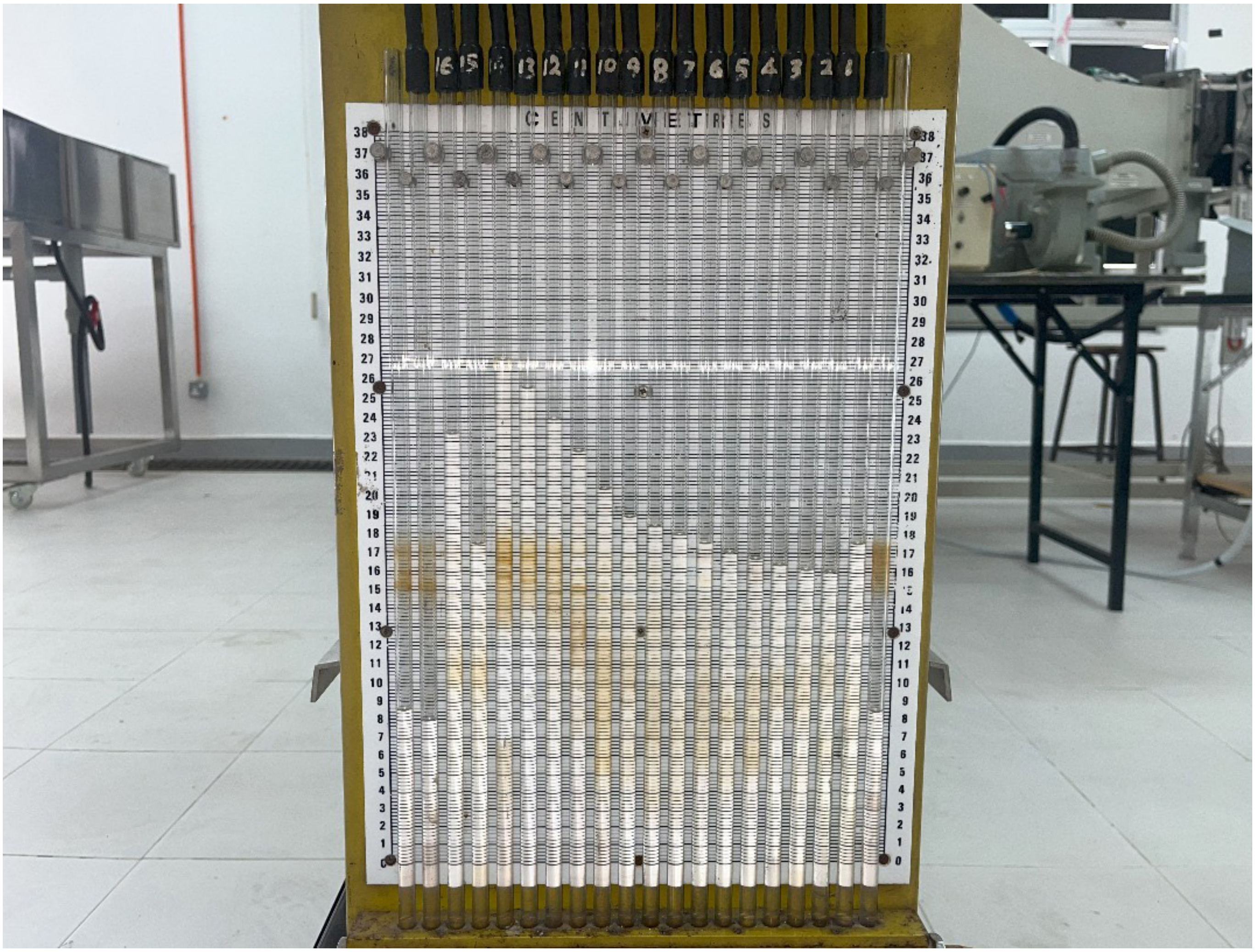
There are three main phases of matters – solid, liquid and gas (including steam). A simpler category would be just two - solid and fluid, as fluid includes both liquid and gas. We cannot run away from dealing with fluids in our life. Our body constitute of more than 70 percent liquid. The core of our living, blood, is a very important fluid in our body. The air that we breathe is also part of fluid. Can you imagine how life would be without air and water?

Look around us, what do you see? You will see many equipment uses fluid as their medium. Pump, turbine, cars, ventilators, and many other receive fluids and convert it to something else that is more useful.

Since fluid is very important in our lives, we need to understand more about fluid. By understanding how fluid works, we can optimize the operation of the equipment that uses fluid. We can also design better equipment with deep knowledge of fluid mechanics.

Fluid mechanics is a branch of mechanics that deals with fluid when it is stationary (fluid statics) and when it is in motion (fluid dynamics) as well as its interactions with solid or other fluid at the boundaries.

- ***The study of galaxy and planets*** – galaxies are masses that has gravity, and it consists of very viscous gasses.



This manometer, featured in the Fluid Mechanics lab at the Faculty of Mechanical Engineering, UTM, uses water columns of different heights to measure pressure. The varying elevations of the water columns indicate the pressure differences within the fluid system.

CHAPTER 2

FLUID STATICS

At the end of this chapter, you will be able to:

- explain the concept of fluid statics
- identify pressure and manometer with their applications
- calculate forces on submerged surfaces
- analyze buoyancy and stability of floating objects

The analysis on fluids can be categorized into two: statics and dynamics of fluids. We will explore the statics of fluids first and move to the dynamics of fluids in the later chapter. Statics of fluid is defined as the conditions where the fluids are free from any shear stresses. A moving fluid without the presence of shear stresses is also categorized as statics of fluids.

2.1 Pressure in Statics of Fluid

In the absence of shear stresses, the only force that is present in the fluid is normal force as shown in Figure 2.1. If this force is acting on a surface dA, we can define pressure to be

$$P = \frac{dF}{dA} \tag{2.1}$$

and integrating this over a finite surface A, will yield

$$P = \frac{F}{A}$$

Eulerian description is a technique for observing particular quantities at fixed points in space. An analogy can be drawn to monitor a specific region in the movement of a duckling

CHAPTER 3

FUNDAMENTALS OF FLUID FLOW

At the end of this chapter, you will be able to:

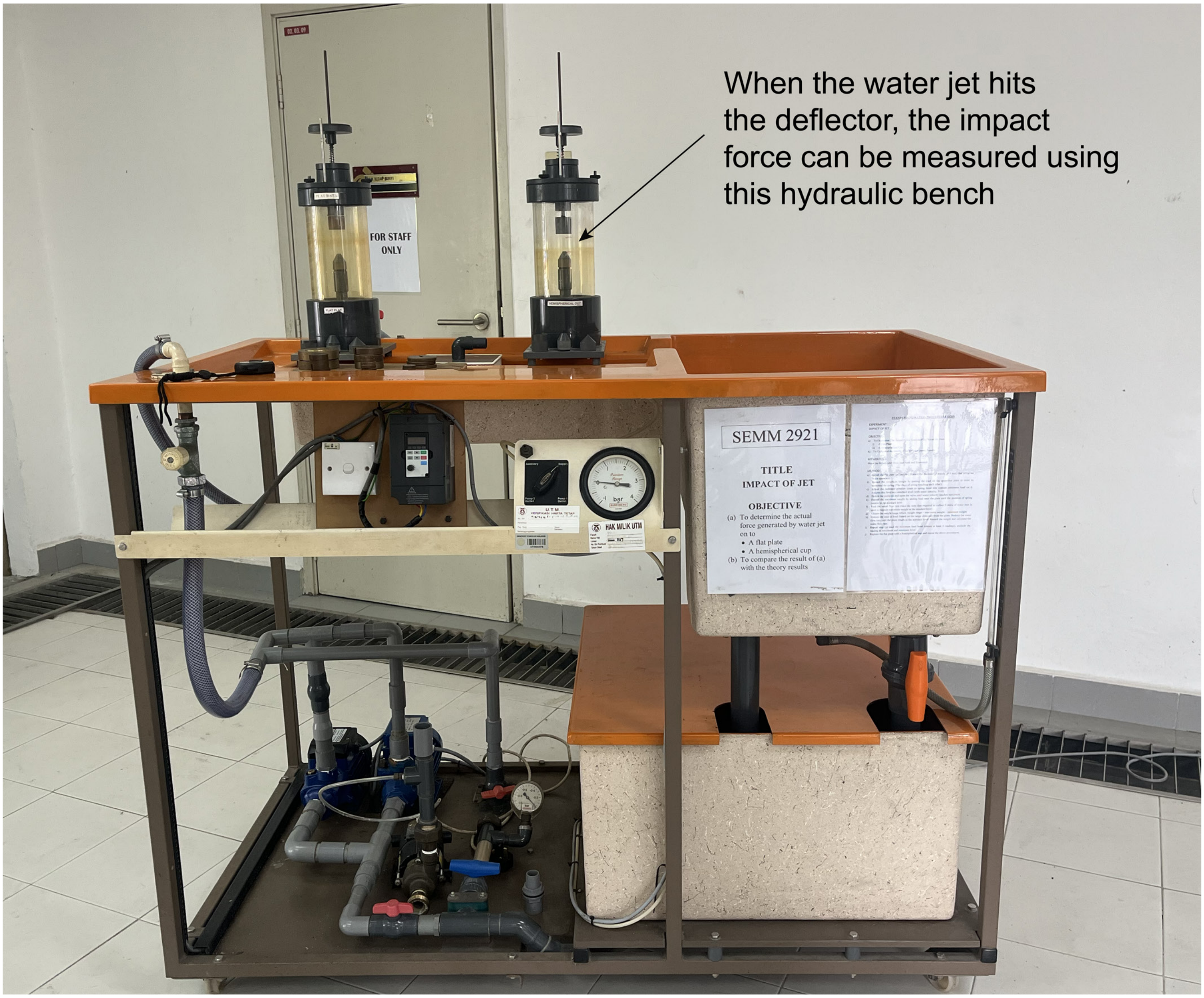
- understand the fundamental theory of fluid dynamic and its basic definition.
- recognize the type of fluid flow analysis.
- learn the basic laws of fluid dynamics and identify the method to represent fluid flow.
- analyse fluid dynamics and derive differential equation.

3.1 Introduction

In engineering practice, we can see many situations involving moving fluids that are categorized in fluid dynamics. Therefore, the knowledge of fluid statics alone is insufficient for engineering students. The study of stationary or static fluids is simpler than the study of dynamic fluids. This is because a stationary fluid analyses static body. However, the analysis for fluid dynamics discussed in this chapter is sometimes similar to the analysis of a solid body.

Fluid dynamics is the study of the movement or flow of a fluid. As fluids move, the shear forces that are negligible in static fluids now become important. Fluid inertia must also be considered. Although fluid dynamics problems, in general, can be represented by mathematical equations. However, only a few simple cases can be solved accurately. The three obstacles that make it difficult to solve the problem of moving fluids are flow geometry, viscosity, and turbulent conditions.

Many engineering problems involve fluids flow across solid boundaries. While solid boundaries sometimes have complex geometric shapes. In the automotive field, an example is flow through carburettors and valves. Viscosity makes the mathematical equation of a flowing fluid nonlinear. If the viscosity is ignored, the resulting equation is simpler but does not represent the actual flow conditions. Turbulence in turn causes the velocity of fluid flow to be volatile and destabilizes the flow of fluid. Based on the factors mentioned, many assumptions are made to solve the problem of moving fluids. The assumptions made help facilitate fluid flow even if the resulting results are not as accurate as expected.



The impact force from the jet can be calculated using the Reynolds Transport Theorem (RTT)

CHAPTER 4

CONTROL VOLUME ANALYSIS

At the end of this chapter, you will be able to:

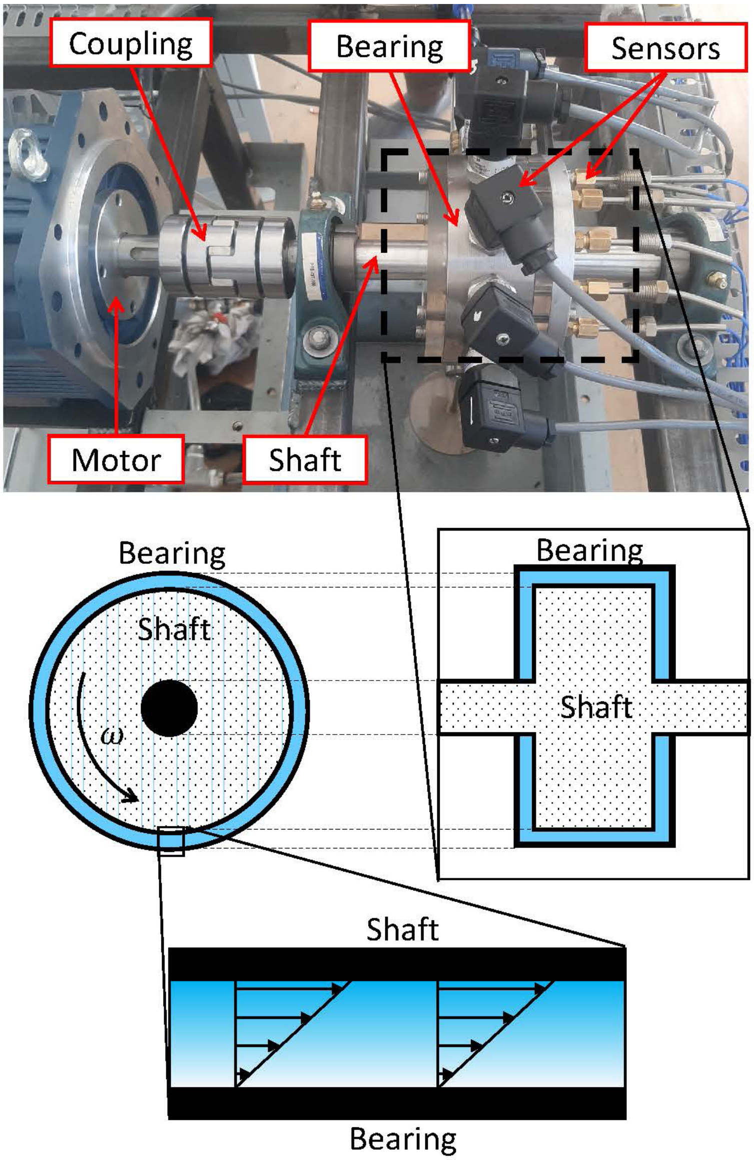
- define the control volume method.
- derive Bernoulli's equation using integral form.
- understand basic Navier – Stokes equation.
- derive Bernoulli's equation using elemental method.
- derive conservation of mass, momentum and energy using Reynold Transport Theorem.

4.1 Introduction to Control Volume

In this section, we will see different approaches analysing fluid dynamics problems from two perspectives: differential and integral. A brief description of both approaches is as follows.

Differential method - this method focuses on a detailed study of the points contained in the stream flow or fluid domain. The result of this approach is subsequently solved in certain ways. The solution of the differentiation equation can be done by two methods, namely analysis and numerical. The analysis method requires that the boundary conditions refer to the problem to be solved. If the resulting differential equation is quite complex and impossible to solve by the analysis method, the numerical method may be used. In the numerical method, the solution for the differential equation is estimated with the finite difference, the finite volume or the boundary element.

Integral method or also known as Control Volume Method is a technique to emphasize the use of basic law on only a part of the moving fluid. The control volume definition is a volume assigned to a particular coordinate system in a stream for flow analysis. The concept of control volume gives the focus on the inlet, the outlet part, and the change inside the volume of the control itself. The basis of the control volume is the conservation of mass. A simple analogy of the control volume can be stabilized by looking at the phenomena of the vehicle moving on the road. Observe a



The differential equations to be discussed in this chapter find practical application, such as in determining the velocity profile of lubricant within a journal bearing. As illustrated in the above, the journal bearing rig at the Tribology Lab, E07, Faculty of Mechanical Engineering, UTM, serves to support rotating components like shafts. However, for more intricate configurations, solving these equations necessitates advanced computational fluid dynamics (CFD) techniques, employing numerical methods like the finite difference method and finite volume method.

CHAPTER 5

DIFFERENTIAL ANALYSIS

At the end of this chapter, you will be able to:

- derive the differential form of the continuity equation for incompressible flow using Cartesian and polar coordinates.
- derive the Navier-Stokes equations for Newtonian and incompressible flow using Cartesian coordinate.
- define the required boundary and initial conditions for determining the velocity and pressure distributions within a fluid flow.
- demonstrate how simple fluid flow problems are solved using differential form of fundamental laws.
- transform differential equations into dimensionless form.

5.1 Introduction

In Chapter 4, we developed integral equations for analyzing fluid flow by applying integral form of the conservation law within an enclosed control volume. Integral equations can be valuable and applicable in cases where the focus is on the general characteristics of a flow, without needing extensive information on variations in flow within the control volume. There are many situations where detailed point-by-point data of the flow field are important for engineers and scientists. Unfortunately, the finite control volume method is limited in its ability to provide intricate flow details because the inner region of the control volume is regarded as a "black box". For example, the aerodynamic drag of an airfoil that is partly due to the pressure difference it created when the airfoil is flying can be estimated using the integral equation, provided that we know the detailed pressure distribution. However, the same approach cannot provide information on the pressure distribution that produced drag on the airfoil (see Figure 5.1).

In this chapter, we focus on understanding the fundamental principles governing fluid flow through single and multiple pathways, as well as various piping arrangements. Through your exploration with the apparatus in our fluid laboratory, you'll conduct experiments to observe how different factors such as pipe diameter, flow rate, and pipe fittings influence flow behavior including pressure loss, head loss, major loss, minor loss, and contribute to energy losses within the system. By analyzing these phenomena, you'll gain valuable insights into optimizing piping designs for efficiency and performance across a diverse range of engineering applications.

CHAPTER 6

FLOW IN PIPES

At the end of this chapter, you will be able to:

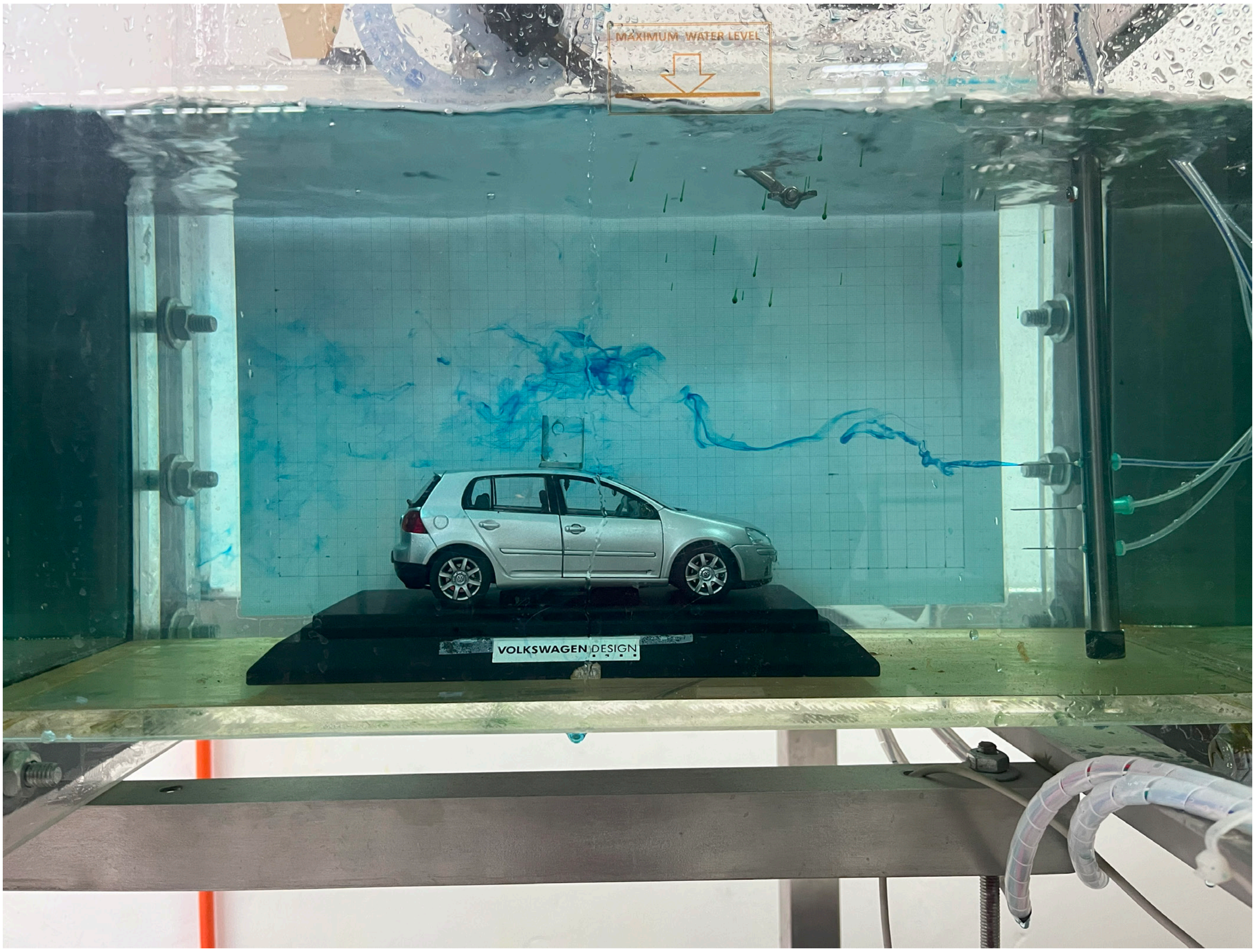
- classify a few types of flow in the piping system
- calculate the velocity of flow in the piping system
- determine the minor and major losses in both laminar and turbulent flow in the piping system
- use the Moody Chart
- analyse the laminar and turbulent flow in pipe
- analyse the piping system with multiple paths

6.1 Introduction

One of the important considerations in analyzing a piping system is the depletion of energy, often known as pressure drop. This is significant because if there is a pressure decrease, the fluid in a pipe may not be able to reach its intended destination. The pressure in the pipe flow is diminished due to the following:

- Changes in height (elevation).
- Changes in velocity due to variations in cross-sectional area.
- Friction and viscosity.
- Alterations in channel shape.

We cannot ignore the effects of changes in elevation and velocity. However, under certain conditions, the impacts of friction or viscosity may be negligible. For example, this holds true for flows in short distances of pipe. Nevertheless, if the flow travels through a long-distance pipe – such as water distribution from a reservoir to houses – then friction and viscosity must be taken into consideration.



Scaled model provides convenient and cost-effective ways of analyzing aerodynamics of any engineering marvels as compared to prototype. The reduced size car model placed in water tunnel faculty at Fluid mechanics laboratory produced comparable phenomenon as in full scale as long as the similarity criteria are fulfilled.

CHAPTER 7

DIMENSIONAL ANALYSIS AND SIMILARITY

At the end of this chapter, you will be able to:

- derive the dimensionless parameters from the relevant parameters of fluid mechanics problem using dimensional analysis of Buckingham Pi Theorem.
- solve fluid mechanics problem related to modelling and similitude.

7.1 Introduction

Dimensional analysis is used in science and engineering for checking consistency of physical equations, validating experimental results, and deriving relationships between physical quantities. In addition, dimensional analysis is a powerful tool in understanding the physical laws that govern and predict the behaviour of various engineering systems. To do the prediction, dimensional analysis is used to derive the dimensionless parameters. Common dimensionless parameters include Reynolds number in fluid dynamics, Mach number in aerodynamics, and the Froude number in hydraulics. In an experiment, dimensional analysis correlates selected variables into dimensionless parameters. The correlations are based on the concept that physical quantities possess dimensions. The fact that physical laws will not be changed if we change the units of measuring dimensions can also be used to improve our experimental works. Consider, for instance, the challenge of conducting experiments on a ship that sails in the sea. Direct experimentation at sea is expensive, as is replicating the exact ship size in a laboratory setting. However, through dimensional analysis, correlations between laboratory experiments and real-world sea conditions can be established. For a practical and economical execution of experiments, small-scaled model is used and flow parameters to simulate sea condition is adjusted. Thus, by constructing a scaled-down model of a ship and conducting experiments in a laboratory environment, results closer to the real sea condition can be obtained.

Let us look at the dimensions that are commonly being used. The fundamental or primary dimensions are length (L), time (T), mass (M) and temperature (t). The common derived dimensions are density, viscosity, acceleration, velocity, pressure,

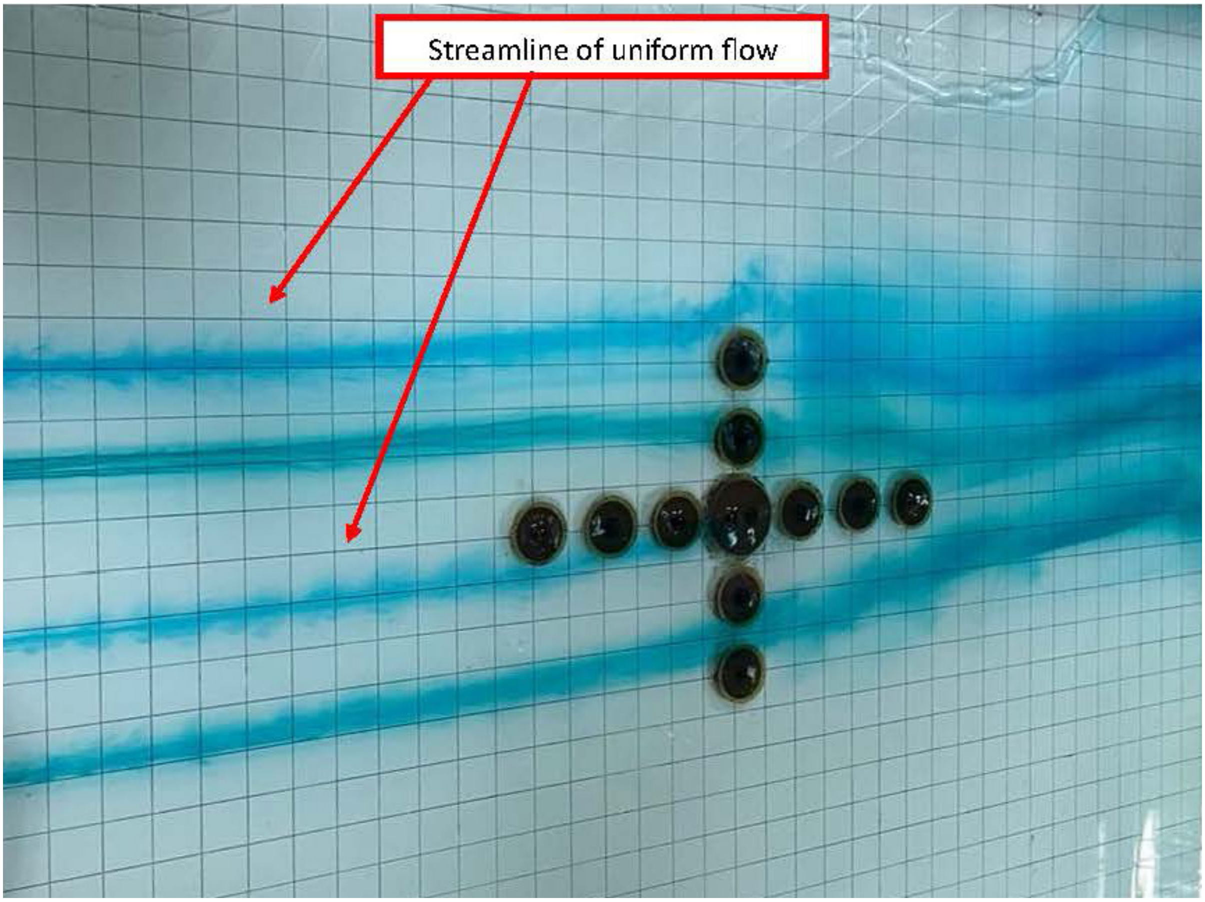
Boundary layer ceased to exists over the airfoil at high angle of attack. The test was performed in wind tunnel at Fluid mechanics lab (Source: Fluid Mechanics Lab, UTM).

CHAPTER 8

BOUNDARY LAYER THEORY

In this chapter, we will look at the effects of friction that exist in a flow when passing through a surface. In short, this effect will cause the occurrence of velocity profile and subsequently form a boundary layer. At the end of this chapter, students will able;

- to explain the mechanism of boundary layer formation and the importance of studying this chapter.
- to explain what is meant by boundary layer thickness, displacement thickness and momentum thickness.
- to calculate the values of boundary layer thickness, displacement thickness, momentum thickness, drag force and drag coefficient by using Von-Karman and Blasius equations.
- to solve the turbulent boundary layer problem only.
- to solve the problem of boundary layers that contain laminar and turbulent boundary layers.



In this chapter, we focus on understanding ideal flow theory and its applications. Through your fluid laboratory apparatus, you'll observe key principles such as streamline patterns, velocity profiles, and pressure distributions, bridging theory with practical understanding. Ideal flow theory serves as a launchpad for exploring real-world engineering challenges and scientific inquiries, making it an essential tool in your journey through fluid mechanics.

CHAPTER 9

IDEAL FLOW THEORY

At the end of this chapter, you will be able to:

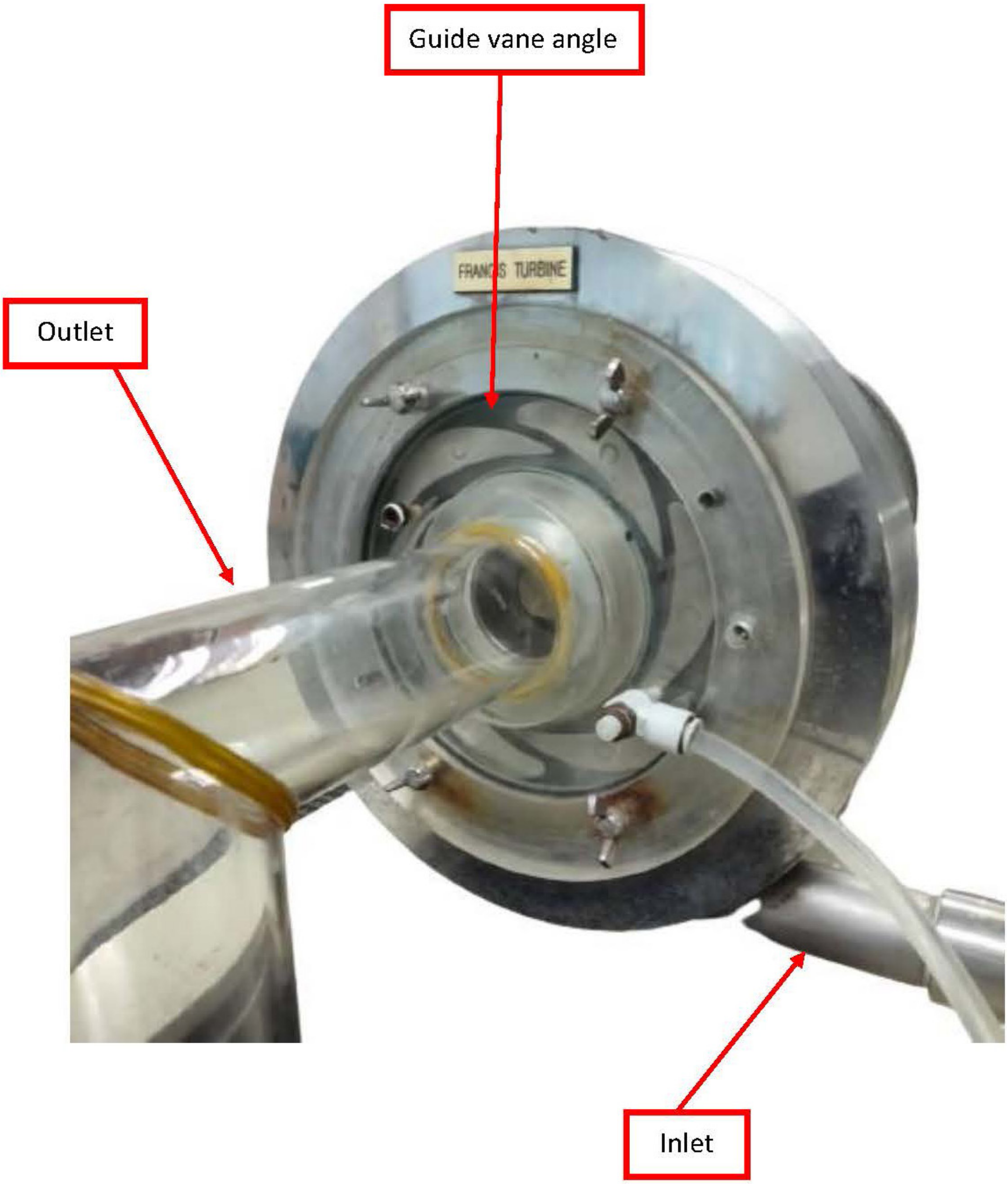
- formulate stream function and velocity potential equations for basic flows, as well as combinations of these basic flows
- conduct detailed analysis to obtain the pressure and velocity of these flows
- sketch streamlines and equipotential lines of these flows

9.1 Introduction to Ideal Flow Theory

Fluid dynamics are integral to our understanding of the engineering marvels that shape our modern lives. The Navier-Stokes equation, as explored in Chapter 5 (Differential Analysis), offers detail insight into the intricate behaviour of fluid dynamics. However, this approach can be tedious to solve, considering that the viscosity and compressibility of the fluid may complicate the analysis. Ideal flow, also known as potential flow, provides a simplified way for comprehending fluid behavior, without the constraints of viscosity and compressibility.

For wall bounded flow at high Reynolds number, viscous effects are confined within the boundary layers adjacent to wall surfaces. Beyond these layers, the flow can be considered nearly inviscid flow, characterized by the absence of viscosity effects. Hence, it is often reasonable to assume the fluid as ideal, as long as the flow remains incompressible. Ideal flow theory provides a good approximation to the actual flow, enabling us to predict pressure distributions on the surfaces, thereby giving a good estimate of aerodynamic behaviours.

This theory, despite its inherent simplifications, serves as a powerful tool for engineers and scientists alike. It offers simpler way of examining and understanding a multitude of fluid flow phenomena, from the simple flow of water inside pipe system to the elegant flow feature of air around an airfoil. In the subsequent sections, we will introduce this approach to provide insight into how these methods are employed in engineering analysis. We will commence by elucidating the process of



This chapter delves into understanding how turbines perform and their crucial role in converting water power into electricity. Through experiments and theory, we will examine turbine efficiency, power output, and flow control. Using the equipment in our fluid lab, you will investigate how changes in flow rate, head, applied load, and guide vane angle affect turbine performance. By understanding these factors, you'll learn to optimize turbine design and operation for efficient hydropower generation.

CHAPTER 10

FLUID MACHINERY

At the end of this chapter, you will be able to:

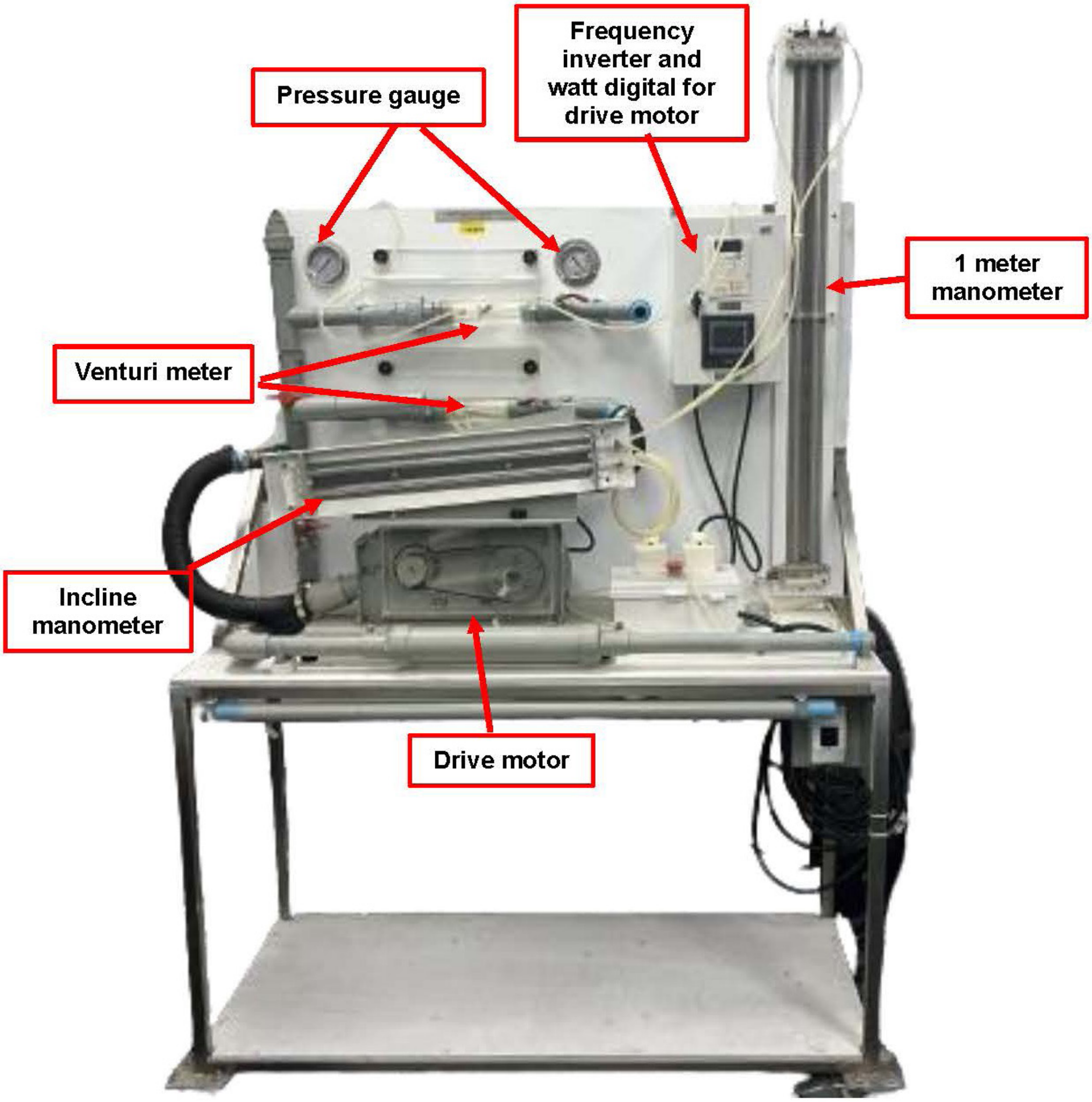
- understand the working principles and applications of turbomachines
- sketch velocity diagram for turbomachines
- conduct detailed analysis to obtain the power output of turbomachines, as well as their efficiencies

10.1 Introduction

In the simplest term, turbomachinery is a rotating machine that either supply or extract energy from the fluid. There are many types of turbomachines depending on the mechanisms, as well as the medium they are working on. Devices that are supplying energy to the fluid are called pumps or compressors. When the working medium is liquid, we call it pumps and when the working medium is gas, we call it compressors. Meanwhile, devices that extracts energy from the fluid is called turbines.

In the Malaysian context, turbomachines are the driving force in a few critical applications. With a nation blessed with abundant water resources, centrifugal pump serves as the lifeline of irrigation systems, ensuring agricultural productivity and food security. The hilly terrain of Malaysia presents the perfect backdrop for hydroelectric power generation, where Francis turbine and Pelton wheel efficiently convert water's energy into electricity, supplying power to homes and industries.

Based on the above statement, it can be said that turbomachines represent a diverse family of mechanical devices designed to perform various tasks either to supply kinetic and potential energies into or from the fluid flow. In this chapter, we will delve into three turbomachine categories: centrifugal pump, Francis turbine, and Pelton wheel.



The compressible flow theory discussed in this chapter can be validated by comparing the experimental data obtained from compressible flow experiments. The test rig, as illustrated above, serve as a means to analyse compressible (pressurized) flow behaviour through venturi tubes, contraction areas, and bends. It is located at the Fluid Laboratory, E07, Faculty of Mechanical Engineering, UTM. This experiment helps researchers and students to understand the fundamental principles of fluid mechanics in regimes where the compressibility of the fluid becomes significant. These principles find applications in various fields including aerospace engineering, turbomachinery design, and high-speed propulsion systems.

CHAPTER 11

COMPRESSIBLE FLOW

At the end of this chapter, you will be able to:

- outline the necessary equations for addressing uniform-flow issues in compressible gas dynamics.
- construct a comprehensive set of equations that dictate isentropic flow in a nozzle.
- cover the concept of a normal shock wave.
- provide numerous engineering application that uses the theory of isentropic flow and flow through normal shockwave

11.1 Introduction

We define the compressibility of a fluid as the degree to which its density changes in response to a given pressure change. Generally, gases are highly compressible, while liquids exhibit minimal compressibility. Traditional studies of incompressible fluid mechanics focus on flows where pressure and kinetic energy variations are minimal, rendering any resulting changes in density and temperature inconsequential to the flow. Conversely, gas dynamics is the field that examines compressible flows, where velocities approach or surpass the speed of sound, leading to notable alterations in temperature and pressure.

One of the clearest uses of compressible fluid flow principles is in the design of high-velocity aircraft, which continues to be a significant area of application. Understanding compressible fluid flow is also essential in the design and functioning of various engineering devices. These applications are illustrated in Figure 11.1.

Test Your Understanding #11.1

How do you perceive the influence of compressibility on the shape of an aircraft's nose?

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FLUID MECHANICS

THEORY AND APPLICATIONS

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