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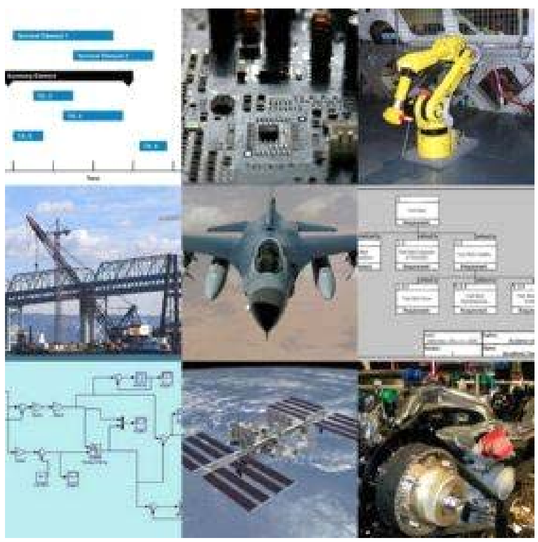

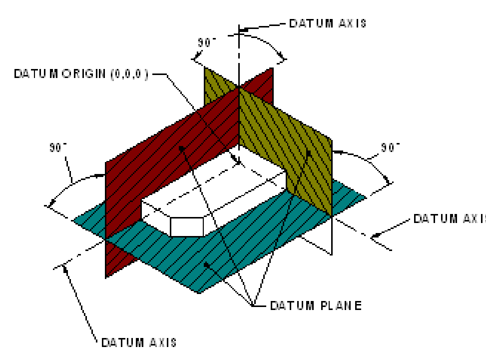

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# DOE FUNDAMENTALS HANDBOOK

## THERMODYNAMICS, HEAT TRANSFER, AND FLUID FLOW

## Volume 3 of 3

**U.S. Department of Energy** **FSC-6910**
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# ABSTRACT

The *Thermodynamics, Heat Transfer, and Fluid Flow Fundamentals Handbook* was developed to assist nuclear facility operating contractors provide operators, maintenance personnel, and the technical staff with the necessary fundamentals training to ensure a basic understanding of the thermal sciences. The handbook includes information on thermodynamics and the properties of fluids; the three modes of heat transfer - conduction, convection, and radiation; and fluid flow, and the energy relationships in fluid systems. This information will provide personnel with a foundation for understanding the basic operation of various types of DOE nuclear facility fluid systems.

**Key Words:** Training Material, Thermodynamics, Heat Transfer, Fluid Flow, Bernoulli's Equation

# FOREWORD

The *Department of Energy (DOE) Fundamentals Handbooks* consist of ten academic subjects, which include Mathematics; Classical Physics; Thermodynamics, Heat Transfer, and Fluid Flow; Instrumentation and Control; Electrical Science; Material Science; Mechanical Science; Chemistry; Engineering Symbology, Prints, and Drawings; and Nuclear Physics and Reactor Theory. The handbooks are provided as an aid to DOE nuclear facility contractors.

These handbooks were first published as Reactor Operator Fundamentals Manuals in 1985 for use by DOE Category A reactors. The subject areas, subject matter content, and level of detail of the Reactor Operator Fundamentals Manuals was determined from several sources. DOE Category A reactor training managers determined which materials should be included, and served as a primary reference in the initial development phase. Training guidelines from the commercial nuclear power industry, results of job and task analyses, and independent input from contractors and operations-oriented personnel were all considered and included to some degree in developing the text material and learning objectives.

The *DOE Fundamentals Handbooks* represent the needs of various DOE nuclear facilities' fundamentals training requirements. To increase their applicability to nonreactor nuclear facilities, the Reactor Operator Fundamentals Manual learning objectives were distributed to the Nuclear Facility Training Coordination Program Steering Committee for review and comment. To update their reactor-specific content, DOE Category A reactor training managers also reviewed and commented on the content. On the basis of feedback from these sources, information that applied to two or more DOE nuclear facilities was considered generic and was included. The final draft of each of these handbooks was then reviewed by these two groups. This approach has resulted in revised modular handbooks that contain sufficient detail such that each facility may adjust the content to fit their specific needs.

Each handbook contains an abstract, a foreword, an overview, learning objectives, and text material, and is divided into modules so that content and order may be modified by individual DOE contractors to suit their specific training needs. Each subject area is supported by a separate examination bank with an answer key.

The *DOE Fundamentals Handbooks* have been prepared for the Assistant Secretary for Nuclear Energy, Office of Nuclear Safety Policy and Standards, by the DOE Training Coordination Program. This program is managed by EG&G Idaho, Inc.

# OVERVIEW

The *Department of Energy Fundamentals Handbook* entitled *Thermodynamics, Heat Transfer, and Fluid Flow* was prepared as an information resource for personnel who are responsible for the operation of the Department's nuclear facilities. A basic understanding of the thermal sciences is necessary for DOE nuclear facility operators, maintenance personnel, and the technical staff to safely operate and maintain the facility and facility support systems. The information in the handbook is presented to provide a foundation for applying engineering concepts to the job. This knowledge will help personnel more fully understand the impact that their actions may have on the safe and reliable operation of facility components and systems.

The *Thermodynamics, Heat Transfer, and Fluid Flow* handbook consists of three modules that are contained in three volumes. The following is a brief description of the information presented in each module of the handbook.

Volume 1 of 3

Module 1 - Thermodynamics

This module explains the properties of fluids and how those properties are affected by various processes. The module also explains how energy balances can be performed on facility systems or components and how efficiency can be calculated.

Volume 2 of 3

Module 2 - Heat Transfer

This module describes conduction, convection, and radiation heat transfer. The module also explains how specific parameters can affect the rate of heat transfer.

Volume 3 of 3

Module 3 - Fluid Flow

This module describes the relationship between the different types of energy in a fluid stream through the use of Bernoulli's equation. The module also discusses the causes of head loss in fluid systems and what factors affect head loss.

The information contained in this handbook is by no means all encompassing. An attempt to present the entire subject of thermodynamics, heat transfer, and fluid flow would be impractical. However, the *Thermodynamics, Heat Transfer, and Fluid Flow* handbook does present enough information to provide the reader with a fundamental knowledge level sufficient to understand the advanced theoretical concepts presented in other subject areas, and to better understand basic system and equipment operations.

**Department of Energy**
**Fundamentals Handbook**

# THERMODYNAMICS, HEAT TRANSFER, AND FLUID FLOW,
# Module 3
# Fluid Flow

# TABLE OF CONTENTS


LIST OF FIGURES . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . iv

LIST OF TABLES . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . v

REFERENCES . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . vi

OBJECTIVES . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . vii

CONTINUITY EQUATION . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1

Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1
Properties of Fluids . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2
Buoyancy . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 2
Compressibility . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3
Relationship Between Depth and Pressure . . . . . . . . . . . . . . . . . . . . . . 3
Pascal's Law . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7
Control Volume . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
Volumetric Flow Rate . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 9
Mass Flow Rate . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 9
Conservation of Mass . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
Steady-State Flow . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10
Continuity Equation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 11
Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

LAMINAR AND TURBULENT FLOW . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17

Flow Regimes . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
Laminar Flow . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
Turbulent Flow . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
Flow Velocity Profiles . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 18
Average (Bulk) Velocity . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 19
Viscosity . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 19
Ideal Fluid . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 19
Reynolds Number . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 19
Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 20

# TABLE OF CONTENTS (Cont.)

BERNOULLI'S EQUATION . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21

General Energy Equation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21
Simplified Bernoulli Equation . . . . . . . . . . . . . . . . . . . . . . . . . . . 22
Head . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23
Energy Conversions in Fluid Systems . . . . . . . . . . . . . . . . . . . . . . 23
Restrictions on the Simplified Bernoulli Equation . . . . . . . . . . . . . . . 25
Extended Bernoulli . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25
Application of Bernoulli's Equation to a Venturi . . . . . . . . . . . . . . . . 27
Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 30

HEAD LOSS . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31

Head Loss . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31
Friction Factor . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31
Darcy's Equation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 32
Minor Losses . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34
Equivalent Piping Length . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34
Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 36

NATURAL CIRCULATION . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37

Forced and Natural Circulation . . . . . . . . . . . . . . . . . . . . . . . . . 37
Thermal Driving Head . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37
Conditions Required for Natural Circulation . . . . . . . . . . . . . . . . . . 38
Example of Natural Circulation Cooling . . . . . . . . . . . . . . . . . . . . . 39
Flow Rate and Temperature Difference . . . . . . . . . . . . . . . . . . . . . 39
Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 40

TWO-PHASE FLUID FLOW . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 41

Two-Phase Fluid Flow . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 41
Flow Instability . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 42
Pipe Whip . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43
Water Hammer . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43
Pressure spike . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43
Steam Hammer . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 45
Operational Considerations . . . . . . . . . . . . . . . . . . . . . . . . . . . 45
Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 46

# TABLE OF CONTENTS (Cont.)

CENTRIFUGAL PUMPS . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 47

- Energy Conversion in a Centrifugal Pump . . . . . . . . . . . . . . . . . . . . . . . . . . . . 47
- Operating Characteristics of a Centrifugal Pump . . . . . . . . . . . . . . . . . . . . . . . . . 48
- Cavitation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 48
- Net Positive Suction Head . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 49
- Pump Laws . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 49
- System Characteristic Curve . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 52
- System Operating Point . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 52
- System Use of Multiple Centrifugal Pumps . . . . . . . . . . . . . . . . . . . . . . . . . . . 53
- Centrifugal Pumps in Parallel . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 53
- Centrifugal Pumps in Series . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 54
- Summary . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 56

APPENDIX B Fluid Flow . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . B-1

# LIST OF FIGURES

Figure 1 Pressure Versus Depth . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3

Figure 2 Pascal's Law . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 7

Figure 3 Continuity Equation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 12

Figure 4 "Y" Configuration for Example Problem . . . . . . . . . . . . . . . . . . . . . . . . 14

Figure 5 Laminar and Turbulent Flow Velocity Profiles . . . . . . . . . . . . . . . . . . . . 18

Figure 6 Venturi Meter . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 27

Figure 7 Typical Centrifugal Pump Characteristic Curve . . . . . . . . . . . . . . . . . . . . 48

Figure 8 Changing Speeds for Centrifugal Pump . . . . . . . . . . . . . . . . . . . . . . . . . 51

Figure 9 Typical System Head Loss Curve . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 52

Figure 10 Operating Point for a Centrifugal Pump . . . . . . . . . . . . . . . . . . . . . . . . 52

Figure 11 Pump Characteristic Curve for Two Identical
Centrifugal Pumps Used in Parallel . . . . . . . . . . . . . . . . . . . . . . . . . . . . 53

Figure 12 Operating Point for Two Parallel Centrifugal Pumps . . . . . . . . . . . . . . . . 54

Figure 13 Pump Characteristic Curve for Two Identical
Centrifugal Pumps Used in Series . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 54

Figure 14 Operating Point for Two Centrifugal Pumps in Series . . . . . . . . . . . . . . . 55

Figure B-1 Moody Chart . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . B-1

# LIST OF TABLES

Table 1 Typical Values of $\frac{L_{eq}}{D}$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34

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# TERMINAL OBJECTIVE

1.0 Given conditions affecting the fluid flow in a system, **EVALUATE** the effects on the operation of the system.

# ENABLING OBJECTIVES

1.1 **DESCRIBE** how the density of a fluid varies with temperature.

1.2 **DEFINE** the term buoyancy.

1.3 **DESCRIBE** the relationship between the pressure in a fluid column and the density and depth of the fluid.

1.4 **STATE** Pascal's Law.

1.5 **DEFINE** the terms mass flow rate and volumetric flow rate.

1.6 **CALCULATE** either the mass flow rate or the volumetric flow rate for a fluid system.

1.7 **STATE** the principle of conservation of mass.

1.8 **CALCULATE** the fluid velocity or flow rate in a specified fluid system using the continuity equation.

1.9 **DESCRIBE** the characteristics and flow velocity profiles of laminar flow and turbulent flow.

1.10 **DEFINE** the property of viscosity.

1.11 **DESCRIBE** how the viscosity of a fluid varies with temperature.

1.12 **DESCRIBE** the characteristics of an ideal fluid.

1.13 **DESCRIBE** the relationship between the Reynolds number and the degree of turbulence of the flow.

1.14 **DESCRIBE** the relationship between Bernoulli's equation and the First Law of Thermodynamics.

# ENABLING OBJECTIVES (Cont.)

1.15 **DEFINE** the term head with respect to its use in fluid flow.

1.16 **EXPLAIN** the energy conversions that take place in a fluid system between the velocity, elevation, and pressure heads as flow continues through a piping system.

1.17 Given the initial and final conditions of the system, **CALCULATE** the unknown fluid properties using the simplified Bernoulli equation.

1.18 **DESCRIBE** the restrictions applied to Bernoulli's equation when presented in its simplest form.

1.19 **EXPLAIN** how to extend the Bernoulli equation to more general applications.

1.20 **RELATE** Bernoulli's principle to the operation of a venturi.

1.21 **DEFINE** the terms head loss, frictional loss, and minor losses.

1.22 **DETERMINE** friction factors for various flow situations using the Moody chart.

1.23 **CALCULATE** the head loss in a fluid system due to frictional losses using Darcy's equation.

1.24 **CALCULATE** the equivalent length of pipe that would cause the same head loss as the minor losses that occur in individual components.

1.25 **DEFINE** natural circulation and forced circulation.

1.26 **DEFINE** thermal driving head.

1.27 **DESCRIBE** the conditions necessary for natural circulation to exist.

1.28 **EXPLAIN** the relationship between flow rate and temperature difference in natural circulation flow.

1.29 **DESCRIBE** how the operator can determine whether natural circulation exists in the reactor coolant system and other heat removal systems.

1.30 **DESCRIBE** how to enhance natural circulation flow.

1.31 **DEFINE** two-phase flow.

# ENABLING OBJECTIVES (Cont.)

1.32 **DESCRIBE** two-phase flow including such phenomena as bubbly, slug, and annular flow.

1.33 **DESCRIBE** the problems associated with core flow oscillations and flow instability.

1.34 **DESCRIBE** the conditions that could lead to core flow oscillation and instability.

1.35 **DESCRIBE** the phenomenon of pipe whip.

1.36 **DESCRIBE** the phenomenon of water hammer.

1.37 **DEFINE** the terms net positive suction head and cavitation.

1.38 **CALCULATE** the new volumetric flow rate, head, or power for a variable speed centrifugal pump using the pump laws.

1.39 **DESCRIBE** the effect on system flow and pump head for the following changes:
   a. Changing pump speeds
   b. Adding pumps in parallel
   c. Adding pumps in series

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# CONTINUITY EQUATION

*Understanding the quantities measured by the volumetric flow rate and mass flow rate is crucial to understanding other fluid flow topics. The continuity equation expresses the relationship between mass flow rates at different points in a fluid system under steady-state flow conditions.*

**EO 1.1 DESCRIBE how the density of a fluid varies with temperature.**

**EO 1.2 DEFINE the term buoyancy.**

**EO 1.3 DESCRIBE the relationship between the pressure in a fluid column and the density and depth of the fluid.**

**EO 1.4 STATE Pascal's Law.**

**EO 1.5 DEFINE the terms mass flow rate and volumetric flow rate.**

**EO 1.6 CALCULATE either the mass flow rate or the volumetric flow rate for a fluid system.**

**EO 1.7 STATE the principle of conservation of mass.**

**EO 1.8 CALCULATE the fluid velocity or flow rate in a specified fluid system using the continuity equation.**

## Introduction

Fluid flow is an important part of most industrial processes; especially those involving the transfer of heat. Frequently, when it is desired to remove heat from the point at which it is generated, some type of fluid is involved in the heat transfer process. Examples of this are the cooling water circulated through a gasoline or diesel engine, the air flow past the windings of a motor, and the flow of water through the core of a nuclear reactor. Fluid flow systems are also commonly used to provide lubrication.

Fluid flow in the nuclear field can be complex and is not always subject to rigorous mathematical analysis. Unlike solids, the particles of fluids move through piping and components at different velocities and are often subjected to different accelerations.

Even though a detailed analysis of fluid flow can be extremely difficult, the basic concepts involved in fluid flow problems are fairly straightforward. These basic concepts can be applied in solving fluid flow problems through the use of simplifying assumptions and average values, where appropriate. Even though this type of analysis would not be sufficient in the engineering design of systems, it is very useful in understanding the operation of systems and predicting the approximate response of fluid systems to changes in operating parameters.

The basic principles of fluid flow include three concepts or principles; the first two of which the student has been exposed to in previous manuals. The first is the principle of momentum (leading to equations of fluid forces) which was covered in the manual on Classical Physics. The second is the conservation of energy (leading to the First Law of Thermodynamics) which was studied in thermodynamics. The third is the conservation of mass (leading to the continuity equation) which will be explained in this module.

## Properties of Fluids

A *fluid* is any substance which flows because its particles are not rigidly attached to one another. This includes liquids, gases and even some materials which are normally considered solids, such as glass. Essentially, fluids are materials which have no repeating crystalline structure.

Several properties of fluids were discussed in the Thermodynamics section of this text. These included temperature, pressure, mass, specific volume and density. *Temperature* was defined as the relative measure of how hot or cold a material is. It can be used to predict the direction that heat will be transferred. *Pressure* was defined as the force per unit area. Common units for pressure are pounds force per square inch (psi). *Mass* was defined as the quantity of matter contained in a body and is to be distinguished from weight, which is measured by the pull of gravity on a body. The *specific volume* of a substance is the volume per unit mass of the substance. Typical units are $ft^3$/lbm. *Density*, on the other hand, is the mass of a substance per unit volume. Typical units are lbm/$ft^3$. Density and specific volume are the inverse of one another. Both density and specific volume are dependant on the temperature and somewhat on the pressure of the fluid. As the temperature of the fluid increases, the density decreases and the specific volume increases. Since liquids are considered incompressible, an increase in pressure will result in no change in density or specific volume of the liquid. In actuality, liquids can be slightly compressed at high pressures, resulting in a slight increase in density and a slight decrease in specific volume of the liquid.

## Buoyancy

*Buoyancy* is defined as the tendency of a body to float or rise when submerged in a fluid. We all have had numerous opportunities of observing the buoyant effects of a liquid. When we go swimming, our bodies are held up almost entirely by the water. Wood, ice, and cork float on water. When we lift a rock from a stream bed, it suddenly seems heavier on emerging from the water. Boats rely on this buoyant force to stay afloat. The amount of this buoyant effect was first computed and stated by the Greek philosopher Archimedes. When a body is placed in a fluid, it is buoyed up by a force equal to the weight of the water that it displaces.

If a body weighs more than the liquid it displaces, it sinks but will appear to lose an amount of weight equal to that of the displaced liquid, as our rock. If the body weighs less than that of the displaced liquid, the body will rise to the surface eventually floating at such a depth that will displace a volume of liquid whose weight will just equal its own weight. A floating body displaces its own weight of the fluid in which it floats.

## Compressibility

*Compressibility* is the measure of the change in volume a substance undergoes when a pressure is exerted on the substance. Liquids are generally considered to be incompressible. For instance, a pressure of 16,400 psig will cause a given volume of water to decrease by only 5% from its volume at atmospheric pressure. Gases on the other hand, are very compressible. The volume of a gas can be readily changed by exerting an external pressure on the gas

## Relationship Between Depth and Pressure

Anyone who dives under the surface of the water notices that the pressure on his eardrums at a depth of even a few feet is noticeably greater than atmospheric pressure. Careful measurements show that the pressure of a liquid is directly proportional to the depth, and for a given depth the liquid exerts the same pressure in all directions.

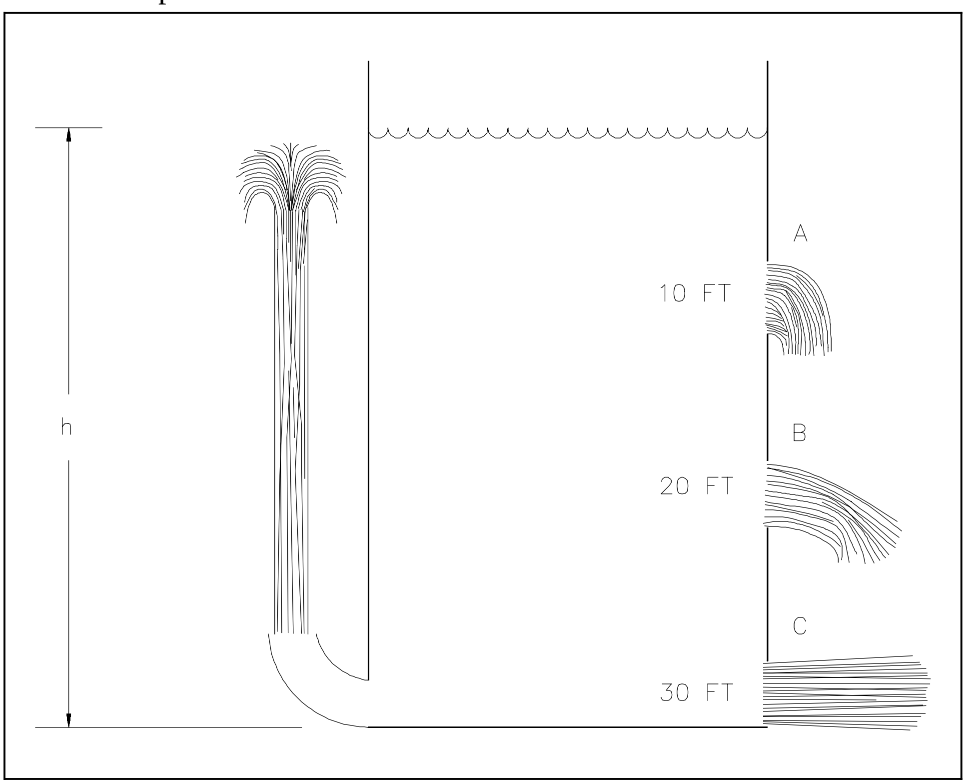


Figure 1 Pressure Versus Depth

As shown in Figure 1 the pressure at different levels in the tank varies and this causes the fluid to leave the tank at varying velocities. Pressure was defined to be force per unit area. In the case of this tank, the force is due to the weight of the water above the point where the pressure is being determined.

Example:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$= \frac{\text{Weight}}{\text{Area}}$$

$$P = \frac{m\ g}{A\ g_c}$$

$$= \frac{\rho\ V\ g}{A\ g_c}$$

where:

m = mass in lbm

g = acceleration due to earth's gravity $32.17 \frac{\text{ft}}{\text{sec}^2}$

$g_c$ = $32.17\ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}$

A = area in $\text{ft}^2$

V = volume in $\text{ft}^3$

$\rho$ = density of fluid in $\frac{\text{lbm}}{\text{ft}^3}$

The volume is equal to the cross-sectional area times the height (h) of liquid. Substituting this in to the above equation yields:

$$P = \frac{\rho\ A\ h\ g}{A\ g_c}$$

$$P = \frac{\rho\ h\ g}{g_c}$$

This equation tells us that the pressure exerted by a column of water is directly proportional to the height of the column and the density of the water and is independent of the cross-sectional area of the column. The pressure thirty feet below the surface of a one inch diameter standpipe is the same as the pressure thirty feet below the surface of a large lake.

Example 1:

If the tank in Figure 1 is filled with water that has a density of 62.4 $lbm/ft^3$, calculate the pressures at depths of 10, 20, and 30 feet.

Solution:

$$P = \frac{\rho \ h \ g}{g_c}$$

$$P_{10 \text{ feet}} = \left(62.4 \ \frac{\text{lbm}}{\text{ft}^3}\right)(10 \ \text{ft}) \left(\frac{32.17 \ \frac{\text{ft}}{\text{sec}^2}}{32.17 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}\right)$$

$$= 624 \ \frac{\text{lbf}}{\text{ft}^2} \left(\frac{1 \ \text{ft}^2}{144 \ \text{in}^2}\right)$$

$$= 4.33 \ \frac{\text{lbf}}{\text{in}^2}$$

$$P_{20 \text{ feet}} = \left(62.4 \ \frac{\text{lbm}}{\text{ft}^3}\right)(20 \ \text{ft}) \left(\frac{32.17 \ \frac{\text{ft}}{\text{sec}^2}}{32.17 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}\right)$$

$$= 1248 \ \frac{\text{lbf}}{\text{ft}^2} \left(\frac{1 \ \text{ft}^2}{144 \ \text{in}^2}\right)$$

$$= 8.67 \ \frac{\text{lbf}}{\text{in}^2}$$

$$P_{30\ \text{feet}} = \left(62.4\ \frac{\text{lbm}}{\text{ft}^3}\right)(30\ \text{ft})\left(\frac{32.17\ \frac{\text{ft}}{\text{sec}^2}}{32.17\ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}\right)$$

$$= 1872\ \frac{\text{lbf}}{\text{ft}^2}\left(\frac{1\ \text{ft}^2}{144\ \text{in}^2}\right)$$

$$= 13.00\ \frac{\text{lbf}}{\text{in}^2}$$

Example 2:

A cylindrical water tank 40 ft high and 20 ft in diameter is filled with water that has a density of 61.9 lbm/ft$^3$.

(a) What is the water pressure on the bottom of the tank?
(b) What is the average force on the bottom?

Solution:

(a)
$$P = \frac{\rho\ h\ g}{g_c}$$

$$P = \left(61.9\ \frac{\text{lbm}}{\text{ft}^3}\right)(40\ \text{ft})\left(\frac{32.17\ \frac{\text{ft}}{\text{sec}^2}}{32.17\ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}\right)$$

$$= 2476\ \frac{\text{lbf}}{\text{ft}^2}\left(\frac{1\ \text{ft}^2}{144\ \text{in}^2}\right)$$

$$= 17.2\ \frac{\text{lbf}}{\text{in}^2}$$

(b)

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$\text{Force} = (\text{Pressure})\ (\text{Area})$$

$$\text{Area} = \pi r^2$$

$$F = \left(17.2\ \frac{\text{lbf}}{\text{in}^2}\right) \pi\ (10\ \text{ft})^2 \left(\frac{144\ \text{in}^2}{1\ \text{ft}^2}\right)$$

$$= 7.78\ \text{x}\ 10^5\ \text{lbf}$$

## Pascal's Law

The pressure of the liquids in each of the previously cited cases has been due to the weight of the liquid. Liquid pressures may also result from application of external forces on the liquid. Consider the following examples. Figure 2 represents a container completely filled with liquid. A, B, C, D, and E represent pistons of equal cross-sectional areas fitted into the walls of the vessel. There will be forces acting on the pistons C, D, and E due to the pressures caused by the different depths of the liquid. Assume that the forces on the pistons due to the pressure caused by the weight of the liquid are as follows: A = 0 lbf, B = 0 lbf, C = 10 lbf, D = 30 lbf, and E = 25 lbf. Now let an external force of 50 lbf be applied to piston A. This external force will cause the pressure at all points in the container to increase by the same amount. Since the pistons all have the same cross-sectional area, the increase in pressure will result in the forces on the pistons all increasing by 50 lbf. So if an external force of 50 lbf is applied to piston A, the force exerted by the fluid on the other pistons will now be as follows: B = 50 lbf, C = 60 lbf, D = 80 lbf, and E = 75 lbf.

This effect of an external force on a confined fluid was first stated by Pascal in 1653.

> *Pressure applied to a confined fluid is transmitted undiminished throughout the confining vessel of the system.*

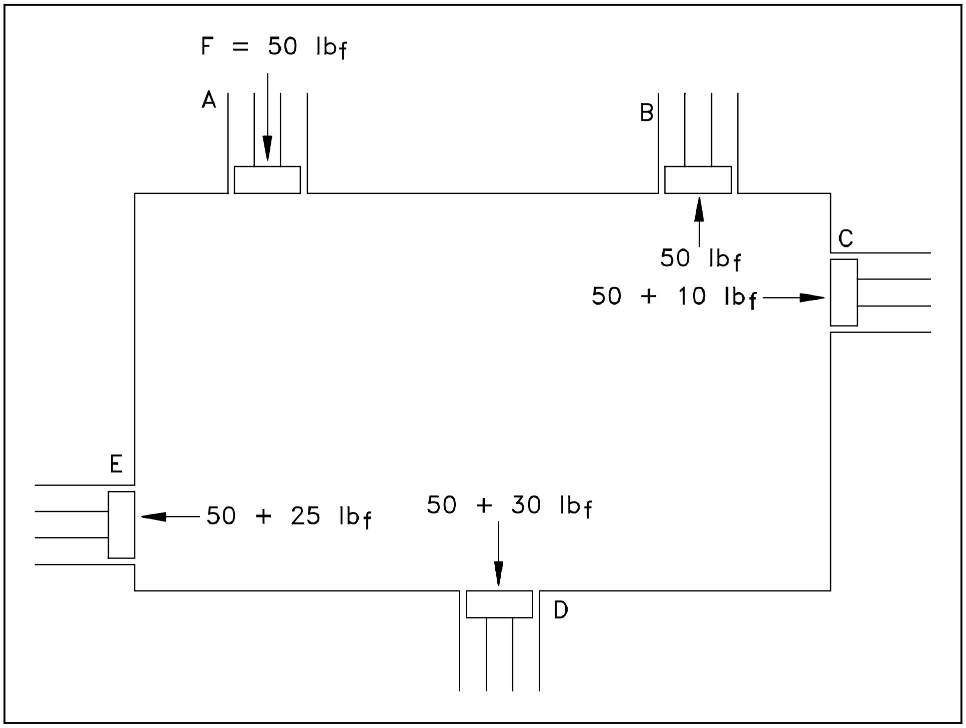


Figure 2 Pascal's Law

## Control Volume

In thermodynamics, a *control volume* was defined as a fixed region in space where one studies the masses and energies crossing the boundaries of the region. This concept of a control volume is also very useful in analyzing fluid flow problems. The boundary of a control volume for fluid flow is usually taken as the physical boundary of the part through which the flow is occurring. The control volume concept is used in fluid dynamics applications, utilizing the continuity, momentum, and energy principles mentioned at the beginning of this chapter. Once the control volume and its boundary are established, the various forms of energy crossing the boundary with the fluid can be dealt with in equation form to solve the fluid problem. Since fluid flow problems usually treat a fluid crossing the boundaries of a control volume, the control volume approach is referred to as an "open" system analysis, which is similar to the concepts studied in thermodynamics. There are special cases in the nuclear field where fluid does not cross the control boundary. Such cases are studied utilizing the "closed" system approach.

Regardless of the nature of the flow, all flow situations are found to be subject to the established basic laws of nature that engineers have expressed in equation form. Conservation of mass and conservation of energy are always satisfied in fluid problems, along with Newton's laws of motion. In addition, each problem will have physical constraints, referred to mathematically as boundary conditions, that must be satisfied before a solution to the problem will be consistent with the physical results.

## Volumetric Flow Rate

The *volumetric flow rate* ($\dot{V}$) of a system is a measure of the volume of fluid passing a point in the system per unit time. The volumetric flow rate can be calculated as the product of the cross-sectional area (A) for flow and the average flow velocity (v).

$$\dot{V} = A \ v \tag{3-1}$$

If area is measured in square feet and velocity in feet per second, Equation 3-1 results in volumetric flow rate measured in cubic feet per second. Other common units for volumetric flow rate include gallons per minute, cubic centimeters per second, liters per minute, and gallons per hour.

Example:

A pipe with an inner diameter of 4 inches contains water that flows at an average velocity of 14 feet per second. Calculate the volumetric flow rate of water in the pipe.

Solution:

Use Equation 3-1 and substitute for the area.

$$\dot{V} = (\pi \ r^2) \ v$$

$$\dot{V} = (3.14) \ (\frac{2}{12} \ \text{ft})^2 \ (14 \ \frac{\text{ft}}{\text{sec}})$$

$$\dot{V} = 1.22 \ \frac{\text{ft}^3}{\text{sec}}$$

## Mass Flow Rate

The *mass flow rate* ($\dot{m}$) of a system is a measure of the mass of fluid passing a point in the system per unit time. The mass flow rate is related to the volumetric flow rate as shown in Equation 3-2 where $\rho$ is the density of the fluid.

$$\dot{m} = \rho \dot{V} \tag{3-2}$$

If the volumetric flow rate is in cubic feet per second and the density is in pounds-mass per cubic foot, Equation 3-2 results in mass flow rate measured in pounds-mass per second. Other common units for measurement of mass flow rate include kilograms per second and pounds-mass per hour.

Replacing $\dot{V}$ in Equation 3-2 with the appropriate terms from Equation 3-1 allows the direct calculation of the mass flow rate.

$$\dot{m} = \rho \, A \, v \tag{3-3}$$

Example:

The wate culate the mass

Solution:

$\dot{m}$

$\dot{m}$

$\dot{m}$



## Conservation

In thermodynami anged in form. The sa g that states that all ma of the control volume ple is expressed mathe

$$\dot{m}_{in} = \dot{m}_{c} \tag{3-4}$$

where:

$\frac{\Delta m}{\Delta t}$ = ver a

## Steady-State

Steady-state flow in the system do not change over time. These fluid properties include temperature, pressure, and velocity. One of the most significant properties that is constant in a steady-state flow system is the system mass flow rate. This means that there is no accumulation of mass within any component in the system.