INTRODUCTION TO

THERMO-FLUIDS SYSTEMS DESIGN

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Preface

Design courses and projects in contemporary undergraduate curricula have focused mainly on topics in solid mechanics. This has left graduating junior engineers with limited knowledge and experience in the design of components and systems in the thermo-fluids sciences. ABB Automation in their handbook on *Energy Efficient Design of Auxiliary Systems in Fossil-Fuel Power Plants* has mentioned that this lack of training in thermo-fluids systems design will limit our ability to produce high-performance systems. This deficiency in contemporary undergraduate curricula has resulted in an urgent need for course materials that underline the application of fundamental concepts in the design of thermo-fluids components and systems.

Owing to the urgent need for course materials in this area, this textbook has been developed to bridge the gap between the fundamental concepts of fluid mechanics, heat transfer, and thermodynamics and the practical design of thermo-fluids components and systems. To achieve this goal, this textbook is focused on the design of internal fluid flow systems, coiled heat exchangers, and performance analysis of power plant systems. This requires prerequisite knowledge of internal fluid flow, conduction heat transfer, convection heat transfer with emphasis on forced convection in tubes and over cylinders, analysis of constant area fins, and thermodynamic power cycles, in particular, the Rankine and Brayton cycles. The fundamental concepts are used as tools in an exhaustive design process to solve various practical problems presented in the examples. For junior design engineers with limited practical experience, use of fundamental concepts of which they have previous knowledge will help them to increase their confidence and decision-making capabilities.

The complete design or modification of modern equipment and systems will require knowledge of current industry practices. While relying on and demonstrating the application of fundamental principles, this textbook highlights the use of manufacturers' catalogs to select equipment and practical rules to guide decision-making in the design process. Some of these practical rules are included in the text as ***Practical Notes***, to underline their importance in current practice and provide additional information. While great emphasis is placed upon the use of these rules, an effort was made to ensure that the reader understands the fundamental concepts that support these guidelines. It is strongly believed that this will also enable the design engineer to make quick and accurate decisions in situations where the guidelines may not be applicable.

The topics covered in the text are arranged so that each topic builds on the previous concepts. It is important to convey to the reader that, in the design process, topics are not stand-alone items and they must come together to produce a successful design. There are three main topical areas, arranged in six chapters.

Introductory material on the design process is presented in *Chapter 1*. Since the book focuses on the detailed, technical design of thermo-fluids components and systems, the chapter ends with an abridged version of the full design process.

Chapters 2 and 3 deal with the design of air duct and liquid piping systems, respectively. It is in these initial chapters that a brief review of internal fluid flow is presented. System layout, component sizing, and equipment selection are also covered.

An introduction to heat exchanger design and analysis is presented in *Chapter 4*. This chapter presents the most fundamental material in the textbook. Extensive charts are used to design and analyze the performance of bare-tube and finned-tube coiled heat exchangers. The chapter ends with a description of excerpts from a manufacturer's catalog used to select heating coil models that are used in high-velocity duct systems.

Chapter 5 continues the discussion of heat exchangers by focusing on the sizing and selection of various heat exchangers such as boilers, water heaters, and finned-tube baseboard heaters. Various rules and data are presented to guide the selection and design process.

Chapter 6 focuses on the analysis of power plant systems. Here, the reader is introduced to a review of thermodynamic power cycles and various practical considerations in the analysis of steam-turbine and gas-turbine power generation systems. Combined-cycle systems and waste heat recovery boilers are also presented.

There are seven *Appendices* at the end of this book. They contain a wide variety of charts, tables, and catalog sheets that the design engineer will find useful during practice. Also included in the appendices are: a possible solution of a design project, the names of organizations that provide applicable codes and standards, and the names of some manufacturers and suppliers of equipment used in thermo-fluids systems.

The writing of this textbook was inspired, in part, by the difficulty to find appropriate textbooks that presented a detailed practical approach to the design of thermo-fluids components and systems in industrial environments. It is hoped that the readers and design engineers, in particular, will find it useful in practice as a reference during design projects and analysis.

The authors have made no effort to claim complete originality of the text. We have been motivated by the work of many others that have been appropriately referenced throughout the textbook.

While we feel that this textbook will be a valuable resource for design engineers in industry, it is offered as a guide, and as such, judgement is required when using the text to design systems or for application to specific installations. The authors and the publisher are not responsible for any uses made of this text.

We express our deepest gratitude to and acknowledge the advice, critiques, and suggestions that we received from, our advisory committee of professors, professional engineers, and students. These individuals include Dr. Roger Toogood, P. Eng.; Mr. Mark Ackerman, P. Eng.; Mr. Curt Stout, P. Eng.; Dr. Larry Kostiuk, P. Eng.; Mr. Dave DeJong, P. Eng.; Mr. Michael Ross; and Mr. David Therrien.

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List of Conversion Factors

Dimension	Conversion
Energy	1 Btu = 778.28 lbf ft 1 kWh = 3412.14 Btu 1 hp h = 2545 Btu 1 therm = 10^5 Btu (natural gas)
Force	1 lbf = 32.2 lbm ft/s^2 = 16 ozf 1 dyne = 2.248×10^{-6} lbf
Length	1 ft = 12 in. 1 yard = 3 ft 1 in. = 25.4 mm 1 mile = 5280 ft
Mass	1 slug = 32.2 lbm 1 lbm = 16 ounces (oz) 1 ton mass = 2000 lbm
Power	1 kW = 3412.14 Btu/h 1 hp = 550 lbf ft/s 1 hp (boiler) = 33475 Btu/h 1 ton refrigeration = 12000 Btu/h
Pressure	1 atm = 14.7 psia 1 psia = 2.0 in Hg at 32°F
Temperature	$T(\text{R}) = T(^\circ\text{F}) + 460$ $T(^\circ\text{F}) = 1.8T(^\circ\text{C}) + 32$
Viscosity (dynamic)	1 lbm/(ft s) = 1488 centipoises (cp)
Viscosity (kinematic)	1 ft^2/s = 929 stokes (St)
Volume	1 British gallon = 1.2 US gallon 1 ft^3 = 7.48 US gallons 1 US gallon = 128 fluid ounces
Volume Flow Rate	35.315 ft^3/s = 15850 gal/min (gpm) = 2118.9 ft^3/min (cfm)

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Design of Thermo-Fluids Systems

1.1 Engineering Design—Definition

Process of devising a system, subsystem, component, or process to meet desired needs.

1.2 Types of Design in Thermo-Fluid Science

(i) *Process Design:* The manipulation of physical and/or chemical processes to meet desired needs.
Example: (a) Introduce boiling or condensation to increase heat transfer rates.

(ii) *System Design:* The process of defining the components and their assembly to function to meet a specified requirement.
Examples: (a) Steam turbine power plant system consisting of turbines, pumps, pipes, and heat exchangers.
(b) Hot water heating system, complete with boilers.

(iii) *Subsystem Design:* The process of defining and assembling a small group of components to do a specified function.
Example: Pump/piping system of a large power plant. The pump/piping system is a subsystem of the larger power plant system used to transport water to and from the boiler or steam generator.

(iv) *Component Design:* Development of a piece of equipment or device.

Introduction to Thermo-Fluids Systems Design, First Edition. André G. McDonald and Hugh L. Magande.

1.3 Difference between Design and Analysis

Analysis: Application of fundamental principles to a well-defined problem. All supporting information is normally provided, and one closed-ended solution is possible.

Design: Application of fundamental principles to an undefined, open problem. All supporting information may not be available and assumptions may need to be made. Several alternatives may be possible. No single correct answer exists.

1.4 Classification of Design

(i) Modification of an existing device for
  (a) cost reduction;
  (b) improved performance and/or efficiency;
  (c) reduced mean time between "breakdowns";
  (d) satisfy government codes and standards;
  (e) satisfy customer/client preferences.
(ii) Selection of existing components for the design of a subsystem or a complete system.
(iii) Creation of a new device or system.

1.5 General Steps in Design

The general steps in the design process are shown schematically in Fig. 1.1.

1.6 Abridged Steps in the Design Process

1. *Project Definition*: One or two sentences describing the system or component to be designed. Check the problem statement for information.
2. *Preliminary Specifications and Constraints*: List the requirements that the design should satisfy. Requirements could come from the problem statement provided by the client or from the end users' preferences.

   At this point, develop detailed, quantifiable specifications. For example, the client wants a fan-duct system that is quiet. What does "quiet" mean? What are the maximum and minimum noise levels for this "quiet" range? 60 dB may be satisfactory. Could the maximum noise level be 70 dB?

   Detailed specifications or requirements could originate from the client ("client desired"), could be internally imposed by the designer to proceed with the design, or could be externally imposed by international/federal/provincial/municipal/industry standards or codes.

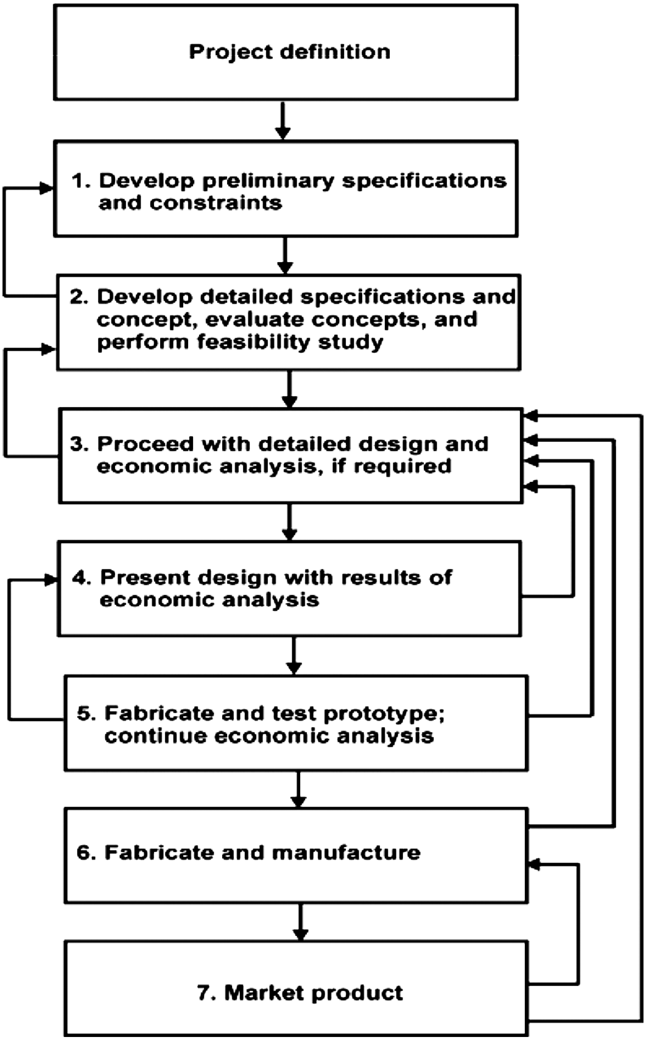

Figure 1.1 General steps in the design process

3. *Detailed Design and Calculations*
   (i) Objective
   (ii) Data Given or Known
   (iii) Assumptions/Limitations/Constraints
   (iv) Sketches (where appropriate)
   (v) Analysis
   (vi) Drawings (where appropriate) or other documentation such as manufacturer's catalog sheets and Specifications.
   (vii) Conclusions