Peter O'Kelly

Computer Simulation of Thermal Plant Operations

Springer

Computer Simulation of Thermal Plant Operations

Peter O'Kelly

Computer Simulation of Thermal Plant Operations

Springer

Peter O'Kelly
Costec Systems Pty Ltd.
Unit 66 42-46, Wattle Road
Brookvale (Sydney)
Australia

ISBN 978-1-4614-4255-4 ISBN 978-1-4614-4256-1 (eBook)
DOI 10.1007/978-1-4614-4256-1
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2012950340

© Springer Science+Business Media New York 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

Chapter 1
Introduction

Unlike many other books on a technical subject with a fairly substantial mathematical orientation, this book has not evolved from several years of teaching the subject material to undergraduate and graduate courses but rather from many years of development, design, delivery and performance testing of a wide variety of power station and utility plant training simulators.

Mathematical simulation covers a very large number and diversity of applications. At a fundamental level, the broad field of mathematical simulation divides into two major areas. The first of these, and the subject of this book, is concerned with *continuous* processes, that is, processes whose states and outputs continuously follow their changing inputs and environmental circumstances. They are generally described by some form of differential equations expressed in terms of continuous time. They include most chemical and power generation processes and other diverse fields such as meteorology and weather forecasting. Possibly the best known example is that of flight simulators for pilot training and certification. These incorporate mathematical modelling of aircraft flight and structural dynamics and other aircraft systems coupled to a realistic or even facsimile reproduction of the aircraft's cockpit equipment and layout. On the other hand, *discrete event simulation* is concerned with processes whose behaviour can best be described as a sequence of discrete events, such as the arrival of cars at an intersection, the arrival of ships at a port, the passage of widgets along a production line or the arrival and processing of telephone calls at a call centre. These processes are characterised by a strong stochastic aspect and are described mathematically in the form of transition events with defined probabilities, durations and outcomes. They can be applied to economies, health and medicine, manufacturing scheduling, transport scheduling and coordination and such like.

Continuous mathematical process modelling, both static and dynamic, is well established in many chemical process fields, particularly the paper and petrochemical industries, and within the power generation industry. As a tool for the analysis of *thermal* plant dynamics and control and for the implementation of high fidelity simulators for operator training, simulation techniques have, broadly speaking,

P. O'Kelly, *Computer Simulation of Thermal Plant Operations*,
DOI 10.1007/978-1-4614-4256-1_1,

been restricted to large central power stations, with the largest scope of simulated plant and the highest performance standards demanded from those using nuclear power generation. There is now an increasing interest in the application of these methodologies and devices to other process plant thermal, steam and power utilities. These tend to use smaller steam generators with a wide variety of fuel types—coal, oil and gas—also biofuels and a variety of combustible by-products.

As the training simulator business matured, it adopted higher levels of system organisation and repeatability. The early use of assembler coding and fixed-point arithmetic, even for large simulators, produced teams of engineer-programmers, low productivity rates—measured by lines of code—and time-consuming and difficult debugging. The use of assembler was dictated by the need to achieve maximum execution speeds as these simulators were expected to run in “real time”, and computing power was limited. Fixed-point arithmetic gave way to a universal use of floating point as appropriate hardware and better compilers became available. The use of modern structured languages such as C++ and Java and graphical configuration tools has led to the development of reusable mathematical modelling libraries which have brought with them a substantial reduction in engineering hours spent on simulator development and debugging. The combination of cheaper but more powerful computing systems and reduced engineering hours has seen a marked reduction in the base price of every category of power and process plant simulator. The price reduction can also be attributed in no small part to the move from hard-wired control panels to screen-based operator interfaces in the plant control room as plant control moved to screen-based DCS systems.

Automated configuration of simulation modelling systems has become the norm in recent years. Complex simulations can be assembled from standard suites of models with little or no new code. These have predefined links to other modules and to their associated data. Data required by each module is also predefined and is usually readily available or can be easily derived from plant design information. Combined with proven libraries, tools reduce engineering time and configuration errors.

All of which brings us to this book. It is the author’s attempt to present an overview of the objectives and methods of practical thermal plant mathematical simulation to engineers who either want to know or need to know. This includes engineers involved in the design, specification, procurement, performance testing and use of power and process utility plant training simulators, or who wish to use simulation as a tool for plant dynamic behaviour analysis, or who wish to build realistic plant simulations for the development and test of plant automation systems. The increasing use of software tools and their pre-configured models is moving the user away from the underlying mathematical principles and physical bases of the models. This book is an attempt to reacquaint the tool user with some of these principles.

A primary objective has been to demonstrate that the computational methods and mathematical assumptions commonly employed derive from and are consistent with the underlying fundamental physical source equations and to derive all of the modelling equations in terms of actual physical data while avoiding, as far as possible, artificial constants of no clear physical meaning, sometimes unkindly called fudge factors. While these have their place by substituting for substance when substance is unachievable, because of either process or computational complexity, they should be used sparingly and then only when their significance is clear and predictable.

This book concerns itself with broad issues of plant *operation* as opposed to a minute examination of some aspect of plant component *design*. An example of the latter might be the use of computational fluid dynamics to predict the flight paths of coal particles through a furnace in order to map the distribution of particle density, heat flux and flow velocities throughout the combustion chamber for different firing configurations and load rates. These issues lie outside the scope of this book, not being of an *operational* nature. The information they yield, however important it may be to the optimum design of the component, is not of immediate concern to operating staff and management and does not of itself influence the design and conduct of operating procedures. To distinguish these approaches, we might speak of *macro simulation* to describe an operational emphasis and *micro simulation* to describe the other.

Simulation as an engineering analysis tool is widely used. Mathematical modelling is routinely used as an aid in the design of critical mechanical components such as steam turbines, gas turbines and compressors. Detailed pressure and flow modelling is used in the design and optimisation of hydraulic piping networks. Complex modelling of heat fluxes and their distribution is an essential element of boiler and superheater design. For each of these and many other fields, standard commercial software packages are available. In many cases, equipment manufacturers have developed their own proprietary analysis tools, specifically tailored to their own products and requirements. As a general rule, these packages provide very detailed information on steady-state or static conditions but rarely do they handle unsteady transient conditions.

The simulation methods described in this book are not intended for design analysis, in the sense of the previous paragraph. They are well suited, and have been applied successfully, to the implementation of operator training simulators, of any scope, and to the analysis of a wide variety of plant operations, both normal and abnormal, over the full range of operating phases, from cold shut-down, through start-up, to full load and back down again, with all manner of variations and transients in between.

The book starts with a general review of simulation concepts. It describes a simulation-oriented classification of thermal plant systems and suggests a typical structure of a simulation run-time environment. Chapter 3 presents a review of the numerical methods used for implementation and solution of the modelling equations derived later in the book. Chapter 4 brings together the fundamental thermodynamic concepts which serve as the starting point for many of the later model derivations. Chapter 5 discusses the statement, reduction and solution methods of the three basic conservation equations of mass, momentum and energy.

Chapters 6–16 discuss simulation modelling of specific plant components and cover static components (pipes, ducts, valves and dampers), turbomachines (fans, pumps and compressors), heat exchangers, furnaces, boilers and steam generators, steam turbines, condensers—water and air-cooled—deaerators and feedwater heaters. Chapter 17 is concerned with the simulation of pressure/flow networks, both incompressible and compressible. Other chapters discuss specific matters such as heat transfer processes (Chap. 8) and the calculation of heat conduction through thick-walled components (Chap. 10). Chapter 13 surveys empirical methods for the treatment of two-phase steam flow.

While having an obvious mathematical orientation, the book seeks to relate these theoretical aspects to the practical design, construction and operating principles of the equipment. To that end, each mathematical development is accompanied by a discussion and description of the relevant physical plant.

The book covers a wide range of equipment types and modelling methods but gives no more than a brief snapshot of any one. For each field touched by this coverage, there exists a large body of specialised knowledge and available material to which the reader is referred should more detail of any of these areas be sought. No attempt has been made to provide a comprehensive review of the literature of any of these subject areas. The literature references provided with the book are limited to those which have contributed directly to the development of the book's own material.

Chapter 2
Plant Simulation Modules and Functional Groups

Most industrial process plant, including power generation and process utility plant, can be conveniently divided into:

1. Simple or complex components
2. Interconnecting piping and duct networks

This facilitates the definition of a modular organisation of plant components for which libraries of common standard modelling modules can be developed, together with their individual data sets and computational methods. Modularity is the key to an effective systematic organisation of components and their interconnection into sub-systems. Given a modular system of building blocks, we can approach any configuration of plant as a set of discrete units or components linked together by a network of fluid conduits containing control, heat, and momentum transfer elements.

A small process utility steam system is shown by Fig. 2.1. Four gas-fired boilers supply high-pressure steam to turbine drives and through controlled letdown valves to a number of low-pressure consumers. One turbine is configured to exhaust to the low-pressure system, the others exhausting to condensers. This is typical of the steam utility plant which might be found in an oil refinery, steelworks or chemical process plant.

Branches containing pipework, valves, and steam turbines connect to nodes and to peripheral devices such as boilers, condensers, tanks, and a deaerator.

2.1 Components

A plant component may take one of the following forms:

1. A simple mechanical unit of plant (pump, valve, header, pipe element, pressure loss element, gearbox, etc)
2. A simple electrical unit of plant (line, RLC element, circuit breaker, etc)

P. O'Kelly, *Computer Simulation of Thermal Plant Operations*,
DOI 10.1007/978-1-4614-4256-1_2,

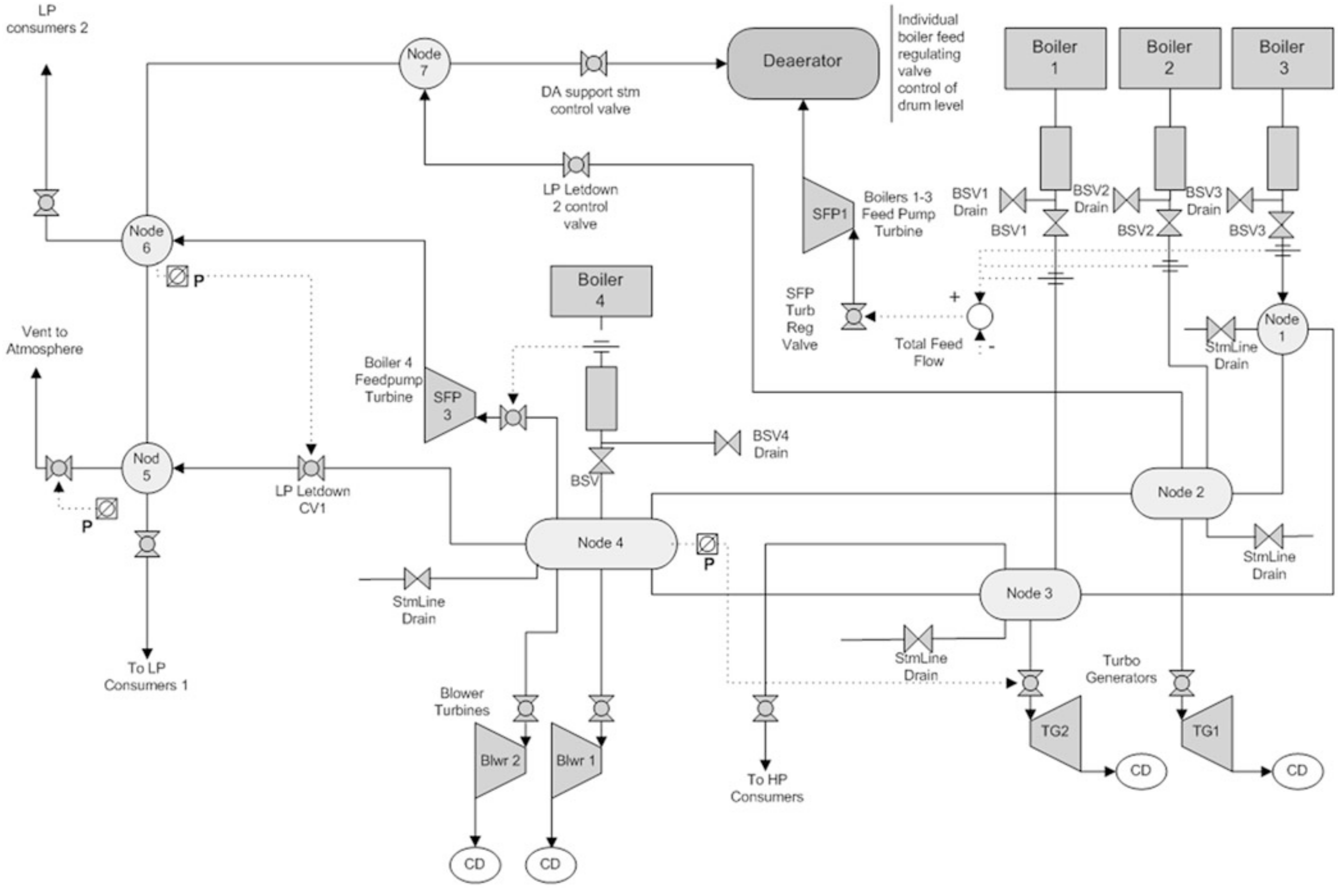

Fig. 2.1 A typical process plant steam system

3. A complex unit of mechanical plant (single-cylinder steam turbine, furnace, evaporator, drum, deaerator, condenser, feedwater heater, flash tank/standpipe, cooling tower, precipitator, gas turbine, bearing, etc)
4. A complex unit of electrical plant (motor, generator, transformer)
5. A compound unit of plant, being a complex assembly of components (e.g. multi-cylinder turbine, multi-effect evaporator, gas turbine, multi-element shaft, heat recovery boiler)
6. An automation interfacing unit (transducer, switchgear, drive/actuator positioner, tap changer)

Broadly speaking, plant equipment can be grouped into systems identified by the principle working medium, allowing us to identify, for example:

(a) Hydraulic systems
(b) Gas systems
(c) Steam systems
(d) Solids handling equipment

Using modern object-oriented coding methods, the implementation code of a component simulation module can be organised as a self-contained object and a specific instance of each created as required by the application scope. Each instance is configured to match the specific application by the setting of a (sometimes large) number of model parameters and configuration options. Component objects can be organised into libraries.

2.2 Networks

A network consists of:

- Branches, a branch being a contiguous arrangement of series-connected components through which the working fluid flows while exchanging heat and performing useful work
- Nodes, being points of connection of branches with each other
- Links, being points of connection to external interfacing components or atmosphere

Nodes and links can be thought of as two flavours of the same species and referred to individually as *internal* or *external* nodes.

Networks are ephemeral and come into existence only as required by a specific application. There are no libraries of networks. Networks are built up as the interconnection of simple components into branches. Individual networks are joined together by connection to discrete components at their external nodes or interfacing points. Discrete components will usually contain significant mass or energy storage and can serve as stable sources of boundary conditions for the more fragile networks which typically feature small volumes, coupled non-linearities and rapid