Baligh El Hefni · Daniel Bouskela

Modeling and Simulation of Thermal Power Plants with ThermoSysPro

A Theoretical Introduction and a Practical Guide

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ISBN 978-3-030-05104-4 ISBN 978-3-030-05105-1 (eBook)
https://doi.org/10.1007/978-3-030-05105-1

Library of Congress Control Number: 2018962771

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Modelling and simulation is becoming an essential tool to assess the behavior of large complex energy systems against ever more stringent safety, availability, environmental, economic and societal constraints prompted by the ongoing energy transition. Indeed, the large number of requirements to be considered and the complex physical interactions between systems and their environment call for efficient means for quantitative and qualitative analysis of the systems physical and functional behavior.

System modelling, also called 0D/1D modelling, is the discipline at the crossroads between detailed 3D physical modelling such as computational fluid dynamics and functional modelling such as control system design. It aims at representing the physical behavior of the whole system using first principle physical laws. These laws are averaged in space and are closed with empirical correlations in order to compute the quantities of interest to the engineer while avoiding unrealistic assumptions and minimizing computational time. Physical modelling is most often used for simulation which consists in predicting the system's behavior from given initial conditions over a given time period. Thanks to 0D/1D modelling, the time periods can extend over several time scales (from seconds to years), and simulation can usually be performed much faster than real time on ordinary laptops. This convenience is especially needed for simulation over long time periods. 0D/1D modelling is also used for assessing and monitoring the system current state in combination with other techniques such as data assimilation that aim at using the knowledge embedded in the models to improve data quality.

0D/1D modelling can cover the whole system engineering lifecycle, from preliminary design to commissioning, operation and maintenance. It can be used for diverse tasks such as the optimal sizing of a refueling cavity, the optimal plant startup that consists in minimizing startup delay while meeting operational constraints, the assessment of steam generator clogging while the plant is in operation, the monitoring and diagnostics of efficiency degradation due to thermal losses, operators training, etc.

This book is about the science and art of physical system modelling applied to thermal power plants with a library of component models called ThermoSysPro which is used at EDF (and also other organizations) for the engineering of power plants at the design and operation phases. The ambition is to show how to make power plant models that provide convincing simulation results. To that end, it contains EDF's long standing experience in power plant modelling and simulation. The equations used in the component models are presented in detail with their validity domains using mathematical notation in a tool-independent way. They are justified with respect to fundamental knowledge in thermodynamics and heat transfer using analytical derivations or proofs when necessary. For each component model, a small test-case with simulation results is given. Models of thermal power plants (fossil fuel fired and solar) are presented with results of numerical simulation and practical hints on how to build them with the library. In addition, comparison with real manufacturer data is provided in the case of a combined cycle power plant. Some insight is also given on the internal structure of the library for the interested reader.

The whole space of the book is dedicated to the physical and mathematical aspects of power plant modelling. Although they are important, the numerical aspects are not considered. This is made possible thanks to the Modelica technology that emerged at the turn of the twenty-first century and that is now fully operational in several commercial and open source tools. It allows to translate automatically models equations into efficient simulation code. Therefore, although this book relies on Modelica to produce numerical results, it is not an introduction to modeling and simulation with Modelica, so it does not present the language nor does it mention the associated techniques. Moreover, the lessons learned from this book can be used with any kind of tool, not only Modelica tools.

The book is intended to students and confirmed practitioners in power plant modelling and simulation. All models presented in the book can be found in the ThermoSysPro library which is released under open source license and freely available to the public.

Chatou, France
October 2018

Daniel Bouskela
Baligh El Hefni

Acknowledgements

First thanks to the PRISME department of EDF Lab for their support to the accomplishment of this book.

Many thanks to Audrey Jardin for fruitful comments and to Benoît Bride for providing combustion component models.

Thanks to all ThermoSysPro enthusiastic users for their comments and feedback on the library.

Thanks to the Modelica community who developed the Modelica language that made ThermoSysPro possible.

Thanks to Peter Fritzson and the OpenModelica team for their support of ThermoSysPro in the OpenModelica open source platform.

Finally, thanks to the Eureka ITEA cluster program and dedicated team for providing the innovative framework that boosted the development of Modelica and ThermoSysPro.

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About the Authors

Dr.-Ing. Baligh El Hefni has 35 years of research, industry and teaching experience. He specialised in physical modelling of various types of power plants. In 2002, he joined EDF Research & Development division (R&D). He contributed to the development of power plants modeling activities, within the EDF and its subsidiaries, thanks to the use of ThermoSysPro library (developed by the authors). This has allowed him to collaborate with major industrial players, research and academics in the framework of many European projects (DLR, Dassault-Systèmes, Dassault-Aviation, Siemens, IFP, OpenModelica …), in which EDF's contribution was recognized. The main objectives of these projects are: to improve the modeling languages, the tools, the methods (stat estimation), and to extend the modeling domains (multi-mode systems, property modeling). The experience in the power plant modeling has allowed him to develop solid competencies and a specific know-how that has allowed him to expand our activity towards the development of solar power plants, and collaborate with CENER (Spain), Chinese Academy of Sciences (China), CEA (France) and other partners. He is in charge of training courses of the modelling of power plants and energy systems, for EDF staff and partners. He was also in charge of the same training at Ecole Centrale de Paris "Engineering Training School".

Daniel Bouskela graduated from Ecole Centrale de Paris (France). He is currently Senior Researcher at EDF Research and Development Division where his main interests are in the domain of the modeling and simulation of energy systems.

Daniel Bouskela is strongly involved in European and French cooperative projects. He was in particular the leader of the European MODRIO project. He is the co-author of the open source ThermoSysPro Modelica library for the modeling and simulation of power plants.

Chapter 1
Introduction to Modeling and Simulation

Abstract Power plant modeling plays a key role in many purposes, like process design assessment, the assessment, and prediction of plant performance, operating procedure evaluation, control system design, and system prognosis and diagnosis. The present chapter introduces the discipline of 0D/1D modeling applied to thermal hydraulics and their main applications to real-life systems: how 0D/1D modeling relates to the 3D physical equations, what are the fundamental assumptions underlying 0D/1D physical models and the main limitations of the numerical solvers commonly used for such models, what is the rationale for a 0D/1D component models library and what kinds of real-life systems can be modeled and simulated for different purposes (plant sizing, control, operation and maintenance, prognosis, diagnosis and monitoring). Also, in this chapter, many questions are answered: what is a system, what is a model and modeling, what is simulation and why is modeling important?

1.1 Systems, Complex Systems, and Cyber-Physical Systems

A usual systems engineering definition of a system is that it is "a set of interrelated parts that work together to accomplish a common purpose or mission" (Cloutier et al. 2015).

Systems are decomposed into subsystems and objects at the lowest level. They are dynamically structured using abstract concepts such as modes, states, events, and trajectories. Modes refer to the logical or functional states of the system (e.g. started, stopped, closed, open, dysfunctional, under maintenance), whereas states refer to the physical states of the system (e.g. temperature, mass flow rate, angular velocity). Events cause switching between modes. Trajectories are the evolution in time of the states. Systems interact with their environment via inputs and outputs. The inputs represent the action of the environment on the system, whereas the outputs represent the influence of the system on the environment.

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For instance, a cooling system whose mission is to cool machines can be decomposed into three subsystems: a pumping system composed of pumps that circulates water around the equipment to be cooled, a feed water system composed of a tank and switch valves that ensures sufficient water pressure at the pumping system inlet, and a group of heat exchangers that transfers heat to the environment. A given pump can be in various normal or dysfunctional modes: started, stopped, cavitating, broken, etc. The pump hydraulic state is most frequently described by the pump head (the variation of pressure through the pump) and the pump volumetric flow rate (the amount of liquid volume that goes through the pump casing per time unit). The mechanical state of the pump can be given by the angular velocity and the torque of the shaft. However, if the shaft is broken into two parts, then the mechanical state involves the angular velocities and the torques of each end of the broken shaft. Therefore, the state of a broken shaft has twice as many state variables as a normal one. This shows that mode switching can cause a complete structural change in the system description. The temperature of the environment is an input of the system (in such case it is assumed that the system does not change the temperature of the environment), and the heat released to the environment is an output of the system.

Although there is no widely accepted definition of a complex system, we will consider as complex systems the systems composed of numerous tightly interacting subsystems. Cyber-physical systems are complex systems having software and physical subsystems in tight interaction or deeply intertwined. Good examples of cyber-physical systems are power plants, cars, planes, power grids, etc. Cyber-physical systems exhibit *emerging* behaviors that are not necessarily foreseen at design time and that appear at operation time due to the multiple interactions (the whole is more than the sum of its parts). One of the main challenges of physical modeling and simulation is to be able to predict emerging behaviors. However, the objective of this book is not to show how to do that, but to provide the fundamental knowledge in terms of physical equations for the thermal hydraulic parts of the systems that are necessary for this goal in particular, and more generally for any other purpose requiring the understanding of the physical behavior of the system.

1.2 What is System Modeling?

Generally speaking, modeling is the process of representing a particular concept, physical phenomenon, or real-world object using abstract notations including but not limited to mathematical symbols. In this book, modeling is referred to as deriving from physical laws a valid set of mathematical equations that describe the system *physical behavior* in order to assess quantitatively how the system performs its duties according to some prescribed mission, e.g., to verify whether a power plant complies with operating rules during start-up or shutdown. Other ways of modeling complex systems such as state diagrams or other kinds of schemas, in particular for the purpose of expressing requirements, assumptions, or *logical* *behavior*, are not considered here. However, such models are necessary for the design of control systems and can be considered as the environment of the physical system (i.e., they interact with the physical system via inputs and outputs). Also, stochastic models are not explicitly dealt with, but randomness can be introduced into physical models by replacing scalar variables with distributions in the physical equations and using Monte Carlo simulations to compute the response of the system to uncertainties.

Physical modeling is not limited to assessing the dynamic behavior of the system. It can also be used to compute isolated operating points. This is called *static modeling*, as opposed to *dynamic modeling* that aims at computing systems trajectories. Static modeling is mainly used for system sizing and optimization at design time, while dynamic modeling is often used for system control design and optimization at operation time. System diagnosis may use static or dynamic modeling depending on the phenomena to be explored.

1.3 What is Simulation?

Simulation is an experiment conducted on a model. As mathematical models are considered here, simulations are numerical experiments conducted with a computer-executable version of the model, which is usually obtained by compiling with a compiler the model expressed in a computer language into a machine executable code. The computer language used for modeling is called a modeling language. The challenge for the user is then to write the model's equations in the modeling language.

There are roughly two kinds of modeling languages: imperative languages and equational languages. Imperative languages such as Fortran, C, C++, Java, Python, etc. are used for imperative programming, which consists in writing explicitly the algorithms that compute the model's equations. This requires a significant effort from the user who must translate manually the equations that express mathematical relations into sequence of computing instructions that computes the numerical solution of the equations. It is more convenient to perform this tedious task automatically by using an equational language that lets the user express the model's equations directly in equational form, hence, with very little transformation of the original equations as written on paper. Modelica is an equational language. Modelica compilers translate equational models into imperative programs, which are in turn compiled with regular compilers (C, C++, Fortran, etc.) to produce executable code. Modelica has been used in this book to write and verify models equations.

Experiments with the same model differ according to the numerical values provided to the inputs of the model and to the initial values of the state variables, which are also called inputs in the sequel. Those values must be physically consistent in order to provide correct results. Consistency cannot be obtained using the model's equations because the unknowns are computed using the inputs as known variables. In other words, the known variables are not constrained by the model's equations. So although, from a numerical point of view, any input can produce numerical results, any input cannot produce *valid* numerical results. Therefore, consistency of the inputs must be achieved by other means such as data assimilation, for instance, which is the science of producing the best estimate of the initial state of a system by combining information from observations of that system (e.g. via sensors) with an appropriate model of the system (i.e., the model at hand to be initialized), see Swinbank et al. (2003). This technique which uses continuous optimization algorithms is successfully used in meteorology and can be applied to any physical system provided it has only continuous inputs to be assimilated (this excludes the assimilation of logical inputs such as the on–off position of a switch). Another technique, which is used in this book, is to compute the inputs from the knowledge of the nominal operating point using inverse computation on square systems of equations (i.e., having as many unknowns as equations). The drawback of this technique is that one has to make a choice between redundant information in order to obtain a square system (e.g., if two valve positions influence a single state, one has to make a choice between the two valve positions). This technique is used in this book as it is more readily available with existing modeling and simulation tools than optimization techniques.

To summarize, a simulation run consists essentially in solving an initial value problem, i.e., a differential-algebraic equation with correct initial values for the state variables and correct values for the inputs. Inputs with fixed values all along a simulation run are often called parameters. This will be looked at in more detail in the sequel.

1.4 What is 0D/1D Modeling?

Physical equations are functions of space and time. 3D models involve the three space coordinates. However, when dealing with space and time, it is often desirable to reduce the number of space coordinates to speed-up the computation of trajectories as the full model's equations must be computed at each time step. Reducing the dimensionality of the problem by going from three space coordinates down to one or even zero space coordinates is called 0D/1D modeling as opposed to 3D modeling. This is obtained by exploiting the geometrical properties of the model such as the cylindrical symmetry of a pipe. In the sequel, this discussion is restricted to thermal hydraulic systems which are the scope of this book.

Thermal hydraulics is the application of fluid dynamics for heat and mass transfer in energy systems such as power plants. Phenomena studied include convection, conduction, radiation, phase change, single-phase (liquid or vapor), two-phase (liquid and vapor), and multi-phase flows (for example water/steam with air). The most common fluids used in power plants are water/steam and flue gases, but other fluids can be used as well such as molten salt.

The dynamic physical behavior of thermal hydraulic systems is described with partial derivative equations (PDEs) that express the three fundamental conservation laws of mass (1.1), momentum (1.2), and energy (1.3).

$$\frac{\mathrm{D}}{\mathrm{D}t}\int_V \rho \cdot \mathrm{d}V = 0 \tag{1.1}$$

$$\frac{\mathrm{D}}{\mathrm{D}t}\int_V \rho \cdot \vec{v} \cdot \mathrm{d}V = \vec{f} \tag{1.2}$$

$$\frac{\mathrm{D}}{\mathrm{D}t}\int_V \rho \cdot u \cdot \mathrm{d}V = \dot{Q} + \dot{W} \tag{1.3}$$

where $\mathrm{D}/\mathrm{D}t$ stands for the material derivative (that takes into account the fluid motion), V is the fluid volume, ρ is the fluid density, $\vec{v}$ is the fluid velocity, $\vec{f}$ are the external volume and surface forces acting upon the fluid (such as pressure and friction), u is the fluid internal energy, $\dot{Q}$ and $\dot{W}$ are, respectively, the amount of heat and work received by the fluid per unit time.

These equations are closed by closure laws (fluid correlations) that compute unknown quantities found in $\vec{f}$ such as pressure loss or heat exchange coefficients as functions of the pressure P and the temperature T of the fluid. State equations are used to compute ρ and u with respect to P and T.

The 0D/1D modeling approach consists in averaging physical quantities over the cross-sectional area A perpendicular to the main flow direction x, then along the main flow direction x:

$$\int_V \bullet \mathrm{d}V = \int_{\Delta x} \left[\int_A \bullet \mathrm{d}A\right] \cdot \mathrm{d}x \tag{1.4}$$

where Δx is a length increment and $V = A \cdot \Delta x$.

In practice, this method consists in:

1. Dividing the system into control volumes $V = A \cdot \Delta x$ along the main flow direction;
2. Averaging the physical quantities using (1.4) for all individual control volumes;
3. Connecting the control volumes along the main flow direction to account for the variation of the physical quantities along that direction in steps corresponding to the lengths Δx of the control volumes.

Δx is adapted to the study at hand. It, therefore, can be small or large without limitation. Δx is equal to zero for components considered as a singularities such as valves. It is large for long pipes or large vessels when no information is needed regarding the distribution of physical quantities along the component length. One must note that the choice of Δx does not induce any approximation in itself as computed quantities are considered as averaged quantities over $V = A \cdot \Delta x$, but the larger Δx, the lower the resolution of the computation in space.

0D/1D modeling gives the ability to choose the space resolution of realistic models described from first principle physics. It, therefore, allows to adjust the space resolution in order to compute large transients for complex systems for engineering studies that often require simulation speed orders of magnitude faster than real time. Therefore, the main benefit of this method is to allow the realistic modeling and simulation of complex systems over large transients.

As the only differential variable left in 0D/1D models is dt, 0D/1D models are sets of differential-algebraic equations (DAEs):

$$C \cdot \dot{x} = f(x, p, u) \tag{1.5}$$

where C is a coefficient matrix, x is the state vector of the system, $\dot{x}$ is the time derivative of x (not to be confounded with the length increment Δx above), p are fixed parameters (such as fixed boundary conditions), and u are inputs of the system (such as variable boundary conditions). Note that x may contain time derivatives.

If C is invertible, then (1.5) can be transformed into an ordinary differential equation (ODE) and integrated with standard ODE numerical solvers:

$$\dot{x} = C^{-1} \cdot f(x, p, u) \tag{1.6}$$

If C is not invertible, then (1.5) is a true DAE that cannot be transformed into an ODE and its resolution is more problematic.

If C is not invertible because it contains rows equal to zero, then (1.5) can be written as the following DAE:

$$\begin{cases} \dot{x} = D^{-1} \cdot f(x, a, p, u) \\ 0 = g(x, a, p, u) \end{cases} \tag{1.7a, b}$$

where a are the algebraic variables, i.e., the variables from x in (1.5) with zero coefficients for $\dot{x}$, coefficient matrix D is coefficient matrix C without the rows and columns corresponding to the algebraic variables a, and x are the remaining differential variables, i.e., the variables from x in (1.5) with nonzero coefficients for $\dot{x}$.

Equation (1.7b) is a frequent case that appears when dynamics are neglected. It can be solved with numerical solvers that combine the resolution of ODEs with algebraic equations. If the size of x is equal to zero, then (1.7a, b) boils down to (1.7b) and the model is purely static. This case is frequently encountered in sizing problems. Off-the-shelf Modelica tools solve (1.7a, b) although they allow to express the problem as (1.5). If C is not invertible, then a division by zero occurs at simulation time.

If C contains predicates (i.e., Boolean conditions) that depend on elements of x, and if the predicates are such that C is not invertible at some instants t, then the system may be considered as a series of commuting DAEs such as (1.7a, b) with varying structure (i.e., varying sizes for x, a, p, and u) from one DAE to the other. Such systems are called multi-mode systems. There is currently no industrial tool able to solve such systems although a prototype was developed in the framework of the ITEA2 MODRIO project (2012–2016); (Elmqvist et al. 2014; Bouskela 2016), and the development of an industrial tool is ongoing in the framework of the FUI ModeliScale project (started in 2018).

1.5 What is a 0D/1D Thermal Hydraulic Component Models Library?

When using DAEs such as (1.5) to represent the fundamental equations of thermal hydraulics, integration of (1.1)–(1.3) must be performed over the various component volumes considered in the system model (pipes, valves, pumps, heat exchangers, turbines, etc.). The various ways of choosing the appropriate closure laws and of performing the integration over the various component volumes commonly found in the systems to be modeled result in the different 0D/1D component models that populate the library.

Therefore, a library component model is a DAE such as (1.5) that depends on inputs u and parameters p. The parameters are set according to the problem at hand. They usually represent quantities that are given as designers' assumptions or as measured quantities on the system or on its environment. The inputs are given as test scenarios or as outputs from neighboring components. The latter case is known as *connecting* the model component to its neighboring components. The way to perform such connections has a strong influence on the structure of the component models. The way to organize the component models in the library in order to be able to compose a full model by interconnecting them is referred to as the *structure of the library* in the sequel.

In order for library component models to be fully reusable, i.e., to be used in any model without modification, they should exhibit the following good properties:

1. Be acausal;
2. Be properly parameterized.

Being acausal means that when written as (1.7a, b), the DAE may be solved in any of the variables x, $\dot{x}$, a, p, or u. This is needed because the outputs of one component model are the inputs of its connected ones, and therefore, the known or unknown status of the variables depends on the way the component models are connected together to form the full model. The process of assigning this status to all variables in the model is known as *causality analysis*[1] and is performed automatically by Modelica tools.

Be properly parameterized means that a proper set of parameters should be defined in order to account for most possible usages of the component model, while keeping the size of the set as small as possible.

1.6 What are 0D/1D Models Useful for?

The purpose of 0D/1D models is not to discover or study new physical phenomena, but to understand the physical behavior of systems using the standard laws of physics complemented with physical correlations for various engineering purposes at design, commissioning, or operation time. To that end, it is only necessary to monitor a small number of significant variables called the *variables of interest*. This is why the space averaging operations to reduce the dimensionality of the problem from 3 to 1 or 0 are acceptable, provided that uncertainty margins are correctly computed to take into account requirements related to safety limits for instance. This allows fast computation of the system behavior all along its trajectory in time.

In the very early phases of system design, one is generally concerned with the logical behavior of the system in order to verify that the system will correctly perform its missions from a functional standpoint. The physical aspects are not very important at this stage. However, at the detailed design phase, when functions must be implemented into physical pieces of equipment, it becomes important to evaluate different implementation alternatives quantitatively in order to make sure that the system's requirements, in particular those involving real-time physical constraints such as safety, are satisfied while avoiding oversizing (as lack of precise quantitative assessment most often results in excessive operational margins), oversizing leading in turn to delays and over costs. This can be achieved using 0D/1D models, in particular static models for the sizing of nominal operating points, and dynamic models for the design, verification, and validation of control systems.

At commission time, 0D/1D models can be used to prepare the acceptance tests.

[1]The word *causality* in *causality analysis* should not be confounded with the word *causality* in *physical causality* which means that causes always precede their effects. However, there is a relationship between the two notions. The objective of causality analysis is to assign each unknown variable to a unique equation that computes this variable and vice versa. State derivatives are assigned in the most obvious way to equations such as (1.7a). Such assignments are conformant with physical causality as state derivatives (predictors) are thus computed from the state past values. However, algebraic variables are assigned to equations such as (1.7b) whose physical causalities are lost as algebraic equations are obtained by neglecting the dynamics of the system that force the physical causalities. The result of the analysis may, thus, not reflect the physical causality of the real system for the algebraic variables. This is why algebraic variables should not be used in a model when causalities are important, such as the feedback loop of a control system.

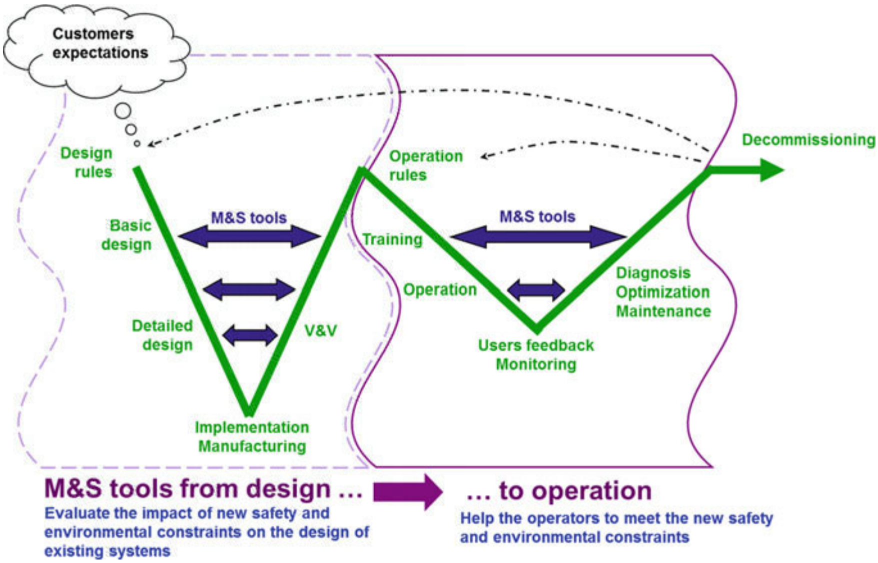

Fig. 1.1 Using 0D/1D models from system design to system operation. (*Source* MODRIO project, with permission from the author: Audrey Jardin)

At operation time, 0D/1D models are useful to predict the short-term behavior of the system to make the right operation decision, for instance, to optimize plant start-ups while complying with equipment operational constraints. Operators can be trained for the conduct of difficult transients (i.e., transients that are rarely performed and are subject to tight safety constraints) using 0D/1D models. 0D/1D models can also be used in combination with plant onsite measurements to monitor and assess the plant performance degradations such as wear or clogging in order to provide key economic performance indicators for the plant and anticipate on maintenance actions in order to reduce plant shutdown for maintenance and correlatively increase plant availability.

Beyond individual power plants, there is a growing need to assess the collective behavior of energy networks when submitted to perturbations such as changes in regulatory, economic, or weather conditions, and how well the power system can adapt to dynamic and changing conditions, see, e.g., EPRI (2016). The growth in variable generation such as solar (photovoltaic and thermodynamic) and wind is a strong driver for the use of 0D/1D for large-scale energy systems. This new need prompted the launch of the ModeliScale project that aims at upscaling Modelica to very large multi-mode physical systems.

Figure 1.1 presents the different stages of the systems lifecycle, from design to operation, where 0D/1D models are useful.

References

Bouskela D (2016) Multi-mode physical modelling of a drum boiler, complex adaptive systems. Proc Comput Sci 95:516–523

Cloutier R, Baldwin C, Bone MA (2015) Systems engineering simplified. CRC Press, Taylor & Francis

Elmqvist H, Mattsson SE, Otter M (2014) Modelica extensions for multi-mode DAE systems. In: Proceedings of the 10th international Modelica conference

EPRI (2016) Electric Power System Flexibility, challenges and opportunity. Available from https://www.epri.com/#/pages/product/3002007374/?lang=en

MODRIO project (2012–1016), ITEA 2 11004 MODRIO. Available from https://github.com/modelica/modrio and https://www.modelica.org/external-projects/modrio

Swinbank R, Shutyaev V, Lahoz WA (2003) Data assimilation for the earth system. In: Series IV: earth end environmental sciences, vol 26. Kluwer

Chapter 2
Introduction to Thermodynamics and Heat Transfer

Abstract Thermodynamics is the science that deals with the exchange of energy in the form of heat and work and with the different states (solid, liquid, gas, etc.) and properties (density, viscosity, thermal conductivity, etc.) of substances that are related to energy and temperature. Thermodynamics is formalized into three basic laws, the first law being the conservation of energy, and the second and third laws being related to the notion of entropy and is completed by the three main laws for heat transfer: radiation, convection, and conduction. In this chapter, we introduce first the properties of substances (density, pressure, and temperature), energy, enthalpy, and entropy, then the concept of state variables, the different types of thermodynamic systems, the first and second thermodynamic laws, the thermodynamics cycles (ideal and actual Brayton cycles, ideal and actual Rankine cycles), the ideal gas law, and the three heat transfer processes (radiation, convection, and conduction). It is shown why these different notions are essential in order to compute the complete thermal-hydraulic state of the system, which is the main challenge of 0D/1D modeling and simulation for that field.

2.1 What Are Thermodynamics and Thermal Hydraulics?

Thermodynamics can be defined in two ways: the science of heat and thermal machines or the science of large systems (i.e., composed of many particles) in equilibrium. In this book, the two aspects will be considered because power plants are thermal machines that produce mechanical energy using heat and mass transfer. As thermal machines, they are subjected to thermodynamic cycles (cf. Sect. 2.9), and as they use fluids to transfer energy from the reactor to the turbine, they are subjected to the laws of thermal hydraulics which is the combination of hydraulics with thermodynamics.

The two main concepts in thermodynamics are heat and temperature. These two quantities are defined and used in two ways that reflect the two aspects of thermodynamics: via the efficiency of thermal machines and via statistics (averages) over volumes containing large numbers of particles. These quantities are governed

B. El Hefni and D. Bouskela, *Modeling and Simulation of Thermal Power Plants with ThermoSysPro*, https://doi.org/10.1007/978-3-030-05105-1_2

by the first and second laws of thermodynamics. Heat and temperature are related via the concept of entropy, with the fundamental formula:

$$dS = \frac{\delta Q_{rev}}{T} \quad (2.1)$$

where dS is the variation of entropy of the system that receives δQ_{rev} amount of heat energy during a reversible process at temperature T.

The two additional concepts used for hydraulics are the conservation of mass and the conservation of momentum.

2.2 Thermodynamic Processes

A thermodynamic process is a change in the system state from an initial state in equilibrium to a final state in equilibrium. When the initial and final states are the same, the process is called a *cycle*.

A *reversible process* is a process in which the system is in equilibrium at each step. This corresponds to an ideal infinitely slow transformation of the system where each step of the process is a system state.

An *irreversible process* is a process that is not reversible. This corresponds to real processes where changes between the initial and final states occur out of equilibrium.

2.3 Properties of Substances

Properties of substances are quantities such as mass, temperature, volume, and pressure. Properties are used to define the current physical state of a substance.

Thermodynamic properties are divided into two general classes: intensive and extensive properties.

An intensive property is independent of the mass of the substance. Temperature, pressure, specific volume, and density are examples of intensive properties.

The value of an extensive property is directly proportional to the mass of the substance. The internal energy or the enthalpy is an example of extensive properties. Mass and volume are also extensive properties.

Thus, if a quantity of matter in a given state is divided into two equal parts in mass, each part will have the same value of the intensive property as the original and half the value of the extensive property.

Relationships between properties are expressed in the form equations which are called equations of state. The most famous state equation is the ideal gas law that relates the pressure, volume, and temperature of an ideal gas (cf. Sect. 2.10).

2.3.1 Density and Specific Volume

Density, also called mass density, is an intensive property defined as the mass of a substance per unit volume:

$$\rho = \frac{m}{V} \tag{2.2}$$

where m is the mass and V is the volume of the body.

The specific volume is the inverse of the density:

$$v = \frac{V}{m} = \frac{1}{\rho} \tag{2.3}$$

The SI unit for volume is m^3 (cubic meters), for density is kg m^{-3} (kilograms per cubic meter), and for specific volume is m^3 kg^{-1} (cubic meters per kilogram).

2.3.2 Pressure

Pressure is an intensive property. The pressure at a point of fluid continuum is defined as the normal compressive force per unit area at that point.

Atmospheric pressure serves as a suitable reference for pressure measurement. Pressure above the atmospheric pressure is called the gauge pressure. Pressure below the atmospheric pressure is called vacuum or subatmospheric pressure. The relationships between the pressures stated for different references are shown in Fig. 2.1.

The SI unit for pressure is Pa (pascal). Pressure is also commonly expressed in bars (1 bar = 10^5 Pa).

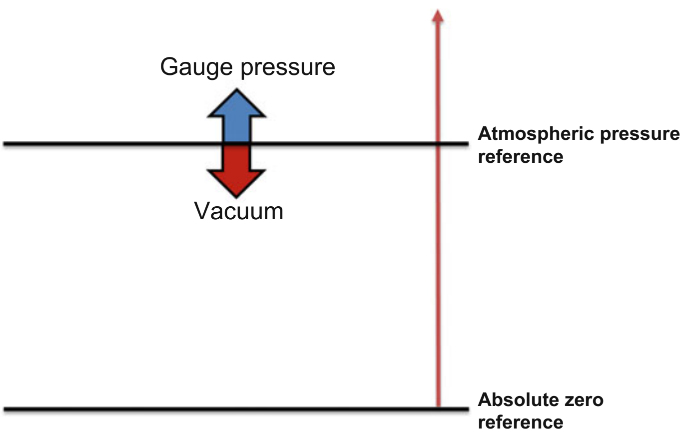

Fig. 2.1 Pressure references