DESIGN AND OFF-DESIGN SIMULATION OF COMPLEX ENERGY SYSTEMS

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Contents

Summary

This chapter deals with the simulation of off-design problems, i.e., with the analysis of situations in which the operating point of the process is removed from the “nameplate” or “design” point. The behavior of the system may be steady, in which case we have a process that operates under approximately fixed conditions at a point characterized by

process parameters different from the design ones, or unsteady, in which case the operating point shifts in time, either periodically or aperiodically, spanning a set of operating points which may or may not include the design point. We shall examine both steady and unsteady off-design problems. We first describe the problem position and its correct formalization, and then proceed to present a schematic and general-purpose review of the solution methods.

1. Introduction

The practical operation of energy systems often requires that they function, for either brief or prolonged periods of time, under boundary conditions different from those upon which their design has been developed. The derangement may be casual (varying environmental conditions, different outlet requirements, accidental or scheduled variations in the operating points of connected systems, etc.) or intentional (load following, scheduled load variation, start-ups and shut-downs, etc.): in either case, the result is a shift of some or all of the process parameters from those corresponding to the “design point” (often called “nameplate point”). One could actually say that steady operation is rather the exception than the rule: most energy systems we know are intrinsically operating under constantly varying conditions (they are said to be in unsteady operation), and most of those that seem to work in a steady mode, often do so for a limited period of time, and then switch to another steady point, different both from the first one and from the design point (they are said to be working quasi-steadily at an off-design point). The question arises spontaneously: if so much emphasis has been placed in the “optimal” design of a system, i.e., in the proper choice of the process parameters so that its “performance” (be it measured by a thermodynamic, economic, or thermo-economic parameter) attains an extreme, why have all other operating conditions been neglected? The answer is that steady-state design-point optimization is an approximate procedure, because all performance indicators are in general strongly affected by the actual operational conditions and the “optimal” design ought in reality to be chosen under consideration of the real foreseen load curve. The chapter on *Operation optimization of Energy Systems* discusses the matter to great detail. Our interest here is more limited: since designers must assess the performance of the systems they are designing not only at, but also away from, the “design point”, they need tools to predict the behavior of the systems under the changed conditions. The simulation tools we discussed in the chapter on *Modeling and Simulation of Energy Systems* must be adapted to accommodate variations of the boundary conditions.

We shall separate the steady from the unsteady off-design problems, not because the logical steps of the respective solution procedures are much different, but because, for numerical reasons, the so-called time-marching, i.e., the solution of unsteady problems, makes use of different algorithms from those employed in the solution of steady off-design cases. While we shall delve extensively into “simulation methods”, it is clear that the existence of suitable models for the (steady or unsteady) off-design performance of each component is subsumed: since for the logic of model development, it is indifferent whether a problem is steady or unsteady (provided some very general conditions apply, like the validity of the continuum hypothesis, etc.), we refer the reader to the chapter on *Modeling and Simulation of Energy Systems* for what modeling is concerned.

2. Definitions

In the following, a *process P* means a connected set of thermodynamic transformations that modify the state of one or more participating media, at least one of which can be identified as the product of *P*. Processes are physically implemented in *systems* or *plants*, that consist of an interconnected set of elementary *components* C_j, with the additional (albeit logically unnecessary) stipulation that each component performs a single thermodynamic transformation. Each participating medium is labeled, at the inlet and at the outlet of each component, with a series of values of thermodynamic functions that exactly and completely define its state.

The "Design Point" is a uniquely defined collection of the possible states of all participating media that satisfies some pre-assigned performance criteria. Any operating point for which at least one of the state parameters of any of the participating media assumes a value different from its Design Point-value is called an Off-Design Point.

If the operating point of the process is constant in time, in the sense that its oscillations do not exceed a conventional limit (for example, ±2%: the actual value is strongly case dependent), the process is said to be operating at *steady state*. Otherwise, it is said to be operating in a transient condition, or *unsteady state*.

When simulating a process, it is convenient to assume that an unsteady operation be composed of a "quasi-continuous" succession of *Steady Off-Design Points*: this is strictly valid for systems near equilibrium, and therefore ought not to apply to most industrial processes, but in reality the technique is so powerful that its convenience overshadows its pitfalls.

3. Position of the "Nameplate Simulation Problem"

For convenience, we repeat here, in an abbreviated form, the procedural steps that define the simulation of a process at *Design Point*. A more complete discussion is found in the chapters on *Modeling and Simulation of Energy Systems* and *Design and Synthesis Optimization of Energy Systems*.

3.1. Problem Formulation

The formulation of a *Design Point Simulation* is the following:

Given a process P, implemented in a System S consisting of N components C_i *(i=1…N), find the quantitative relationship between the output(s) and all of the inputs that contribute to their formation, for a given set of operating conditions of the system that are steady and correspond to the point labeled as "design point".*

Notice that the quantitative relationship mentioned here is calculated for a given process structure and for assigned technical parameters of all components (i.e., for given "characteristic curves"). Therefore, it is a distinct activity from "modeling", in which both the process structure and the characteristic curves are objects of the calculation.

In our illustration of the various steps of the problem formulation, we shall make repeated use of the notations introduced in the chapter on *Modeling and Simulation of Energy Systems*.

3.2. The necessary Data Base

The first item to check is the existence of a complete and congruent database. By this we mean a set of numerical and /or qualitative data that contain all the necessary information to uniquely identify the so-called *system boundary*. This includes:

- An exact definition of the physical system boundary. This boundary is the envelope of the *control volume* used to perform all mass- and energy balances. Fluxes crossing this imaginary (but in practical sense very much real!) line are accounted respectively as inputs or outputs to the process.
- The values of N_D relevant independent thermodynamic variables that identify the thermodynamic state of the input fluxes (the total number of variables characterizing the inputs being $N_I \geq N_D$). For material flows, these include mass flow rate, pressure, temperature and chemo-physical composition; for energy flows, power and possibly an identifier of the energy level of the carrier (temperature, pressure and quality of a steam flow, for instance).
- Some of the values of the variables that characterize the output fluxes. The number N_O of these values must be equal to the sum of the total number of Degrees of Freedom (DOF) and the number of the unspecified input fluxes: $N_O = N_I - N_D + DOF$.

3.3. The Governing Equations

These are all of the independent equations derived from a direct application of conservation equations to the process under consideration. Mass and energy balance, exergy “balance”, species conservation, global angular momentum and kinetic energy conservation, dynamic equations (e.g.: solid rotation), all fall within this category.

Though this is not exact in a mathematical sense, we include in the governing equations all the thermodynamic relations known to link one variable to others, and also all material properties for which there is a constitutive equation (equations of state, c_p-equations, viscosity/temperature dependence, solubility/temperature curve, etc.)

3.4. Independent Variables

We call “independent” a variable for which there is no closed-form equation in the above set. Care ought to be exercised in scrutinizing the set of available equations, to ascertain that all of the proper constitutive relations (thermodynamic relations, material properties, etc.) have been included: otherwise, the problem may result over- or under specified, leading to catastrophic numerical failures.

3.5. Constraints

Constraints are the “limitations” (in the broader sense of the word) known to apply to the solution. They may be specified in the design assignment (e.g.: “⟨fuel = coal⟩ not allowed”, “maximum allowable temperature of the exhaust gases > 403°K”, “O_2 content of the *n*-th gaseous stream > 6% in mass”), or imposed in advance by the designer on the basis of his expert specific knowledge (e.g.: “T_{max} of the first-row stator blades < 1500 °K”, “maximum weight-to-power ratio < 1 kg/kW”, “minimum state-of-charge of the electrical battery > 55%”). Constraints are said to be weak if they include a “≥” or a “≤” sign, and strong if they are expressed by a strict equality. It is good design practice to impose weak constraints in their strong form in the first instance, and to study the sensitivity of the solution to their “release” (their being reset to their original weak form) in a successive step, after a solution has been found.

4. Position of the “Steady-State Off-Design Simulation Problem”

4.1. Problem Formulation

The formulation of a *Steady-State Off-Design Simulation* is the following:

Given a process P, implemented in a System S consisting of N components C_i *(i=*1…*N), find the quantitative relationship between the output(s) and all of the inputs that contribute to their formation, for different sets of operating conditions of the System that are steady and lay significantly outside of the “design point”*. Notice again that the above defined activity is a simulation, based on some previous modeling of the off-design behavior of individual subsystems.

4.2. The necessary Data Base

Same as point 3.2 above.

4.3. The Governing Equations

Same as point 3.3 above, with an important addition: the “characteristic curves” of each component, i.e., the (theoretically or empirically derived) relations that link the value of one of the outputs of the component to the values of other outputs (e.g.: Q/H curve for a pump, m_r/β curve for a compressor or turbine, α/T curve for a combustor, NTU/ε relations for a heat exchanger, etc.).

4.4. Independent Variables

Same as point 3.4 above.

4.5. Constraints

Same as point 3.5 above, with the warning that some of the constraints that apply at steady design point may not apply as such at off-design conditions. Usually, for instance, the emission levels vary, as do the mass- or temperature constraints and the specific consumption specifications.

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Biographical Sketch

Enrico Sciubba (born July 11, 1949) is a Professor in the Department of Mechanical and Aeronautical Engineering of the University of Roma 1 “La Sapienza”, in Roma, Italy. He received M.Eng. Degree in Mechanical Engineering from University of Roma in 1972. After working for two years (1973-75) as a Research Engineer in the Research & Development Division of BMW, Munich (Germany), he returned to the University of Roma as a Senior Researcher (1975-1978). He then enrolled in the Graduate School of Mechanical Engineering, majoring in Thermal and Fluid Sciences, at Rutgers University, Piscataway, NJ, USA, where he was granted a Ph.D. degree in 1981. He joined the Department of Mechanical Engineering of the Catholic University of America, in Washington DC, USA, as an Assistant Professor in 1981, and worked there until 1986, when he returned to the University of Roma 1 first as a Lecturer, then as an Associate and finally Full Professor. He holds the Chair of Turbomachinery, and lectures on Energy Systems as well, both at the undergraduate and graduate level. In 1999 Dr. Sciubba was elected a Fellow of the American Society of Mechanical Engineers. In 2000, he also received an Honorary Doctoral title from the University Dunarea de Jos of Galati (Romania). His research is related to CFD of Turbomachinery, to Exergy Analysis, and to Artificial Intelligence applications in the design of Energy Systems. His publications include more than 40 archival papers, over 150 articles in international conferences, two books on Turbomachinery (one in Italian and the other in English) and one on Artificial Intelligence (in English).