1 Introduction

1.1 The Purpose of Process Control

In both academic and industrial treatises on process control, the stated purpose for the design of control schemes is to reduce process variation, as illustrated in Figure 1.1.

While this is a true statement, it falls well short of giving a full and complete purpose that is worthy of study and mastery. In addition to the purely mathematical treatment given by most academic (as well as industrial) control courses, the would-be process control engineer has little, if any, guidance on what specific outcomes should result from proper controls design. Thus, we submit the following definition for the purpose of process control:

> *To stably, robustly, and predictably maintain Product Qualities in the face of Measured AND Unmeasured Disturbances with the **LEAST** total and incremental energy input (i.e. minimal movement) to the Process.*

Based on this definition, one begins to understand that there are several elements or attributes that must be considered regarding the proper design and implementation of control schemes. Figure 1.2 illustrates the four bodies of knowledge, which, in the authors' experience, are required for one to be a fully qualified and competent process control engineer.

Entire tomes can be (and have been) written on each of these topical areas. This book, however, while not providing a comprehensive coverage, addresses the first two and portions of the third elements, defined

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Companion website: www.wiley.com/go/Young/DistillationProcessControl

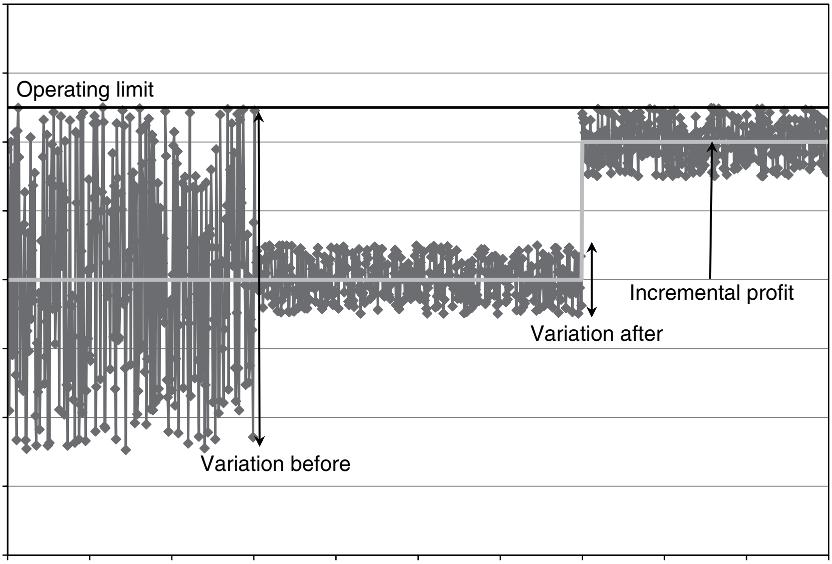

Figure 1.1 Typical definition of the purpose of process control.

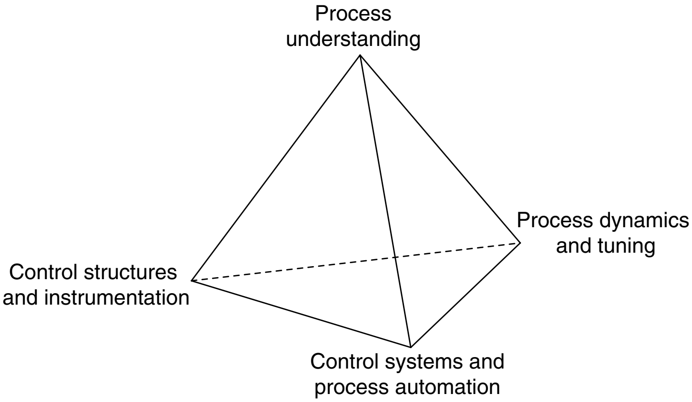

Figure 1.2 Process control bodies of knowledge.

below, to give the engineering student and practicing engineer sufficient insights such that the real-time performance of the actual distillation plant achieves (and even excels) the intended objectives. The working definitions for each of these bodies of knowledge are as follows:

- Process Understanding: By far, the singularly most important area, it encompasses all of the fundamental aspects of fluid dynamics, heat and material transfer, thermodynamics, and reaction kinetics, that is basic process engineering design and operations principles.

- Control Structures and Instrumentation: The former element being the major focus of this book. The latter is also a vital aspect, as the choice of measurement and final control devices play a significant role in the real-time behavior of all the control schemes and these topics are introduced in the text.
- Process Dynamics and Tuning: This body of knowledge is what separates the professional from the novice, in that, while the process engineer's focus is on the steady-state aspects of a process unit's design and operations, only by knowing how a process behaves in real time, that is how measured and unmeasured disturbances propagate through process over time, and then understanding how this dynamic behavior affects regulatory controls such as PID controls (as well as model predictive) controls, the process engineer can ensure that the plant achieves the intended objectives. To be clear, the "black art" of proportional-integral-derivative (PID) and model predictive control (MPC) tuning is *not* addressed herein: due to the variations, nuances and inconsistencies of how control algorithms are implemented across the many control system platforms; that is a topic requiring its own treatment. Detailed tuning is also often not the domain of the process engineer. However, pointing out the potential effects of disturbances and how they should be addressed is covered in this text.
- Control Systems and Process Automation: The proliferation of computer-based control systems has resulted in a wide array of software products and systems' capabilities and features for addressing important aspects of real-time process operations, including a dizzying array of function blocks, high-performance human–machine interfaces (HMI) (i.e. control system operating graphic displays), alarm rationalization and management and control systems design, implementation and maintenance, in addition to cybersecurity measures. Each of these aspects entail significant effort and training. While outside the scope of this book they are, nonetheless, important and vital considerations for robust, resilient, reliable, and secure process operations, and the general aspects of these topics are introduced to the reader.

While the underlying details of each of the preceding four bodies of knowledge can be expanded upon as technology improvements and enhancements are developed, the authors provide the following *Eight Rules* for successful controls implementation to assist the student and practicing engineer with guidance on what elements require focused attention:

1. Know how the process is operated and how it behaves in real time. While seemingly self-explanatory, this rule implies that one must have an intimate understanding of how a specific process unit behaves across its entire operating envelope, including startup and shutdown conditions and knowing equipment design effects (and their limitations) in various operating scenarios (i.e. maximum throughput versus turndown, product selection/optimization, and seasonal influences).
2. Understand all of the primary, secondary, and tertiary operating objectives. Again, seemingly self-explanatory but is necessary to ensure that the controls' design supports (and does not conflict with) these objectives to ensure real-time achievement.
3. Know the control system's capabilities (and limitations) and use it to its fullest; avoid "rolling your own" algorithms(s), unless absolutely necessary.
4. Document the intent of the controls and the reason(s) *why* particular functions or features are utilized. This is both for your own reference but, more importantly, for the person who takes over from you in the on-going maintenance and development of the controls you design.
5. Make the controls design reliable, resilient, robust, and maintainable. The effort required to accomplish this exceeds the typical "safe and operable" criteria applied by many engineering and operations management organizations. But it is required to ensure both the immediate and long-term achievement of the unit's objectives. The essence of this rule is that the controls should behave the same (even predictably) regardless of the conditions (throughput, weather, feed composition, etc.) to which it is subjected.
6. Make a good design into a great implementation with tuning. This is a significant element that separates the professional from the novice and, as described above, detailed tuning is substantially outside the scope of this book. Nevertheless, this is, more

often than not, the reason for poor process performance, in spite of good controls structural design.

7. Provide an intuitive interface for the operator. If/when, in the event the operators must intervene, they should be provided with a readily available (e.g. intuitive) means to "take control" of the process without having to "drill down" through control system detail displays to alter some specific parameter(s) in one, or more, of the control scheme's function blocks.
8. Identify possible or necessary follow-up enhancements for the controls. This includes addressing nonlinear behavior (a significant issue that is detrimental to all controls – both PID and model-predictive technologies) – as well as equipment changes, such as instrumentation selection and process piping and mechanical alterations.

These rules are summarized in what the authors propose should be the process control engineer's *Prime Directive*:

> *Prevent the controls from doing anything unexpected!*

1.2 Introduction to Distillation

Distillation is the process of the physical separation of components in a liquid mixture by heating and then cooling. This is accomplished by utilizing the differences of relative volatility between the mixture components. Distillation may be used to almost completely separate components into nearly pure component products or to partially separate components such that it selectively concentrates specific components into the products.

Distillation is a unit operation of significant industrial importance. For example, in 2019, there were 132 operating refineries in the United States with a crude distillation of 18.7 million US barrels per day (US Energy Information Administration 2019). The energy use of industrial distillation also represents a significant fraction of energy usage in the chemical and process industries. White (2012) reports distillation amounts to 40% of the total energy used to operate plants in the refining and bulk chemical industries. Thus, improving the control and energy efficiency of this unit operation is important to achieving overall energy savings.

Distillation has many applications. Throughout the Hydrocarbon Process Industry (HPI), distillation is used both in upstream and downstream processing. Crude oil is stabilized by partial distillation for safe storage and transport, and, at the refinery, fractional distillation is used to separate it into fuel products and chemical feedstocks. In addition to refining, distillation is used industrially in many other applications. Distillation is used in the chemical industry to separate and purify chemical reaction products to produce sales streams. The distillation of the products of fermentation and other bio-industry processes also produces many products of commercial value, including distilled beverages of high alcohol content. Distillation is also used in cryogenic processes to separate air into its constituent components for use in industrial and medical grade gases, as well as for liquified natural gas (LNG) obtained from the associated gas out of oil and gas wells. And distillation continues to be used as a desalination treatment solution. It is a small wonder that it has been estimated that there are more than 40 000 distillation columns in North America (White 2012).

Distillation has a long history across most, if not all, ancient cultures. Early evidence of distillation has been found on Mesopotamian Babylonian tablets from around 1200 BCE that described distillation for perfumery operations (Levey 1959). Distillation may have been practiced in China as early as the first century of the Common Era (CE) (Haw 2012). Evidence has also been found in Roman (Forbes 1970) and Byzantine (Bunch and Hellemans 2004) Egypt in the first and third centuries CE. Distilled water has been produced since at least 200 CE (Taylor 1945). Distillation was also used to make weak liquor in ancient India (modern Pakistan) in the early centuries of the CE (e.g. Husain 1993).

Medieval Arabic chemists worked on the distillation of various substances from the eighth century of the CE (al-Hassan 2009). By the twelfth century, fractional distillation (Burnett 2001) and the production of ethanol by the distillation of wine with salt (Multhauf 1966) had become known to Western European chemists.

As human history moved from the agricultural era to the first industrial revolution in the nineteenth century, the basis of modern distillation processing was developed – continuous processing, reflux, trayed columns, and preheating (Othmer 1982).

Chemical engineering's genesis as a separate discipline at the end of the nineteenth century provided a scientific foundation to the development of distillation, simultaneously with the second industrial revolution and the developing petroleum industry with the development of design methods, including the Fenske equation (1932), the McCabe–Thiele method (1925), and the unit operations approach (Hougen 1977) in general.

Subsequent to these developments, the advent of heat integration, pinch technology, and process intensification for energy efficiency since the 1970s resulted in more complex and alternative distillation column design proposals, which, in some cases, have been implemented in industry, such as divided wall, reactive distillation, and Petlyuk columns (e.g. Doherty and Malone 2001).

A few words about how calculations are performed before talking about distillation process control are appropriate for a book advocating a real-time (or simulation-based) approach. Before the 1950s, calculations were done manually (e.g. using a slide rule with pencil and paper). As computer technology became more accessible, these manual calculations were implemented using simple programming languages, such as FORTRAN and, later, BASIC as the personal computer (PC) revolution came into being during the third industrial revolution in the 1970s and 1980s. Finally, today's fourth industrial revolution (Industry 4.0) has ushered in a plethora of process simulation software for the fast, accurate steady-state, as well as dynamic, simulation (e.g. as described in detail in Svrcek et al. 2014), and development of "digital twins" of distillation columns and entire process facilities – such tools as Aspen HYSYS, Schlumberger's Symmetry, and Siemens PSE's gPROMS. So, while manual methods still have their place for initial conceptualization and sanity checks, digital modeling tools enable fast, accurate, and precise modeling of complex processes and unit operations.

1.3 Distillation Process Control

The traditional approach to general control loop analysis and design for all processes, including distillation, was based on mechanical and electrical engineering methods very often derived from the frequency domain, such as transfer functions, Laplace transforms, Bode plots, and Nyquist diagrams. While perhaps somewhat helpful for developing a deep understanding of dynamics, these methods are essentially abstract mathematical formulations and were primarily pen and paper techniques for solving linear ordinary differential equations for single-loop systems when the computational resources were unavailable.

By knowing or identifying the Laplace transfer function of the process, a student or engineer could then use a range of controller tuning resources to create an ideal controller equation. However, this approach had major drawbacks that included:

- The mathematical concept was often too abstract for students to grasp and apply practically.
- An apparent disjoint between Laplace with the "time-domain" often results in a lack of intuition for users.
- They use linearized systems equations that oversimplify the complexities of distillation dynamics.
- They are difficult to apply to real, multiple input and output processes, such as when attempting to develop multiloop controls.

Educationalists and industrialists alike have realized these issues and limitations and subsequently have taken a different approach. Present-day distillation control texts tend to either be aimed at being references for practitioners with minimal or no treatment of process calculations or simulations, or be comprehensive academic texts that are similarly lacking in calculations and simulations, and sometimes only treat the fundamentals very lightly.

Notable examples of the former industry-focused texts include (i) Shinskey (1977), which was a classic in the field for its time but was not a teaching text and included no advanced control or simulation; (ii) Luyben (1992), which is an edited volume of leading industry practitioners and academics and very good for its time but not a teaching text with no examples, exercises, or simulations; (iii) Luyben (2013), which includes design and control but whose primary focus is how to use a specific simulator rather than distillation and simulation fundamentals per se; (iv) Nag (2015), which is a practical reference intended for processing engineers and not a teaching text with minimal calculations and simulations.

Academic/teaching texts addressing distillation process control include (i) Robbins (2011), which is geared toward control structure using a lesson style but has very light coverage with little dynamics considered; (ii) Smith (2012) is a comprehensive distillation control book covering lots of basic and advanced control techniques, but no time-varying behavior (dynamics), nor mention of simulation or exercises; (iii) Kiss (2013) that focused on advanced distillation arrangements and is comprehensive in that regard, but has cursory coverage of fundamentals, basic distillation, controls, and advanced process control; (iv) Gorak and Schoenmaker (2014) who present a comprehensive, well-written coverage of the topic, but without sections on advanced process control, light coverage of simulation, and no explicit coverage of energy usage.

1.4 A Real-Time Approach to Distillation Process Control Education

With the ever-improving computational capabilities, high-fidelity distillation modeling (and control) emerged in the late 1980s. These tools explicitly modeled the mass transfer, transport phenomena, thermodynamics, and the vapor–liquid equilibrium (VLE) of a given distillation column. By the early 2000s industrial process simulators were able to accurately and explicitly model the time-dependent behavior of a distillation column (i.e. dynamics). The simulation environment is graphical in nature, somewhat mimicking a distributed control system's (DCS) graphical screen, enabling even modestly experienced users to set up a distillation process with relative ease. The implications for education are that the users could focus on learning the development of controls rather than how to represent a distillation operation using abstract mathematics such as Laplace Transforms; refer to the book *A Real-Time Approach to Process Control* (Svrcek et al. 2014) that includes a step-by-step guide on how this was achieved. The main benefits of applying a simulation-based approach to teaching and learning distillation control for the user/students are as follows:

- Users/students experience realistic nonlinear, coupled process responses that are expected from a distillation column, as opposed to idealized linear, decoupled mathematical functions, as there is a one-to-one correspondence between the dynamic distillation models and the actual plant.
- Users/students are able to learn how to set up sensors, controllers, and valves to achieve both an overall as well as specific control objective(s).
- Through interaction with the dynamic process simulator, users/students can develop an intuitive understanding of the dynamics

of distillation control and relate learnings from other areas of process engineering to the observations.

- Users/students are able to compare candidate control structures and assess the propagation of disturbances through a distillation plant, enabling the evaluation of advanced process control and plant-wide control schemes.

Before summarizing the content of the following chapters, it is appropriate to mention one thing that this book consciously does not cover in detail – instrumentation and control hardware. The hardware of course makes software happen and is therefore very important for control scheme execution. In Svrcek et al. (2014), a broad introduction is given. However, this topic is worth a book in itself, and indeed, there is an excellent text that provides a very comprehensive cover (McMillan and Vegas 2019).

This text is organized into a framework that provides relevant theory and industrial experience, along with a series of hands-on workshops that employ computer simulations that test and explore the theory. This chapter provided conceptual practical basis and a historical overview of the field of real-time distillation process control, including simulation, and the pros (mainly) and cons of a real-time approach. Chapter 2 introduces the fundamentals of distillation control, covering the basic principles of distillation and relevant control information, including pressure and inventory control. Chapter 3 introduces the reader to the fundamentals of hardware that the "software" described in this book runs on. In Chapter 4, we look at distillation inventory control, a key set of issues for stability, in greater detail. Then, in Chapter 5, we look at composition control. Gain analysis, inferential and analyzer control, common control structures, batch distillation, and energy controls are introduced here. Chapter 6 contrasts historical refinery versus chemical plant distillation control and the applicability of traditional refinery and chemical distillation control structures. Chapter 7 focuses specifically on distillation control tuning. Topics covered include integrating versus open-loop stable processes, when to apply tight versus loose control, and handling equipment constraints via tuning. Fine chemical distillation control is examined in Chapter 8 that discusses the key features of nonlinearities, measurements, and basic side draw column controls. Chapter 9 looks at advanced regulatory control – namely feedforward, cascade, and ratio control – and advanced side draw column controls.

Chapter 10 tackles more complex control methods: multivariable model predictive control of distillation columns. Finally, in Chapter 11, we take a look at some of the important issues related to plant-wide control problems, including distillation. A combination of theory and applied methodology provides a practical treatment to this complex topic. And the chapters are matched by a series of simulation workshop exercises that serve to illustrate, teach, and test the concepts developed in each chapter.

Tutorial and Self Study Questions

1.1 What is the fundamental purpose of process control (that does not use “control” in the description)?

1.2 What questions are most important for a process control engineer (PCE) to address when assessing a (new) process and its control design (compared to typical management questions)? What is the effect on time and effort?

1.3 What are the three most important items required for any (complex) control scheme and when/how should it be generated?

1.4 What three (or four) bodies of knowledge are required for a person to be fully competent in process control and what is the order of importance (1 = Most Important)?

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