A REAL-TIME BASED APPROACH TO DISTILLATION CONTROL EDUCATION

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Abstract

Despite the availability of mature and ubiquitous digital tools, such as industrial process simulators, many academic courses on distillation control are taught using classical concepts such as Laplace transforms. While these concepts are intended to provide students with a solid understanding of theoretical control concepts, they fail to convey how to design control structures in an industrial setting. In decades past, many industrial organizations would have taken these students and trained them through their internal and external systems. However, in an era of "value engineering", these policies have all but disappeared. This manuscript details a real-time approach to distillation control that was developed to help address this need. This manuscript details the digital model-based education philosophy that is proposed and illustrates workshops that promote a hands-on learning approach. The expected benefits of transitioning control education from the traditional approach to a simulation-based approach are then identified. This is followed by a discussion of the challenges in making such a transition.

Keywords

Real-time, Digital Models, Distillation, Process Control, Education.

Introduction

With the recent emergence of the digitalization and industry 4.0 mega trend, industries across the globe are rethinking how to incorporate these concepts into their operations and business models (A. Udugama *et al*., 2021; Lee *et al*., 2019). As a result, educational institutes are also reevaluating how curricula in general can be changed both to equip students to potentially deal with these changes and how control concepts can be better leveraged in teaching (Udugama *et al*., 2022).

Distillation is an industrial workhorse used in the chemical process industry, where distillation accounts for over 40% total energy usage of a plant (Department of Energy, n.d.). From a process operations perspective, the efficient operation of a distillation process requires the management of both the mass and energy balances. Control engineers have tackled this need for generations developing basic control configurations (e.g., Luyben, 2006) as well as working on more complicated distillation processes such as high purity distillation (e.g., Fuentes & Luyben, 1983; Skogestad & Morari, 1987). Over the years, some researchers have advocated the use of industrial process simulations as a test bed for developing and testing new control configuration. Today, these simulations can be considered digital models, which is a core concept in the overall drive towards distillation (Udugama *et al*., 2022) . Examples of the use of steady state and dynamic simulations for distillation control purposes can be found as far back as the mid 1990's (e.g., Young & Svrcek, 1996), while in 2006, Luyben (2006) wrote a book outlining how process simulations can be used in distillation design and control. A major benefit of using an industrial process simulation as part of process control development is the level of complexity that can be simulated with relatively low effort which, in turn, enables process control engineers to focus on developing control solutions. For example, (Halager *et al.*, 2021) employed an industrial process simulator to develop a dynamic model of a high purity, multi-component integrated distillation configuration.

Despite these developments and the adoption of state-of-the-art industrial process simulations by the research community, distillation control teaching in many universities is taught solely using the classical concepts of Laplace. Employing Laplace transformations in modeling complex distillation operations means many of the non-linearities present are simply ignored. The Laplace models are then used by instructors to teach students how to select control configurations and controller tuning. Many students who then enter the workforce find this abstract concept difficult to understand and too complicated to apply to solve real-world control problems.

Figure 1 compares the Laplace approach with the alternative 'real-time' approach of using industrial process simulations in teaching distillation control. The key benefits of using the real-time approach employing industrial process simulation for teaching distillation control, is the ability to simulate non-linearities, while providing students with intuitive and practical insights into distillation control.

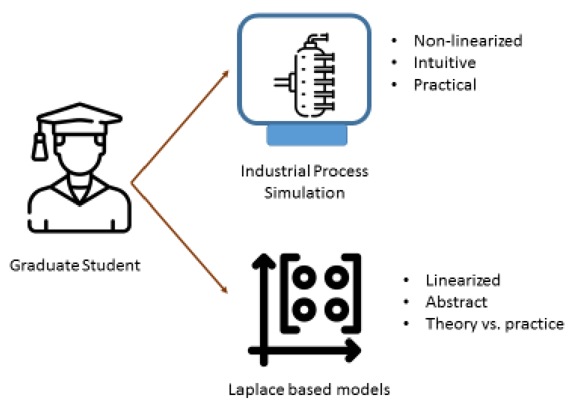

Figure 1. Schematic of the pros and cons of real-time simulation versus Laplace approaches

For undergraduate process control education, Svrcek *et al.*, (2000) identified the need a more insight driven and practical approach to process control education, which lead to the textbook "A real time approach to process control", which is currently it its 3rd edition (Svrcek *et al.*, 2014) where the focus is primarily on a process simulation or real-time approach. (It is worthwhile noting here that we are not naively advocating an "either or" choice: control is best taught by leading with a process simulation techniques backed up by methods like Laplace transforms for deeper insight, e.g., Zhang *et al.*, (2003)). Inspired by this approach, the authors of this manuscript have developed a real-time approach to distillation control that focuses on providing an insights-based and practical approach to distillation control education for graduate level engineers. We are explicitly targeting this course at the graduate level (either graduate students or practicing engineers), because of the specificity of the course (distillation and not general controls), and because we are assuming student familiarity with process simulators, dynamic simulation, and fundamental control techniques. In this manuscript, we will outline the considerations that were considered when developing this graduate level text approach, its content, and the expected outcomes.

Outline of the Approach

The following aspects were taken into consideration when developing the approach:

- The prospective learner has a graduate level understanding of process control
- Due to distillation's ubiquitous use in many industrial applications, complexity, and the need for efficient operations, the prospective students may also include practicing engineers
- The approach may be used as the basis of a graduate level process control course, which means the approach must contain sufficient information for a 13-week course
- The prospective students are likely to be chemical engineers or practicing control and instrumentation engineers

Taking into account the above considerations and the industrial and educational insights of the authors, the outline in Table 1 was proposed.

Table 1. Detailed outline of the real time approach to distillation control content

Sections	Contents
Chapter 1	Introduction
Chapter 2	Fundamentals
Chapter 3	Control Hardware
Chapter 4	Inventory Control
Chapter 5	Composition Control
Chapter 6	Refinery Versus Chemical Plant
Chapter 7	Distillation Controller Tuning
Chapter 8	Fine and Specialty Chemicals
Chapter 9	Advanced Regulatory control
Chapter 10	Model predictive control
Chapter 11	Plant wide control in distillation
Workshop 1	Hands on Learning by Doing
Workshop 2	Fundamental Distillation Control
Workshop 3	Model Predictive Control
Workshop 4	Control in a Plantwide Setting

The approach consists of eleven sections or chapters, and four hands on workshops. The following is a summary of the contents of each Chapter:

- Chapter 1 consists of a brief introduction to distillation processes as well as to process control in general. This chapter also discusses the concept of "real time" process control and its benefits in process control education.
- Chapter 2 lays down the chemical engineering fundamentals of distillation operations followed by a brief introduction to common control configurations (e.g., LD versus DV control). A refresher of control concepts such as degrees of freedom, controller pairing, and gain analysis is also included in this chapter.
- Chapter 3 takes a distillation operations perspective related to control hardware. Sensors, Final control elements and distributed control systems hierarchy are covered with a focus on identifying their influence on process operations and control structure.
- Chapter 4 looks at the pressure and level controls which allow for the inventory in the column to be controlled. Aspects such as tight versus loose inventory control and mechanical considerations are covered. The differences between open loop stable versus integrating levels are covered.
- Chapter 5 focuses on both basic temperature-based control configurations followed by more advanced temperature-based control configurations including dual composition control methods and inference-based methods. The role of dynamic and steady state models for composition control are also covered.
- Chapter 6 The practical differences between refinery versus chemical distillation columns are first discussed. Refining-specific distillation configurations such as pump arounds and side strippers are introduced, and their control discussed. The benefits of operating modern refinery columns more like chemical distillation columns and the impacts of blending on control design are also covered.
- Chapter 7 covers the practical implications of distillation control tuning. The concepts of model identification, process response classification, and basic PID tuning are covered. The chapter also discusses the role of tuning in the era of "value engineering" where distillation columns are no longer built with excess capacity.
- Chapter 8 covers the nuances and intricacies of fine and specialty chemical distillation controls. The chapter focuses on the key features of these separations (e.g., high levels of non-linearity), the measurement challenges that must be overcome, and the control challenges brought on by the use of intensified column configurations such as divided wall columns and side draws.
- Chapter 9 covers advanced regulatory control applications in the context of distillation control. The concepts of cascade control, ratio control, feed forward control, constraint/override control are covered. Decoupling control concepts are also covered in this chapter.
- Chapter 10 covers model predictive control (MPC) and also discusses in detail specific distillation applications when MPC should be used. The chapter also covers the MPC fundamentals including the concept of dynamic matrix control (DMC). The setting up of MPC is also covered. Finally, the positive influence of digitalization on MPC is also covered.
- Chapter 11 The final chapter covers the control of distillation trains, and control configurations that can deal with the inherent complexities of how heat integration and material recycle.

These eleven chapters cover the fundamentals behind distillation control from a chemical engineers' perspective and includes many practical aspects that must be considered in industrial settings. For example, in Chapter 4 a subsection is dedicated on how to understand and deal with the non-linearities brought on by a horizontal vessel used in inventory control. Similarly, Chapter 3 discusses how non-linearities in final control elements can be effectively managed without the need for complex non-linear controls.

Digital models in hands-on education

A key concept of the approach is to enable prospective learners (graduate students in particular) to gain practical understanding of how process control concepts are applied in an industrial setting. To this end, the following four workshops were developed. In these workshops the readers will model progressively more complicated distillation column configurations on an industrial process simulator. These configurations are digital representations of typical configurations that can be found industry and will behave in a similar manner. The workshops are written such that they are "simulator agnostic" (i.e., learners are free to choose the most convenient simulator for them).

The first workshop is about hands on learning by doing and focuses on getting the students to develop a working knowledge of steady state and dynamic simulation packages and to understand the fundamentals of both steady state and dynamic process simulations. A key task in this workshop is to transition a process model from a steady state to dynamics.

The second workshop focuses on fundamental distillation column control and builds upon the first workshop to develop a dynamic model of a simple C_4/C_5 splitter. This workshop demonstrates the impact the selection of a control strategy can have on the operability and controllability of a simple distillation column. A key task in this workshop is the model aided investigation of process dynamics. This type of dynamic investigation forms the core of many model-identification exercises, where step tests can be performed to understand the dynamic response of a distillation column configuration. Another key task is the implementation of base layer stabilizing control structures which are required to stabilize the digital model, which like a physical distillation column, is not stable without these inventory controls. Figure 2 shows a schematic of all the stabilizing controls and other base later controls that are implemented in workshop 2 (implemented in Aspen® HYSYS ®).

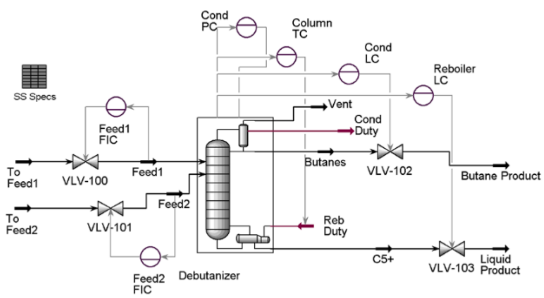

Figure 2. Workshop 2 Simulator P&ID diagram with base layer control (in Aspen® HYSYS ®)

The third workshop focuses on distillation column model predictive control and builds on the dynamic model and the base layer control structure developed in workshop 2. In this workshop, further step tests are performed on the dynamic model and the results are then used to set up a Model Predictive Controller (MPC). Dedicated MPC modules can be found in industrial process simulators. Typically, the process models in these MPCs can be set up to be first order models which can approximate the behavior of a given distillation process. In this workshop the learners are instructed to take the results of the step tests and determine the model parameters of process gain, time constant and delay. It should be noted that the MPC control modules found in industrial process simulators are quite similar to those found in industrial MPC applications. Hence, a prospective student trained on an industrial process simulator would have a much easier time implementing controls on an industrial system than a student implementing an MPC using a programming language. Though this approach is also feasible.

The fourth and final workshop involves distillation column control in a plantwide setting and focuses on the control of an isomerization process which includes distillation columns. The key objective of this workshop is to educate the learner on how to use the steps of a plant wide process control design procedure to design a robust process control strategy for an entire process, rather than just a single unit operation. This workshop requires the student to develop an overall process model consisting of multiple distillation columns, a reactor and heat exchanger (including a furnace) and multiple process recycle loops, and to operate this process dynamically. Developing such a digital model of a process also means that the learner will develop some additional process modelling skills that are also industrially relevant.

Discussion

Transitioning the teaching of distillation control from a more theory driven form, to a digital model enabled method has its benefits.

First, the gap between what is taught in a classroom setting, and what a student is expected to do in a potential industrial setting is reduced. For example, when setting up a PID or a MPC controller in an industrial process simulator, the students need to “configure” the PID controllers as shown in Figure 2. This includes specifying the type of action (direct or reverse), process variable measurement spans, control valves (or other final control elements) and other related characteristics. The students then enter the relevant tuning constants. When comparing these actions to industrial control systems configuration as shown in Figure 3 (Honeywell® control builder), similarities become apparent. In contrast, students working on controls based on Laplace or state-space models will not be exposed to these elements. In some instances, actions that can be taken when developing a controller in Laplace domain might be counter intuitive, such as the ability to implement a controller with a negative gain, as opposed to having to the need to change the type of “action” in an industrial system. Therefore, students trained on Laplace or state-space models will have a steeper learning curve to apply their knowledge in industry.

Another set of benefits in teaching distillation control using an industrial process simulator is the fidelity of the models and ability for the students to focus their efforts on dynamic analysis and control structure implementation. For example, a dynamic multi-component distillation process with a complexity of an additional side stream can be set-up relatively easily. If this task is deemed too time consuming, the instructor can develop the model and make it available for the students. If configured correctly, this type of a distillation model will inherently model aspects such as inventory changes, hydraulic limitations (to some degree) and other dynamic interactions on top of modelling the separation process that is going on inside the column. As a consequence, the output of such a model is very close to industrial reality. In addition, complexities such as sensor noise or disturbances in flows and utilities can be easily added into the system. In comparison, students working on Laplace based or state-space based models will not have the time to implement these interactions. As a result, they will only be exposed to an idealized version of distillation column behavior which is very often far removed from the industrial realities. Moreover, some of the control and tuning concepts that work well within these idealized settings will likely be impractical to implement in industrial settings.

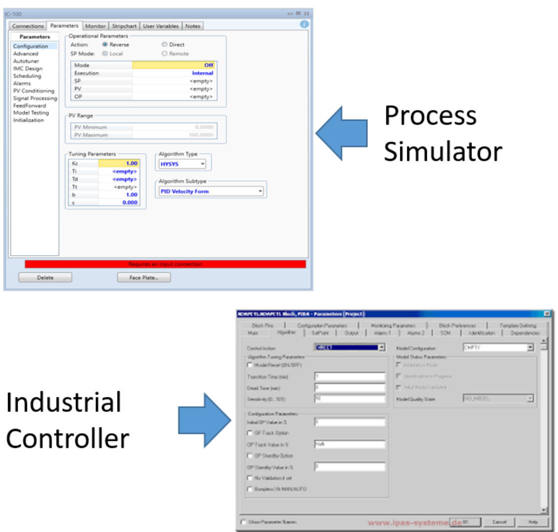

Figure 3. PID configuration procedure of a process simulator (Aspen® HYSYS ®) and a control system (Honeywell® control builder)

In terms of analysis, the students can use the process historian function to plot the behavior of variables and better understand the dynamic interactions between variables. Afterwards, appropriate step-tests can be planned and the progress during the step-test monitored using the process historian. This type of analysis procedure is also directly applicable to industrial settings.

For practicing engineers, proficiency in simulation based dynamic analysis and control configuration opens up the possibility of using digital models as a test bed. In this case, a validated dynamic digital model of a distillation column of interest can be developed in industrial process simulators. In most processing companies, steady state digital models of many key unit operations already exist. In this instance, these steady state models can be transitioned into dynamic models. The dynamic models can then be used as the basis of dynamic scenario analysis and used as the test bed to initially develop and test out control configurations prior to implementation on the physical production process. To this end, the content and workshops of the approach can be used as a preparation for this digital model aided dynamic system analysis and control structure design.

While the above-mentioned benefits are key reasons for transitioning to a real-time, simulator-based distillation control education, there are specific challenges that must also be considered.

The need for an industrial process simulator is one key challenge that must be overcome. Most reputable educational institutes have licenses for one (or more) industrial process simulators that are capable of simulating a distillation process in dynamics. In situations where such industrial simulator licenses maybe unavailable, open access simulators such as DWSim® can be used, as demonstrated by (Rao *et al*., 2022). Despite their relatively user-friendly interfaces, a reasonable amount of time needs to be dedicated to both understand and learn how to use an industrial process simulator in steady state and then to transition a simulation into dynamics. Several existing undergraduate approaches and courses develop these foundation skills such as is described in Svrcek *et al*., (2014) where multiple chapters and workshops are dedicated to build up this understanding. Workshop 1 in the real-time approach to distillation control described here is therefore dedicated to developing or consolidating the understanding of the prospective students.

Industrial simulators are generally robust, however, in certain instances both solver and Vapor-Liquid Equilibrium (VLE) related errors can result in dynamics that are disjointed from reality. Therefore, in a course setting, there is a need to train instructors to an advanced level so that these errors can be picked up and remedied. Instructors on the other hand may also like to maintain the status quo solution, as changing a course requires significant effort in terms of set up. Identifying this need, the real-time approach to distillation control described here developed the workshops alongside the sections/chapters, which reduces the effort required for change over by an instructor.

One benefit of teaching process control from a Laplace or State-space domain is the ability to precisely formulate and synthesize controllers. For example, the Direct Synthesis method allows for a precise solution to be obtained based on the characteristics of the Laplace model used to represent the process. However, with the inherent interactions and complexities that are present even on a simple distillation model, the synthesis and tuning of controller will have some level of ambiguity. This type of ambiguity can be somewhat difficult for some students to handle.

Conclusions

This paper proposes a real-time approach to distillation control education philosophy that involves developing and utilizing digital models on industrial simulators. The detailed content for such an approach is described, including the real-time workshops that are key for promoting a hands-on learning approach. The expected benefits and challenges of transitioning control education from the traditional approach to a simulation-based approach are identified and discussed.

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