



# Process Control Case Study: Fired Heater

## APPENDIX

# K

Short examples of many process control designs are presented in the solved examples in the book. In this appendix, the control of a fired heater is considered *in detail*. A fired heater is chosen because it is one of the most important unit operations in the chemical industry. Also, fired heaters provide excellent learning experiences for nonlinear, multivariable processes with significant interactions. The exercises in this appendix can be completed without the aid of a simulator. However, complementary simulation exercises will substantially enhance the learning experience.\*

This appendix enables readers to apply their process and control skills to the control of a fired heater by performing a series of exercises of increasing complexity. Many of the exercises involve open-ended questions to give you experience in defining and solving realistic problems. Since successful process control relies on knowledge from process technology and instrumentation, readers are encouraged to utilize their library, Internet, and self-study skills to investigate issues raised in these exercises. The references at the end of this appendix provide good initial sources of information and an introduction to the literature on fired heaters and their control.

The exercises in this appendix cover the topics in the same order as in the body of the book. To assist the readers, the exercises are organized according to the six

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\* A menu-driven, fired heater simulation is available in the Software Laboratory, Version 3.0 (Marlin, 1999), which runs within the MATLAB<sup>TM</sup> language (Mathworks, 1998). In addition, commercial flowsheeting programs have the capability to simulate process dynamics using standard models and rigorous physical properties; examples are Aspen Dynamics<sup>TM</sup> (Aspen, 1999) and HYSIS (Hyprotech, 1998).



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major parts of the book. The best manner for using this appendix is as “capstone” exercises at the completion of each part of the book. The student should have the opportunity to review solutions to each part before proceeding to the next, so that prior learning provides a solid foundation for future challenges.

### PART I: INTRODUCTION

In Part I of the book, control terminology, concepts, and objectives are introduced. The exercises in this section of the appendix enable you to apply these topics to prepare for the study of fired heater control. The example fired heater used in this appendix is shown in Figure K.1 with base-case data.

#### K.1. Fired Heater Process Principles

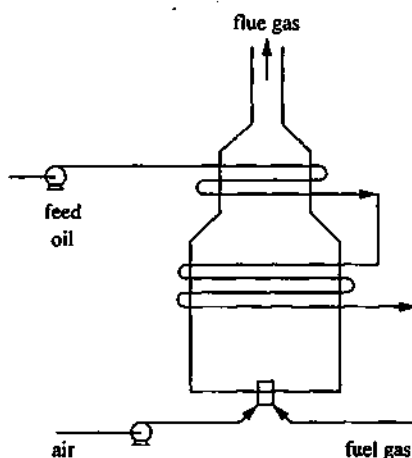
Before beginning control design and implementation, we should always be sure to understand the process technology. The questions in Table K.1 provide this check for the fired heater.

#### K.2. Objectives

Present typical process control objectives grouped into the seven objective categories presented in Chapter 2. You should be as specific as possible, not just saying that “The process should remain safe” or “Profit should be maximized.” Remember, these objectives must be clear enough to direct the control design and implementation.

#### K.3. Potential Benefits from Control

Answer the following questions for a simple fired heater like the one shown in Figure K.1.



Base-Case Data	
Feed flow rate	0.121 m <sup>3</sup> /s
Feed temperature	214° C
Fuel flow rate	0.51 Sm <sup>3</sup> /s
Fuel composition	100% methane
Air flow rate	4.72 Sm <sup>3</sup> /s
Oil outlet temperature	285° C
Box pressure	-177 Pa, gauge
Flue gas oxygen	2.00 mole%
Flue gas temperature	460° C

**FIGURE K.1**

Fired heater with base-case data. Note that the exit oil remains 100% liquid.



TABLE K.1

### Questions on fired heater process principles

1. Describe two applications for a fired heater.
2. Why/when is a fired heater used rather than a steam heat exchanger?
3. Why does the pipe (coil) enter the heater above the radiant section?
4. Define energy efficiency and describe how it is calculated using process measurements.
5. The pressure inside the firebox is lower than outside; why does flue gas exit without compression?
6. How is the best value of the air flow rate determined?
7. Describe potential unsafe operating situations and how they are avoided.
8. A fired heater may have more than one burner. Discuss why.
9. A coil in a fired heater may be split into several pipes that pass through the heater and are combined at the exit of the heater. Discuss why this design might be used. Do you expect challenges with this design?
10. Flue gas exits to the environment via the stack at a high temperature. How might more energy be recovered from the flue gas by heat transfer, with the effect of reducing fuel consumption?
11. Discuss factors that determine the minimum allowable temperature of the flue gas as it leaves the fired heater convection section.

Summary of Historical Data	
Fraction of Time	Oxygen mole %
0.10	1.0
0.12	2.0
0.23	3.0
0.20	4.0
0.27	5.0
0.08	6.0

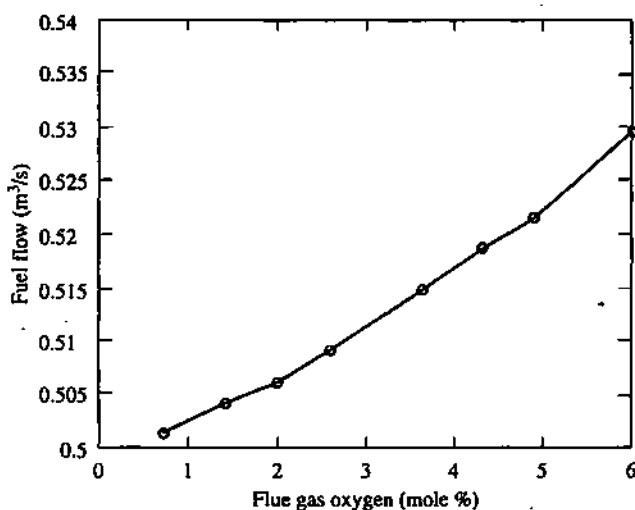


FIGURE K.2

Operating data for the fired heater with a feed flow rate of  $0.121 \text{ m}^3/\text{s}$ .

1. Explain input variables and equipment performance factors that are likely to affect the profit of an operating fired heater; do not include design decisions like the heat transfer area in the radiant section that cannot be changed during normal operation.
2. What information is required to determine the costs for the energy used as fuel?
3. Some data is provided for the fired heater in Figure K.2. From this data, (a) estimate the average energy consumption per  $\text{m}^3$  of feed and (b) the absolute



minimum energy consumption per  $\text{m}^3$  of feed. Recall that the fuel is methane. For this question, you can use the value of  $2200 \text{ J}/(\text{kg K})$  for the capacity of the oil.

## **PART II: PROCESS DYNAMICS**

Process control requires an excellent understanding of the dynamic behavior of the plant. This knowledge is used to

1. Build plants that are easy to control
2. Design control systems
3. Determine the effects of operations changes (production rate, product quality, etc.) on control performance to decide, for example, when adjustments in the computer control calculations are required

Here, questions are presented to help the reader understand the dynamics of a fired heater. Some further material on fired heater modelling and numerical simulation is available in Roffel and Rijnsdorp (1974).

### **K.4. Process Reaction Curves**

The fired heater in Figure K.1 is considered here. Process reaction curves are presented in Figure K.3.

1. What can you conclude about the linearity of the process?
2. Based on your understanding of the fired heater, confirm the directions of the changes in the plotted dependent variables for the specified input changes.
3. Discuss the causal relationships between inputs (air and fuel flow) and outputs (all plotted variables). Looking ahead, what important features in these responses would make feedback control potentially easy or difficult?

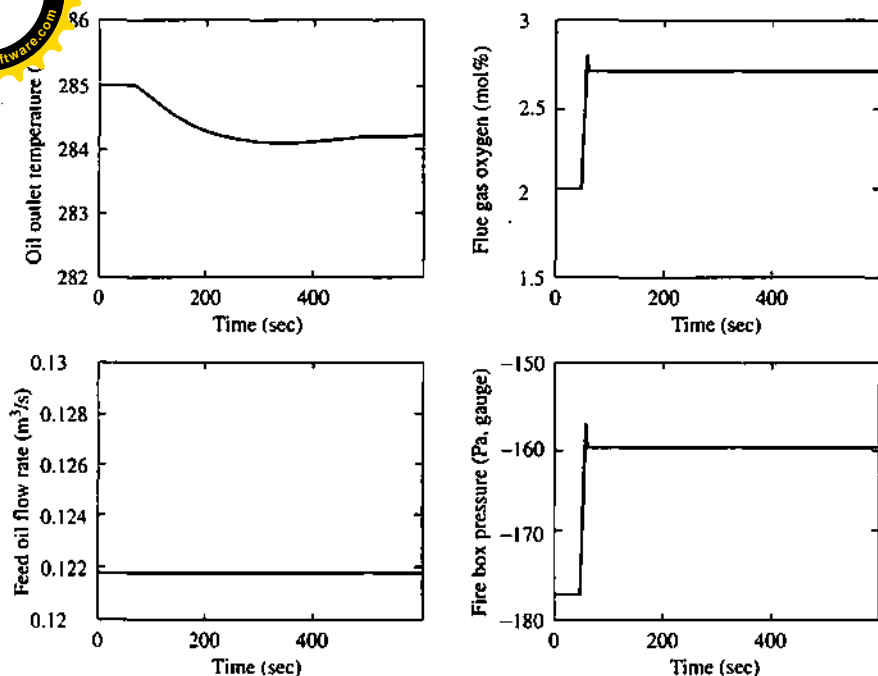
### **K.5. Open-Loop Feedback Dynamics**

The following questions provide thought exercises on the effects of equipment and operating parameters on fired heater dynamics.

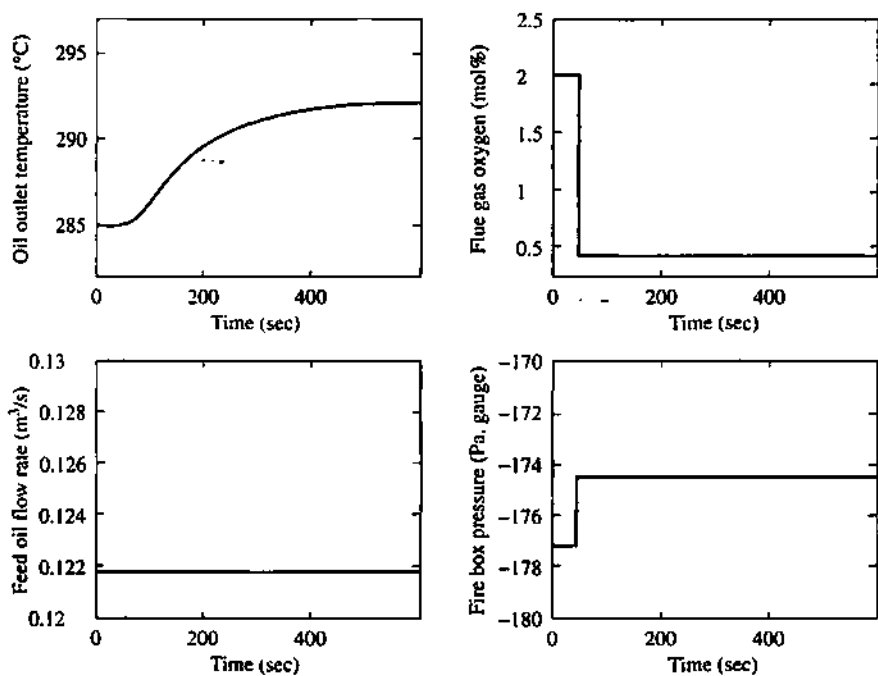
1. How would the approximate steady-state gain, time constant(s), and dead time depend on the oil feed flow rate for the response between the input fuel valve change and the output oil exit temperature?
2. The dynamic response of the oil outlet temperature for a change in fuel takes many minutes to reach steady state in spite of the very short residence time of oil in the pipe. Why?

### **K.6. Disturbance Responses**

The fired heater in Figure K.1 is considered here. Disturbance responses are presented in Figure K.4.



(a)

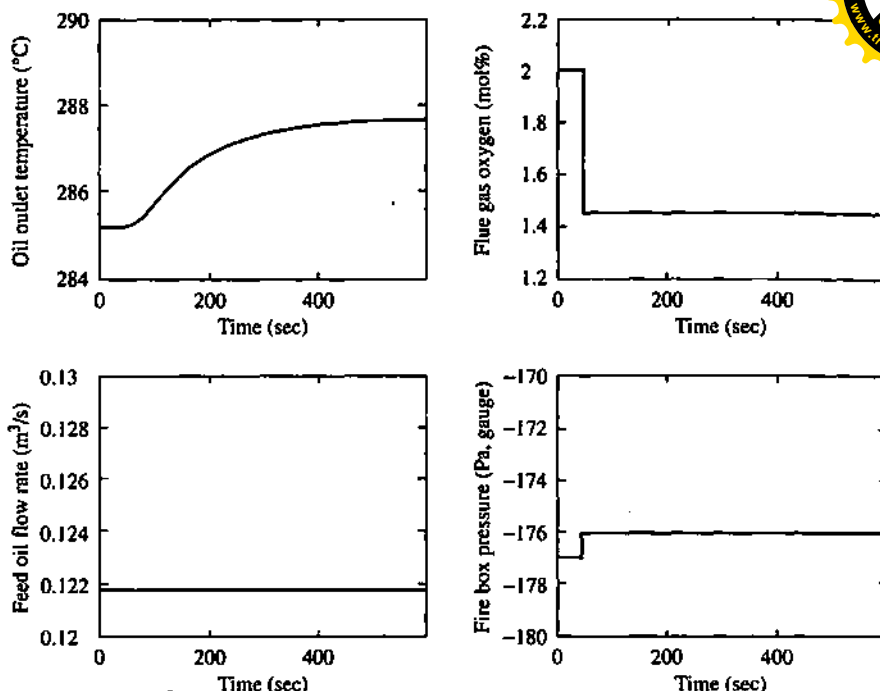


(b)

**FIGURE K.3**

(a) Dynamic response for a step from 46.95 to 49% opening of air valve. All plotted variables are dependent variables. (b) Dynamic response for a step from 20.95 to 23% opening of fuel valve. All plotted variables are dependent variables.

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**FIGURE K.4**

Dynamic response for a step change in fuel composition from 100% methane to 90% methane and 10% ethane at time = 50 minutes.

1. The experimental data in Figures K.3 and K.4 both present input-output results. What is the major difference between the input variables in these two figures?
2. Based on your understanding of the fired heater, confirm the directions of the changes in the plotted dependent variables for various input changes.
3. Discuss the causal relationships between disturbance input and process outputs. Looking ahead, what important features in these responses would make feedback control potentially easy or difficult?

## PART III: FEEDBACK CONTROL

The process dynamics and disturbance characteristics determine the best possible control performance, but the actual performance is strongly influenced by the control design and implementation. A good design often results in safe and profitable operation providing consistently high product quality. The exercises in this part provide the opportunity to combine the process understanding acquired in Part II with control technology to provide good single-loop feedback control.

### K.7. Sensor Selection

Review and enhance the control objectives for the fired heater that you developed in Exercise K.2. For each objective identify one or more sensors required to achieve the objective. Indicate the location of the sensor on a process schematic and indicate



the variable range and physical principle. For analyzers, discuss the sample system needed and determine the locations for the “fast loop” withdrawal and return.

### **K.8. Control Valves**

Process control requires manipulated variables, which are most often valves that affect flow rates. Locate all automated control valves on a process schematic. Determine the maximum flow rating, failure position, and body type. Feedback control tends to transfer variation from the controlled to the manipulated variables; explain briefly why the variation is less costly in the flows affected by these valves than in the controlled variables identified in Exercise K.7.

### **K.9. Control Performance**

Suggest quantitative control performance measures that could be calculated from plant data on the controlled and manipulated variables identified in Exercises K.7 and K.8.

### **K.10. Single-Loop Design**

For each of the controlled variables identified in Exercise K.7, select a manipulated variable to adjust from the valves identified in Exercise K.8. Select modes for each controller.

### **K.11. Controller Tuning**

Tune each single-loop PID controller you designed in Exercise K.10 using models based on the data in Figure K.3. Estimate the longest digital controller execution periods that would not degrade control performance for each controller.

### **K.12. Display**

Sketch a real-time screen to be displayed by a digital control system to be used by a plant operator to monitor and intervene in the operation of the fired heater. Indicate what data should be displayed and how (numbers, bar charts, trend plots, etc.) and what parameters could be changed by the plant personnel.

## **PART IV: ENHANCEMENTS TO SINGLE-LOOP CONTROL**

The performance of feedback is limited by the process dynamics in the feedback and disturbance paths. Substantial improvements to control performance are possible through single-loop enhancements that utilize additional sensors and models. The exercises in this part of the appendix enable the reader to apply these enhancements to a fired heater.

### **K.13. Cascade Control**

List disturbances that will affect the fired heater. For each, determine whether cascade control would improve the performance of the control design you developed in Exercise K.10. Sketch the cascade controls you recommend on a process schematic.



### **K.14. Feedforward Control**

Consider the control of the outlet temperature of the oil in the pipe. List disturbances that affect this temperature, and for each, determine whether feedforward control would improve the performance provided by the feedback controller of the temperature. Sketch one of the feedback-feedforward controller designs on a process schematic. Design the feedforward controller using the data in Figures K.3 and K.4.

### **K.15. Ratio Control**

A colleague suggests that the fuel flow should be adjusted so that it is a constant ratio of the feed flow rate, e.g.,  $\text{fuel/feed} = \text{constant}$ . Discuss the advantages and disadvantages of this design and how oil outlet temperature feedback could be included in the design. Decide whether you would agree to implement the design.

### **K.16. Operating Conditions**

The set point of the temperature of the oil leaving the fired heater is increased by 10 K. Does anything in the control implementation have to be changed in response?

### **K.17. Inferential Control**

You would like to maintain the efficiency of the fired heater as high as possible; however, all measurements to calculate efficiency are not available. Discuss alternative control designs to maintain high efficiency.

### **K.18. Performance Monitoring**

What affects the long-term heat transfer coefficients of the convective heat transfer in the convection section of the heater? What can be done to recover a high heat transfer coefficient?

### **K.19. Internal Model Control**

Replace one or more of the single-loop controllers in Exercise K.11 with IMC or Smith predictor controllers, and calculate the tuning. Estimate the longest digital controller execution periods that would not degrade control performance for each controller.

## **PART V. MULTIVARIABLE CONTROL**

The dynamic behavior of several single-loop controllers applied to a process differs from the individual loop behavior because of interaction. Interaction affects the controllability, operating window, stability and tuning, and dynamic behavior of the controlled and manipulated variables. The exercises in this part provide the opportunity to consider the effects of interaction on the control of a fired heater.





## K.20. Possible Designs

Consider the following controlled variables: (a) coil outlet temperature, (b) fire box pressure, (c) feed flow rate, and (d) combustion excess oxygen. First, provide four control valves for this process.

1. Determine the maximum number of possible loop pairings for this situation.
2. Determine some of these pairings which can be quickly eliminated from consideration and explain why.

## K.21. Operating Window

For the fired heater in Figure K.1, determine the operating window with set points of the feed flow and the oil outlet temperature on the coordinates. For this exercise, the air flow and fuel flow are limited by the following values:  $2.0 \leq F_{\text{air}} \leq 6.3$   $\text{Sm}^3/\text{s}$  and  $0.30 \leq F_{\text{fuel}} \leq 0.60$   $\text{Sm}^3/\text{s}$ . (You will need a steady-state simulator for this exercise.)

## K.22. Relative Gain

Calculate the steady-state gains between the inputs (valves affecting the air flow, fuel flow, feed flow, and flue gas flow) and outputs with sufficient accuracy to reliably evaluate the relative gain array. (You will need a steady-state simulator for this exercise.)

## K.23. Controller Tuning

Based on quantitative and qualitative information, select the control loop pairings for the fired heater. Using the process reaction curves in Figure K.3, calculate the tuning for all feedback controllers.

## K.24. Decoupling

For the fired heater in Figure K.1, answer the following questions.

1. Discuss when decoupling might be advantageous.
2. Design explicit decouplers for two-way decoupling using the data in Figure K.3.
3. Discuss the likely errors in the decouplers and the effect of these errors on dynamic performance of PI controllers with decoupling.

## K.25. Variable Structure

1. Discuss why minimum and maximum bounds exist on the fuel flow rate. Design a control system that normally controls the oil outlet temperature to its set point but maintains the fuel flow within bounds, even if the temperature decreases below its set point.



2. Discuss why minimum and maximum bounds would exist on the air flow. Design a control system that normally controls the oil outlet temperature at its set point but maintains the air flow within bounds, even if the temperature decreases below its set point.

## **PART VI. PROCESS CONTROL DESIGN**

Design enables the engineer to “bring it all together.” In the design process, the engineer applies analysis methods and guidelines to prepare a complete specification of the control structure, calculations, and equipment. The exercises in this part provide the opportunity to complete the control design for a fired heater. Since design depends on the context, you will have to make various assumptions when completing the exercises. In contrast, the practicing engineer would have to determine these factors from market analysis, quality control specifications, ancillary plant equipment layout, and so forth.

### **K.26. Control Design Form**

Prepare a control design form (CDF) for the fired heater described in Figure K.1. You might prepare a preliminary version, and complete the CDF after preparing answers for the following exercises in this part.

### **K.27. Sensors**

Specify the sensors required for safety, control, optimization, and monitoring of the fired heater. For each sensor, define the physical principle, range, accuracy and reproducibility, and indicate the location of each sensor on a process schematic. For analyzers, discuss whether a sample system is needed.

### **K.28. Valves**

Specify all valves (final control elements) that are needed to control the fired heater. For each valve, define the capacity (maximum flow), failure position, and the need for block and bypass “hand valves” that can be opened and closed by a plant operator, but not remotely.

### **K.29. Control Design**

Design a closed-loop control system that will achieve the control objectives you specified in Exercise K.26.

### **K.30. Control for Safety**

Perform a safety review of the process with your control design and add control and equipment to ensure safe operation. Your answer should include automated control and provision for operator monitoring of safety-related issues.



## K.31. Optimization

Discuss opportunities for optimizing a fired heater. Define factors that would appear in a calculation of profit and how these would be measured. Identify variables that can be changed during normal operation that influence profit and what tradeoffs exist that would lead to an optimum, i.e., a maximum when profit is plotted against the variable. Finally, describe a method for optimizing a fired heater in real time.

## K.32. Monitoring

Identify process equipment and operations factors that should be monitored by plant personnel to ensure proper plant operation. For each factor, define the sensors or laboratory data required, the analysis performed by the personnel, the decision and threshold value that would indicate a change is required, and the time frame for this monitoring, i.e., every half hour, once a month, etc. Discuss the use of statistical monitoring methods in the plant monitoring.

Congratulations! You have now completed an analysis and control design for one fired heater. Hopefully, these exercises have reinforced the importance of learning the material in the book and improved your ability to apply the principles to realistic challenges. You should not interpret the large number of exercises as an indication of the documentation typically developed in designing controls for a single fired heater. Here, many exercises have been provided to help you learn. After gaining experience through university education and industrial practice, you will be performing this analysis rapidly, although perhaps on different unit operations.

The exercises in this appendix follow the organization in the book, which introduces topics gradually. Now that you have learned the material, you can apply process control principles and guidelines more directly.

Therefore, the control design approaches in Chapters 24 and 25 are recommended when you apply control engineering to real industrial challenges.

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**APPENDIX K**  
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