Chemical Process Dynamics and Control

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Energy, Water and Food: The New Challenges of the 21st Century (from National Science Foundation)

How to resolve Energy, Water and Food problems?

Question 1: What is the best way to solve the current energy problem?
Good process control saves Energy, Material and Environment!

The US Wastes Enough Energy Each Year to Power the UK for Seven Years

By James Burgess - Aug 26, 2013, 5:05 PM CDT

Each year the Lawrence Livermore National Laboratory releases an analysis of the energy input and energy use of the US economy to determine the energy efficiency.

It might be somewhat surprising to know that in 2012 the US wasted 61% of all energy input into its economy, making it just 39% energy efficient.

Of the 95.1 quadrillion British Thermal Units (BTUs) of raw energy that entered the US economy, only 37.0 quadrillion BTUs were actually used, with the other 58.1 quadrillion BTUs being wasted.

Related article: US Energy Boom to Create 500,000 Additional Jobs by 2020
Example: hot tub

- Maintain temperature
- Suppress the effect of external disturbances
- Reduce the utility cost $\$\$\$\$
A furnace temperature control scheme

Old Controller

New Controller

Hot tub

TT

TC

Temperature

Limit

Time

Hot water

Cooling water

Stack gas

Furnace

Fuel gas / air
How to achieve lower energy costs and lower emissions (CO$_2$, NOx, and unburned hydrocarbons)?

1. Reduce excess air
2. Improve heat transfer
3. Improve heat containment
4. Waste heat recovery
5. Use control theory to optimize above processes

http://www.secat.net/docs/energy_saving_opportunities.pdf
General representation of a process control problem

Disturbance variables (e.g., Environmental temperature)

Manipulated variables (e.g., gas flow rate; gas/air ratio)

Process

Output: Controlled variables (e.g., hot tub water temperature), observable quantity that we want to regulate.
Control Tradeoffs

1. The quality vs quantity of the products
   (waste reduction; Variance reduction; Savings in energy, materials, manpower) vs (production rate and quantity)

2. The safety/reliability of a process vs profitability

The closer that you are able to operate to these constraints, the more profit you may make. For example, maximizing the product production rate usually involving controlling the process against one or more process constraints. (Safety vs. Cost)
why do we need process control?

- **Product quality specifications and production rate**
  - Maintain specifications of product
  - For many cases, reduced variability products are in high demand and have high value added (e.g., drugs)
  - Product certification procedures (e.g., ISO9000) are used to guarantee product quality and place a large emphasis on process control.

- **Energy and material efficiency (Economics)**
  - Economical utilization of raw materials and energy (also human labor)

- **Environmental Regulations**
  - E.g., Flow rates of effluents from plants must be within allowable limits

- **Process Safety**
1. Model and predict the transient behavior of processes (Chapter 1~7).

2. The use of process dynamics to change the process towards an optimal direction for the improvement of process operation and performance or alleviate the effect of unstable process behaviors (Chapter 8~16).
Other classes: Industrially Relevant Process Engineering Skills

Bridging the Gap between Academia and Industry!

• Process design (Spring semester):
  – capital and operating cost estimations; introduction to design and design strategies (Consider process dynamics and control issues early in the process design!)

• Process control laboratory (Spring semester)
  – Control hardware and troubleshooting
  – Controller Implementation and tuning
  – Control systems
  – Advanced PID techniques
  – MIMO control

• Bioprocess Engineering (Spring semester)
What constitutes a control system?

Combination of process sensors, actuators and computer systems designed and tuned to orchestrate safe and profitable operation.

What is required?
1. Process Understanding (modeling)
2. Process Instrumentation (sensor and actuator; computer architecture)
3. Process Control (control strategy)
Control System Development

Objectives

“What are we trying to control?”

Identification of Inputs (affect process) and Outputs of process

Inputs: Disturbance variables/Manipulated variables

Process modeling

“What will process be?”

Controller design

“How to reach our process control objectives?”

What variables should we measure?
What variables should we control?
What are the best manipulated variables?

Implement and tune the controlled process

Monitor performance
Overview of Control System Design
ISA standard (Instrument Society of America)

The first letter defines the measured or initiating variables:
Analysis (A), Flow (F), Temperature (T), Level (L), Pressure (P), Quantity (Q), Weight/Force (W).

Succeeding letters define readout, passive, or output functions:
Alarm (A), Control (C), Indicator (I), Record (R), Transmit (T), Actuator/Driver (Z), Sensor (S), Meter (M).

Pneumatic signal (solid line) and electronic signal (dash line)
Overview of Control System Design
Heat Exchanger Control

Product Stream

TC

Steam

Feed

TT

Condensate
Control Methods

• **Feedback** control
  – The process variable of interest is measured and used to adjust another process variable

• **Feedforward** control
  – Measure disturbances and take corrective action before they upset the process
Types of Feedback Controllers

- **On-Off Control** - e.g., room thermostat
- **Manual Control** - Used by operators and based on more or less open loop responses
- **PID (Proportional, integral and derivative) control**
  - Most commonly used controller. Control action based on error from setpoint.
  - Advanced PID - Enhancements of PID: ratio, cascade.
Feedforward control (measure disturbance variable)

Disadvantage: Need a process model; all disturbance variables have to be measured (can not do with novel disturbances).

Advantage: Respond quickly to measurable kinds of disturbances (A large feedback time delay; A feedback loop period close to the load upset period; A severe feedback operating point nonlinearity).
Heat Exchanger Control

- Controlled variable
- Manipulated variable
- Actuator
- Sensor
- Disturbance
Feedback Control

Example: stirred tank heater

Set-point

Controller

T_{o}, F_{o}, X_{o}

T_{c}

X, F, T

Thermocouple
System components

- Operator dials in a set-point (desired temperature)
- Thermocouple measures temperature in tank
- Measured temperature is compared to set-point
- Controller manipulates steam valve based on difference between set-point and measurement

Block Diagram for feedback control (Text book: Figure 1.6)
Industrial feedback control provides Negative feedback. A process influences the operation of the process itself in such a way as to reduce changes.

Positive feedback is a process in which the effects of a small disturbance on a system include an increase in the magnitude of the perturbation.
Feedforward control
Example: stirred tank heater

Thermocouple → Controller → To, Fo, Xo

Tc → X, F, T
System components

- Operator develops model of system
- Thermocouple measures temperature in inlet stream
- Measured temperature is input to process model
- Controller manipulates steam valve based on model prediction
Schematic of Feedback Loop
Car example

Where the driver wants to go

[Difference]

Driver’s brain

Steering wheel

Driving a car

Current location on road

Signal from eyes to brain

Driver’s eyes

Curve in road

Front wheel orientation

https://www.youtube.com/watch?v=_luhn7TLfWU
Feed Back
All control system contains: the controller, the actuator, the process, and the sensor.
Example 1: A Blending Process

Method 1

Mixture of A and B X₁ and W₁

Pure A X₂=1 W₂

Product A X, W (X>X₁)

????: X=X_{sp}
A Blending Process

Method 2

Mixture of A and B
X₁ and W₁

Pure A
X₂=1
W₂

Product
X, W

???: X=X_{sp}
A Blending Process

Method 3

Mixture of A and B
X_1 and W_1

Pure A
X_2=1
W_2

Product
X, W
1. Control Loop contains many subsystems
2. Each subsystem (control computer, actuator system, and sensor system) should function properly.
Overview of a common digital control System

- Based upon a mainframe digital computer.
- Offered the ability to use data storage and retrieval, alarm functions, and process optimization.
- First installed on a refinery in 1959.
Instrumentation

Sensor, Control loop, Valve (actuator)
Dynamics for Control System Instrumentation

The process responds dynamically to the change in the manipulated variable. Meanwhile, Control systems affect the process through the actuator system which has its own dynamics; The response of the process is measured by sensor system which has its own dynamics.
Consider a steam heater as an example: 1. An increase in the flow rate of steam to the heater. 2. The temperature of the metal tubes in the heater increases in a lagged manner.
Dynamic Model for Sensors

- Case 1: \( Ts \) equations assume that the sensors behave as a first order process.

- Case 2: \( Cs \) assumes that the analyzer behaves as a deadtime element.

\[
\frac{dT_s}{dt} = k_s \cdot [T - T_s]
\]

\[
C_s(t) = C(t - \theta_A)
\]

\( \theta = \text{Length} / v \)
Transmitter Error

Span: adjustable input range
Zero: lower limit (input)
Gain: $K = \text{range (output)} / \text{range (input)}$

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 °C</td>
<td>4 mA</td>
</tr>
<tr>
<td>T=60 °C</td>
<td>?</td>
</tr>
<tr>
<td>150 °C</td>
<td>20 mA</td>
</tr>
</tbody>
</table>
In the fields of science, engineering and statistics, the accuracy of a measurement is the degree of closeness of measurements of a quantity to that quantity's true value. The precision, also called reproducibility or repeatability, is the degree to which repeated measurements under unchanged conditions show the same results.
Error: 1. The difference between the true value and the measured value

Resolution: 2. The variability of a measurement for a specified condition (standard deviation).

Precision: 3. The smallest interval between two numerical values

Bias: 4. A constant error due to a deterministic cause rather than random variation

A pressure gauge reads from 0~20 bars. A student used the gauge to measure a tank pressure for three times. He got the reading: 10.2, 10.3, 10.5 bars. (What is error, resolution, precision, bias?)
Controllers

Pneumatic

- Introduced in the 1920’s
- Installed in the field next to the valve
- Provided automatic control and replaced manual control for many loops
Pneumatic Controller Installation

Transmitter: converts the sensor measurement to a signal

In this book: Transmitter = sensor
Electronic Analog Controllers

- Became available in the late 1950’s.
- Replaced the pneumatic tubing with wires.
- Out sold pneumatic controllers by 1970.
- Allowed for advanced PID control

Transducer: one signal to other signal

Diagram:
- F₁, T₁, 3-15 psig
- Air, I/P, 4-20 ma
- Tₚ, Ts_p
- Electronic Analog Controller
- F₂, T₂, T
- Thermowell
- Thermocouple millivolt signal
- Transmitter
**AIR-TO-CLOSE:** An increase in air pressure to the ACTUATOR is required to cause the valve to close. This is another way of saying the valve is Fail Open.

**AIR-TO-OPEN:** An increase in air pressure to the ACTUATOR is required to cause the valve to open. This is another way of saying the valve is FAIL CLOSED.
For Large Diameter Line (>6”), Use a Butterfly Valve

The closing mechanism takes the form of a disk. The disc is positioned in the center of the pipe, passing through the disc is a rod connected to an actuator on the outside of the valve. Rotating the actuator turns the disc either parallel or perpendicular to the flow.

Control of flow rate by valve

When valve is open, if flow can be linear with the resistance R (constant): $q = \Delta P / R$
Valve Characteristics (Ch 9.2)

\[ q = C_v f(l) \sqrt{\frac{\Delta P_v}{g_s}} \]

- \( q \): flow rate; \( C_v \): valve coefficient
- \( f(l) \): valve characteristic
- \( l \): lift
- \( \Delta P_v \): pressure drop
- \( g \): liquid specific gravity

\( f(l) = l \) (linear)
\( f(l) = l^{1/2}(QO) \)
\( f(l) = R^{l-1}(Eq\%) \)
Types of Globe Valves

- **Quick Opening** - used for safety by-pass applications where quick opening is desired
- **Equal Percentage** - used for about 90% of control valve applications since it results in the most linear installed characteristics
- **Linear** - used when a relatively constant pressure drop is maintained across the valve

Note: The valve would be sized to take most of the pressure drop in the lines (maximum influence over process); economical operation requires small pressure drop (*in general, ¼ or 1/3 P loss in the line*).
Chemical Process Safety
Chemical Process environmental risks
(The temperatures, pressures, and concentrations within the system should all fall within acceptable limits)

• Basic process control system (BPCS)
  – Regulate routine process operation

• Process Alarms
  – Call attention to abnormal situations

• Safety Interlock System (SIS)
  – Independent of BPCS
  – Starts during a critical process variable (e.g. shutting down the process)

Blowout preventer (BP)


Components and Signals of a Typical Control Loop

Distributed control system (DCS): controller elements are distributed throughout the system with each component sub-system controlled by controllers.
Determine which of the 5 valves should be fail-close (F/C) or fail-open (F/O) for safe operation of the distillation column (achieved by the lowest temperature and pressure in the column)
Reliability: the probability that the component does not fail

(Discuss Reliability concepts Table 10.1)
Help session 1

HW1: 1.1; 1.7; 2.3; 2.7; 2.13; 9.1; 9.2; 9.10; 10.3; 10.7

Due on Sept 7