ChEN 403
Process Dynamics & Control

Introduction
Course Topics

- Math Modeling of Chemical Processes
- Solution of ODEs
  - Laplace Transforms – **Primary Emphasis**
  - General Analytical Techniques
  - Numerical Methods
- Transfer Functions
- Behavior of 1st, 2nd, & Higher Order Systems
- Fitting Model Parameters to Data
- Feedback Control - Behavior & Stability
- Design & Tuning of Controllers
- Advanced Control Schemes
- Case Study
Mathematical Nomenclature

• The nomenclature isn't what's important, it’s the concepts!
  » Pretty much any symbols could be (and probably are) used
  » Understand what's going on rather than memorizing symbols
• Will strive for consistency in the notes, homework, exams, etc.
  » May be different from the text books, however
## Typical Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>Volumetric flow rate</td>
</tr>
<tr>
<td>$F'$</td>
<td>Deviation variable</td>
</tr>
<tr>
<td>$\bar{F}'$</td>
<td>Laplace transform of deviation variable</td>
</tr>
<tr>
<td>$F^*$</td>
<td>Steady state value</td>
</tr>
<tr>
<td>$\hat{C}_p$</td>
<td>Heat capacity (mass basis)</td>
</tr>
<tr>
<td>$\tilde{C}_p$</td>
<td>Heat capacity (molar basis)</td>
</tr>
<tr>
<td>$C_v$</td>
<td>Valve coefficient</td>
</tr>
</tbody>
</table>
Importance of Process Control

- Directly affects the safety and reliability of a process
  - Control system must provide safe operation
  - Control system must be able to “absorb” a variety of disturbances & keep the process in a good operating region
- Determines the quality of the products produced by a process
- Can affect how efficient a process is operated
- Bottom Line: process control has a major impact on the profitability of a company.
Benefits of Improved Control

**Old Controller**

- Impurity Concentration
- Limit
- Time

**New Controller**

- Improved Performance
- Impurity Concentration
- Limit
- Time

**Improved Performance**

- Impurity Concentration
- Limit
- Time
Let’s think about a simple household example
The Dynamics of the Household Shower

• What are the controlled or manipulated inputs? (What part of the system can be directly changed?)
• What are the set points? (What end result is desired?)
• What are the uncontrolled inputs? (What disturbances can happen outside of the shower stall?)
• Why might the set points change? (Do you want to run the shower the same way, morning or night, summer or winter, …?)
• What are the benefits of controlling this process?
Design Aspects of Process Control Systems

- **Manipulated variables**
  - Variables that can be adjusted by the operator or controller
- **Disturbances**
  - Uncontrolled changes, such as weather or feed composition
- **Measured variables**
  - Values can be directly measured
- **Unmeasured variables**
  - Values cannot be directly measured
Control Objectives

• Operational objectives
  » Stability of process
  » Suppress influence of disturbances
  » Optimize performance of plant
• What variables should be measured?
• What variables should be manipulated?
• What is the best control configuration?
• How should measurements be used to adjust the manipulated variables?
Process Control Goals

- Suppress the influence of external disturbances
- Ensure the stability of a chemical process
Process Control & Optimization

• Control & optimization are terms that are many times erroneously interchanged
  » Control: adjusting manipulated variables to maintain the controlled variables of the process at specified setpoints
  » Optimization: chooses the values for key setpoints such that the process operates at the “best” economic conditions
Process Control Hardware

- Measurement element
  - Orifice meter
  - Thermocouple
- Transmitter
- Control Valve (with actuator, positioner, & I/P)
- DCS Controller & I/O cards
- DCS Communication Network (a LAN)
- DCS Operator Console
- Advanced Control Computer
Cross-section of a Globe Valve
Information Flow Diagram
Recognize Standard Forms

\[ \frac{y}{\alpha K_p} = \begin{cases} 
\zeta = 0.1 \\
\zeta = 0.5 \\
\zeta = 0.9 \\
\zeta = 1 \\
\zeta = 1.1 \\
\zeta = 5 \\
\zeta = 10 
\end{cases} \]
Recognize Standard Forms

Time

Time

Time
Rate of Mass & Energy Accumulation

- Material Balance Equation

\[
\frac{d(\rho V)}{dt} = \rho_0 F_0 - \rho F_1 \quad \Rightarrow \quad F_0 = F_1
\]

- Heat Balance Equation

\[
\frac{d(\rho V \hat{H})}{dt} = \rho_0 F_0 \hat{H}_0 - \rho_1 F_1 \hat{H}_1 + UA(T_s - T) \quad \Rightarrow \\
\left(\rho V \hat{C}_p\right) \frac{dT_1}{dt} + (\rho F_0 \hat{C}_p + UA) T_1 = \left(\rho F_0 \hat{C}_p\right) T_0 + (UA) T_s
\]
Transfer Functions

- Laplace transforms create a transfer function

\[
\left( \rho V \hat{C}_p \right) \frac{dT'_1}{dt} + \left( \rho F_0 \hat{C}_p + UA \right) T'_1 = \left( \rho F_0 \hat{C}_p \right) T'_0 + \left( UA \right) T'_s
\]

\[
\left( \frac{\rho V \hat{C}_p}{\rho F_0 \hat{C}_p + UA} \right) \frac{dT'_1}{dt} + T'_1 = \left( \frac{\rho F_0 \hat{C}_p}{\rho F_0 \hat{C}_p + UA} \right) T'_0 + \left( \frac{UA}{\rho F_0 \hat{C}_p + UA} \right) T'_s
\]

\[
\tau \frac{dT'_1}{dt} + T'_1 = K_0 \cdot T'_0 + K_s \cdot T'_s
\]

\[
\tau s T'_1 + T'_1 = K_0 \cdot \bar{T}'_0 + K_s \cdot \bar{T}'_s
\]

\[
\bar{T}'_1 = \frac{K_0}{\tau s + 1} \cdot \bar{T}'_0 + \frac{K_s}{\tau s + 1} \cdot \bar{T}'_s
\]
Uncontrolled Tank Temperature

Outlet Temperature, $T_1$ (°C)

Time, $t$ (min)
Control Loop Transfer Functions

- Uncontrolled response to disturbance

\[ \bar{T}_1' = \left[ \frac{K_0}{\tau s + 1} \right] \bar{T}_0' + \left[ \frac{K_s}{\tau s + 1} \right] \bar{T}_s' \quad \Rightarrow \quad T_1' = T_0'K_0 \left[ 1 - \exp\left( -\frac{t}{\tau} \right) \right] \]

- Closed loop response

\[ \frac{\bar{T}_1'}{\bar{T}_0'} = \frac{G_d}{1 + G_c G_p G_m} = \frac{K_0}{\tau s + 1 + G_c K_0} \]

P Control:

\[ \frac{\bar{T}_1'}{\bar{T}_0'} = \frac{K_0}{\tau s + 1 + K_c K_0} \quad \Rightarrow \quad T_1' = T_0' \frac{K_0}{1 + K_c K_0} \left[ 1 - \exp\left( -\frac{1 + K_c K_0}{\tau} t \right) \right] \]
Tank Temperature Under P Control

Outlet Temperature, $T_1$ (°C) vs. Time, $t$ (min) for Uncontrolled and P Control conditions.
Control Loop Transfer Functions

- Closed loop response
  PI Control:

\[
\frac{\bar{T}_1'}{\bar{T}_0'} = \frac{K_0}{\tau s + 1 + K_c \left(1 + \frac{1}{\tau_i s}\right) K_0}
\]

\[
= \left(\frac{\tau_i}{K_c}\right) s
\]

\[
= \left(\frac{\tau_i}{K_0 K_c}\right) s^2 + \tau_i \left(\frac{1}{K_0 K_c} + 1\right) s + 1
\]
Tank Temperature Under PI Control

![Graph showing temperature over time for different control conditions.]

- **Outlet Temperature, \( T_1 (°C) \)**
  - Uncontrolled
  - P Control
  - PI Control

- **Time, \( t \) (min)**
In Summary...

- Introduction to the course material
  - Why is process control important?
  - Some typical control problems
  - Process & information flow diagrams