Introduction to Plantwide Control

1. Introduction
2. Plantwide control issues
3. Reactor/distillation column plant
4. Alternative control strategies
5. Interaction of process design and control
Introduction

- Plantwide control involves the control of multiple, interacting process units

- Control system design
  - Individual unit operations – SISO/MIMO problems
  - Overall plant – manage interactions between units

- Mass recycle and energy integration
  - Improve process economics
  - Produce more difficult control problems
  - Disturbances more easily propagate between interconnected units
  - Can produce unexpected problems including high sensitivities to disturbances

- Motivates integrated plant design and control
Production Rate Control

(a) Downstream method: Plant production rate established with exit stream flow.

(b) Upstream method: Plant production rate established with inlet stream flow.
Heat Integration

• Increase interactions between columns
• Lose second column reboiler duty as a manipulated variable

• Increase interactions between units
• Introduces positive feedback
• Lose hot oil flow as a manipulated variable
Mass Recycle
Reactor/Distillation Column Plant

- Reaction: A $\rightarrow$ B
- Recycle overhead product concentrated in the more volatile component A back to reactor
- Control objective: control $x_B$ at setpoint despite disturbances in $F_0$ and $z_0$
## Candidate Control Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0^\dagger$</td>
<td>Reactor feed flow rate</td>
</tr>
<tr>
<td>$z_0$</td>
<td>Reactor feed composition</td>
</tr>
<tr>
<td>$H_R$</td>
<td>Reactor level (proportional to the holdup)</td>
</tr>
<tr>
<td>$F^\dagger$</td>
<td>Column feed flow rate (saturated liquid)</td>
</tr>
<tr>
<td>$z$</td>
<td>Column feed composition</td>
</tr>
<tr>
<td>$H_D$</td>
<td>Distillate reflux drum level</td>
</tr>
<tr>
<td>$R^\dagger$</td>
<td>Relex flow rate</td>
</tr>
<tr>
<td>$D^\dagger$</td>
<td>Distillate (recycle) flow rate</td>
</tr>
<tr>
<td>$H_B$</td>
<td>Bottoms level</td>
</tr>
<tr>
<td>$B^\dagger$</td>
<td>Bottoms (product) flow rate</td>
</tr>
<tr>
<td>$V^\dagger$</td>
<td>Reboiler (column) vapor flow rate</td>
</tr>
<tr>
<td>$x_D$</td>
<td>Distillate composition</td>
</tr>
<tr>
<td>$x_B$</td>
<td>Bottoms (product) composition</td>
</tr>
</tbody>
</table>

$^\dagger$ Denotes a stream flow rate that can be measured and adjusted by a control valve.

- **Column controlled outputs:** $H_D$, $H_B$, $x_D$, $x_B$
- **Column manipulated inputs:** $D$, $B$, $R$, $V$
- **Disturbances:** $F_0$, $z_0$
- **Remaining variables:** $H_R$, $F$, $z$
Alternative 1: $H_R$ is controlled by manipulating $F$. 

Control Design Alternative 1
The Snowball Effect

- Steady-state mass balances for constant $H_R$

  Column
  \[ F = D + B \]
  \[ F\bar{z} = D\bar{x}_D + B\bar{x}_B \]

  Plant
  \[ F_0 = B \]
  \[ F_0\bar{z}_0 = B\bar{x}_B + k_R H_R \bar{z} \]

- Limiting case: $x_D \approx 1 \quad x_B \approx 0$

- Steady-state distillate flow:
  \[ D = \frac{(F_0)^2\bar{z}_0}{k_R H_R - F_0^2\bar{z}_0} \]

- Distillate flow rate very sensitive to small changes in fresh feed conditions
Control Design Alternative 2

- **Steady-state mass balances for constant** $F$

\[
\bar{D} = \bar{F} - \bar{F}_0 \quad \bar{H}_R = \frac{\bar{z}_0}{k_R \left( \frac{1}{\bar{F}_0} - \frac{1}{\bar{F}} \right)}
\]
Control Design Alternative 3

- $H_R$ is controlled by manipulating $D$
- $z$ is controlled by manipulating the set point of the $H_R$ controller
- $F/F_0$ is maintained constant by means of a ratio controller
Control Design Alternative 4

- $H_R$ is controlled by manipulating $D$
- $x_D$ is controlled by manipulating the set point of the $H_R$ controller
- $F/F_0$ is maintained constant by means of a ratio controller
## Comparison of Control Strategies

<table>
<thead>
<tr>
<th>Loop Number</th>
<th>Controller Type</th>
<th>Purpose of Control Loop</th>
<th>Controlled Variable</th>
<th>Manipulated Variable Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feedback</td>
<td>Reactor holdup</td>
<td>$H_R$</td>
<td>1, Floating, 2, $D^<em>$, 3, $D^</em>$</td>
</tr>
<tr>
<td>2</td>
<td>Feedback</td>
<td>Distillate holdup</td>
<td>$H_D$</td>
<td>2, $D$, 3, $R$, 4, $R$</td>
</tr>
<tr>
<td>3</td>
<td>Feedback</td>
<td>Bottoms holdup</td>
<td>$H_B$</td>
<td>3, $B$, 4, $B$, 4, $B$</td>
</tr>
<tr>
<td>4</td>
<td>Feedback</td>
<td>Bottoms composition</td>
<td>$x_B$</td>
<td>4, $V$, 4, $V$, 4, $V$</td>
</tr>
<tr>
<td>5a</td>
<td>Feedback</td>
<td>Distillate composition</td>
<td>$x_D$</td>
<td>5a, $R$, 5a, $R$</td>
</tr>
<tr>
<td>5b</td>
<td>Cascade**</td>
<td>Reactor composition</td>
<td>$z$</td>
<td>5b, $H_{R,sp}$ (Loop 1)</td>
</tr>
<tr>
<td>5c</td>
<td>Cascade**</td>
<td>Distillate composition</td>
<td>$x_D$</td>
<td>5c, $H_{R,sp}$ (Loop 1)</td>
</tr>
<tr>
<td>6</td>
<td>Feedback</td>
<td>Dist. column feed rate</td>
<td>$F$</td>
<td>6, $F^\dagger$, 6, $F^\dagger$</td>
</tr>
<tr>
<td>7</td>
<td>Ratio</td>
<td>Dist. column feed rate</td>
<td>$F$</td>
<td>7, $F$ set point (Loop 6), 7, $F$ set point (Loop 6)</td>
</tr>
</tbody>
</table>

$^\dagger$Denotes a flow stream adjusted by a flow controller

*Variable controlled in secondary loop of cascade controller (Alternatives 3 and 4 only)

**Primary loop of cascade controller (Alternatives 3 and 4 only)

### Alternative Pairings and Relative Gain ($\lambda$)

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Pairings</th>
<th>Relative Gain ($\lambda$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$x_D-R/x_B-V$</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>$x_D-R/x_B-V$</td>
<td>12.2</td>
</tr>
<tr>
<td>3</td>
<td>$z-H_{R,sp}/x_B-V$</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>$x_D-H_{R,sp}/x_B-V$</td>
<td>0.59</td>
</tr>
</tbody>
</table>
Dynamic Responses for Feed Changes

Fresh feed flow rate (-10%)

Fresh feed composition (-10%)

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Dynamic Responses for Feed Changes

Fresh feed flow rate (-10%)

Fresh feed composition (-10%)

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Dynamic Responses for Feed Changes

Fresh feed flow rate (-10%)

Fresh feed composition (-10%)

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Dynamic Responses for Feed Changes

Fresh feed flow rate (-10%)

Fresh feed composition (-10%)

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Process Design and Control

- **Traditional engineering practice**
  - Design plant based on steady-state considerations
  - Develop control system based on predetermined process design
  - Process design can be dynamically inoperable due to mass recycle and heat integration

- **Integrated process design and control**
  - Dynamic operability considered during process design stage
  - Need to compensate for lost degrees of freedom due to mass recycle and heat integration
  - Especially important for plant startup/shutdown where extra degrees of freedom are used