Batch Process Control

1. Introduction
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5. Batch production management
Introduction

- Batch operation is very common in the specialty chemical, pharmaceutical and materials processing industries
- Multiproduct batch plants produce a range of similar products using the same equipment
- Batch control is particularly difficult because there is no steady-state operating point and processes operate over a wide range of conditions
- Batch process control systems involve sequencing of different process steps and control during the batch
- Run-to-run control uses experience from previous batch runs to improve the current run
- Batch plant scheduling and planning are used to manage the production of different products
Batch Distillation Example

Possible manipulated variables:
- $Q_B$: Heat addition rate
- $Q_D$: Heat removal rate
- $R$: Reflux flow rate
- $D$: Distillate flow rate
- $S$: Solenoid switch

Possible controlled variables:
- $P$: Column top pressure
- $\Delta p$: Pressure drop
- $x_D$: Overhead composition
- $h$: Reflux accumulator level

Composition (ethanol mass fraction) vs. Time (min)

Composition:
- 1
- 0.8
- 0.6
- 0.4
- 0.2
- 0

Time (min):
- -10
- 0
- 10
- 20
- 30
- 40
- 50
- 60

Distillate
Reboiler
Batch Control Systems

- Sequencing and logic – sequencing of control steps according to a predefined recipe
- Control during the batch – tracking of predetermined setpoint trajectories
- Run-to-run control – end-of-batch measurements are used to improve control of the next batch
- Batch production management – planning of production needs and scheduling of product campaigns
Sequential and Logic Control

- Control of batch unit operations involves the proper sequencing and execution of specific steps.
- Sequential logic can be represented in several ways, such as information flow diagrams.
- Information flow diagrams can be translated into digital logic diagrams to be executed by programmable logic controllers (PLCs).
- PLCs can execute sequencing operations as well as standard PID control algorithms.
- PLCs are the key control hardware used in batch plants.
Batch Sequence Control Example

From PLC

VN 7
S
A
LXH 2
LH 2
LL 2

To PLC

VN 8
S
B

From PLC

MN 5

Close HS4

Open VN7

L ≥ LH2

No

Close VN7
Open VN8
Start MN5

L ≥ LXH2

No

Close VN8
Open VN9

L ≤ LL2

No

Close VN9
Stop MN5

End
Control During the Batch

- Execution of sequenced operations often involves feedback control of specified outputs.
- Batch control is challenging because there is no steady-state operating point and processes operate over a wide range of conditions.
- Tracking of predetermined setpoint trajectories is often required.
- Process nonlinearities and model inaccuracies become more pronounced when processes are operated over large regimes.
- Some product properties affected during a batch are irreversible once off target.
Batch Reactor Control
PI Control of Batch Reactors

Standard PI Controller

\[ u(t) = \bar{u} + K_c \left[ e(t) + \frac{1}{\tau_I} \int_0^t e(\tau) d\tau \right] \]

Jacket temperature

Reactor temperature

Set point

Time

Temperature

PI Controller with Preload

\[ u(t) = u_0 + K_c \left[ e(t) + \frac{1}{\tau_I} \int_0^t e(\tau) d\tau \right] \]

Set point

100% preload

0% preload

Correct preload

Time

Temperature

0%

100%
Rapid Thermal Processing

- Rapid Thermal Processing (RTP) is a semiconductor manufacturing process in which silicon wafers are heated to very high temperatures (~1,200°C) on a timescale of seconds.

- During cooling, temperatures must be reduced slowly so the wafer does not break due to thermal shock.

- Rapid heating and cooling rates are attained with high intensity lamps or lasers.

- A key challenge in RTP is accurate measurement and control of the wafer temperature during a batch cycle.

- High temperature ramp rates prevent the wafer from coming to thermal equilibrium with the process chamber where temperature is more easily measured.
Gain Scheduled PID Control

- PID controllers usually provide satisfactory control near the steady-state operating point where the controller was designed.
- If the process is highly nonlinear and/or operates over a large regime a single set of PID tuning parameter may be inadequate.
- RTP processes operate over a very wide range of temperatures and exhibit strong nonlinear behavior.
- Gain scheduling is a simple method to adapt PID controllers to nonlinear processes.
- Gain scheduling is implemented by adjusting the controller gain according to the current operating point.
- IMC PI tuning example

\[ G(s) = \frac{K}{\tau s + 1} \Rightarrow K_c = \frac{\tau}{K\tau_c}, \tau_I = \tau \]
Comparison of PID Controllers

**Standard PID Controller**

**Gain Scheduled PID Controller**

![Graphs comparing standard and gain scheduled PID controllers](image_url)
Run-to-Run Control

- Product quality measurements are usually collected only at the end of each batch run.
- Run-to-run control uses quality measurements from previous runs to adjust conditions of the current run.
- Semiconductor manufacturing
  » Controlled variable: film thickness
  » Manipulated variable: heating rate
- Polymer manufacturing
  » Controlled variable: molecular weight
  » Manipulated variable: chain transfer agent addition rate
Batch Production Management

- Many batch plants produce multiple products for multiple customers
- Specialty polymers plant: ~25 products for ~100 customers
- Planning – procedures to optimally order the raw materials, manufacturer the products, and ship the products to customers
- Scheduling – procedures to optimally implement the manufacturing plan by scheduling the use of available equipment
## Batch Scheduling and Planning

<table>
<thead>
<tr>
<th>DETERMINE</th>
<th>GIVEN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>What</strong></td>
<td><strong>Product requirements</strong></td>
</tr>
<tr>
<td>Product amounts: lot sizes, batch sizes</td>
<td>Time horizon, demands, starting and ending inventories</td>
</tr>
<tr>
<td><strong>When</strong></td>
<td><strong>Operational steps</strong></td>
</tr>
<tr>
<td>Timing of specific operations, run lengths</td>
<td>Precedence order, resource utilization</td>
</tr>
<tr>
<td><strong>Where</strong></td>
<td><strong>Production facilities</strong></td>
</tr>
<tr>
<td>Sites, units, equipment items</td>
<td>Types, capacities</td>
</tr>
<tr>
<td><strong>How</strong></td>
<td><strong>Resource limitations</strong></td>
</tr>
<tr>
<td>Resource types and amounts</td>
<td>Types, amounts, rates</td>
</tr>
</tbody>
</table>
Multiproduct Batch Plant Example

- Raw material A
  - Unit 1
    - Unit 2
      - Storage tank 1 (Product D)
  - Product E
- Raw material B
  - Unit 3
  - Product G
- Raw material C
  - Unit 4
    - Storage tank 2 (Product E)
    - Storage tank 3 (Product F)
    - Storage tank 4 (Product G)
Batch Plant Scheduling Example

**Diagram:**
- Raw materials flow through Unit 1, Unit 2, and Unit 3 to produce products $p_1, p_2, p_3, p_4$.

**Table:**

<table>
<thead>
<tr>
<th>Units</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
<th>$p_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5</td>
<td>4.0</td>
<td>3.5</td>
<td>12.0</td>
</tr>
<tr>
<td>2</td>
<td>4.3</td>
<td>5.5</td>
<td>7.5</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>8.7</td>
<td>3.5</td>
<td>6.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

**Graph:**
- Time axis from 0 to 35 hours.
- Units 1, 2, and 3 show processing and holding times for products $p_1, p_3, p_4, p_2$.
Integrated Batch Control Systems

Recipe management
- Plant recipes
- Product recipes

Production scheduling and optimization
- Production planning
- Production scheduling
- Real-time batch scheduling
- Run-to-run control

Process database
- Process/product data
- Production data
- Batch/equipment data
- Set points

Production management and operations

Control during the batch

Process control system

Sequential control

Safety interlocks