Modelling, Optimisation and Control of a Tunnel Kiln Firing Process

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Outline

- Description of the process
- Mathematical Model
  - Mass Balances
  - Energy Balances
- Model Validation
- Controller Design
- Conclusions
Process Description

Zones Length:
- Pretunnel of length 18m or 6 cars of 3m
- Prefiring zone of length 18m or 6 cars of 3m
- Firing zone of length 27m or 9 cars of 3m
- Fast Cooling zone of length 15m or 5 cars of 3m
- Slow cooling zone of length 42m or 14 cars of 3m

Process characteristics:
- Very slow movement of the cars (semi batch process)
- Very slow system dynamics
- Disturbances (variable ambient temperature, open-close doors, etc)
Process Description

Preheating Zone: 20-700°C
Firing Zone: 700-1000°C
Cooling Zone: 1000-40°C
Process Description

<table>
<thead>
<tr>
<th>Tunner kilns</th>
<th>Unit</th>
<th>Facing bricks and clay pavers</th>
<th>Clay blocks</th>
<th>Horizontally perforated clay blocks</th>
<th>Roof tiles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln length</td>
<td>m</td>
<td>35 – 160</td>
<td>60 – 120</td>
<td>60 – 120</td>
<td>80 – 140</td>
</tr>
<tr>
<td>Cross-section</td>
<td>m²</td>
<td>1.3 – 6.0</td>
<td>4 – 12</td>
<td>4 – 12</td>
<td>4 – 10</td>
</tr>
<tr>
<td>Setting density</td>
<td>kg/m³</td>
<td>650 – 1500</td>
<td>350 – 500</td>
<td>250 – 750</td>
<td>200 – 400</td>
</tr>
<tr>
<td>Firing temperature</td>
<td>°C</td>
<td>1000 – 1300</td>
<td>900 – 1050</td>
<td>950 – 1050</td>
<td>1000 – 1150</td>
</tr>
<tr>
<td>Specific energy requirement (drying + firing)</td>
<td>kJ/kg</td>
<td>1600 – 3000</td>
<td>1000 – 2500³¹</td>
<td>1000 – 2500</td>
<td>1600 – 3500</td>
</tr>
<tr>
<td>Flue-gas volume flow</td>
<td>m³/h</td>
<td>5000 – 20000</td>
<td>10000 – 50000</td>
<td>10000 – 50000</td>
<td>10000 – 40000</td>
</tr>
<tr>
<td>Flue-gas temperature</td>
<td>°C</td>
<td>100 – 230</td>
<td>100 – 300</td>
<td>100 – 150</td>
<td>170 – 200</td>
</tr>
</tbody>
</table>

³¹Including heat content of the pore-forming agent
Mathematical Model

Assumptions

- Dynamic operation
- The gas has uniform temperature and velocity
- The variation of the temperature and flow rates in the vertical direction was not taken into account for simplification.
- Complete and spontaneous oxidation of the natural gas on the roof of the kiln
- Ideal gas law holds in the gas phase
- The heat is transferred between the gas and the bricks by convection and radiation
- The bricks and gas have uniform temperature at each column
- The bricks properties are function of the temperature
- The heat losses are through the roof and walls of the kiln and depend on the ambient temperature
- The car moves along the tunnel with a constant velocity
Mathematical Model Concept

General Idea: Modelling of 1 column of brick instead of the entire car or process
**Mathematical Model**

**Mass Balances**

\[
\frac{dM_i}{dt} = F_{\text{air}} x_{\text{air},i} + F_{\text{fuel}} x_{\text{fuel},i} + F_{\text{sec}} x_{\text{sec},i} - F_{\text{out}} x_{\text{out},i} + r_i
\]

**Total mass holdup**

\[
M_T = \sum_{i=1}^{5} M(i)
\]

\[
M_T = V_{\text{free}} \rho_{\text{out}}
\]

\[
\rho_{\text{out}} = f(T_{\text{out}}, P_{\text{out}}, x_{\text{out},i})
\]

**Mass composition**

\[
M_i = M_T x_{\text{out},i}
\]

**Outlet mass flowrate**

\[
F_{\text{gas\_out}} = A_{\text{free}} \rho_{\text{gas}} u
\]

\[
F_{\text{out}} = f(P_{\text{in}}, P_{\text{out}})
\]
Mathematical Model

Semi-empirical equations:

\[ Nu = \frac{hD_h}{k} \]
\[ Nu = 0.021 Re^{0.8} Pr^{1/3} \]
\[ Re = \frac{uD_h \rho_{out}}{\mu_{out}} \]
\[ Pr = \frac{c_p \rho_{out} \mu_{out}}{k_{out}} \]

Hydraulic diameter

\[ D_h = \frac{4A_b}{2\pi r} \]

Pressure Drop across the column

\[ \Delta P = P_{in} - P_{out} \]
\[ \Delta P = \frac{4Lf \rho_{out} u^2}{2D_h} \]

Friction factor

\[ \frac{1}{\sqrt{f}} = -2 \log \left( \frac{2.51}{Re \sqrt{f}} + \frac{e}{D_h} \frac{3.7}{3.7} \right) \]
Mathematical Model

Energy balances:

Gas

\[ \frac{dU_{\text{out}}}{dt} + V_{\text{free}} \frac{dP_{\text{out}}}{dx} = H_{\text{in}} - H_{\text{out}} - Q_{\text{car}} - Q_{\text{tiles}} - Q_{\text{loss}} + \Delta Hr \]

Bricks

\[ M_b c_p_b \frac{d(T_b)}{dt} = H_{b,\text{in}} - H_{b,\text{out}} + Q_b + Q_{\text{rad}} \]

Car

\[ M_{\text{car}} c_p_{\text{car}} \frac{d(T_{\text{car}})}{dt} = H_{\text{car,\text{in}}} - H_{\text{car,\text{out}}} + Q_{\text{car}} \]

Total enthalpy holdup

\[ H_T = M_T h \]

Specific system enthalpy

\[ h = f(T, P, x_i) \]

Specific system enthalpy

\[ Q_{\text{car}} = h_{\text{car}} A_{\text{car}} \left( T_{\text{out}} - T_{\text{car,\text{out}}} \right) \]
\[ Q_b = h A_{\text{brick}} \left( T_{\text{out}} - T_b \right) \]
Mathematical Model

Radiation

\[ Q_{\text{rad}} = \sigma F_b \varepsilon \alpha_b (T_{\text{out}}^4 - T_b^4) \]

Heat losses from the kiln

\[ Q_{\text{losses}} = Q_w + Q_r \]

Heat losses from the walls

\[ Q_w = A_w h_w (T_{\text{out}} - T_w) + Q_{\text{rad},w} \]

Heat losses from the roof

\[ Q_r = A_r h_r (T_{\text{out}} - T_r) + Q_{\text{rad},r} \]

Wall temperature

\[ k_{\text{kiln}} A_w \frac{T_w - T_{\text{amb}}}{L_w} = Q_w \]

Roof temperature

\[ k_{\text{kiln}} A_r \frac{T_{\text{roof}} - T_{\text{amb}}}{L_r} = Q_r \]
Model Validation

**Process Data**

- Mass flowrate of the main air stream
- Pressure in the kiln
- Gas temperature inside the furnace
- Total fuel consumption
- Dimension of the tunnel, the bricks and the car
- Total load of each column

*total average fuel consumption 0.012kg/kg brick*
Model Validation

Problem formulation

\[
\min_{F_i, T_s} \sum_{i=1}^{N}(T_{process,i} - T_{gas,i})^2 + \sum_{i=1}^{N}(F_{f,i} - F_{f, process,i})
\]

Massflowrate results for the validation of the firing process

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet air mass flux (kg/m²s)</td>
<td>1</td>
</tr>
<tr>
<td>Outlet air mass flux(kg/m²s)</td>
<td>1.4</td>
</tr>
<tr>
<td>Total fuel consumption(kg/kg brick)</td>
<td>0.014</td>
</tr>
<tr>
<td>Total secondary air (kg/m²s)</td>
<td>0.3</td>
</tr>
<tr>
<td>Secondary air temperature(°C)</td>
<td>450</td>
</tr>
<tr>
<td>Outlet CO₂ mass fraction</td>
<td>3%</td>
</tr>
</tbody>
</table>
Model Validation

Temperature results for the validation of the firing process

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>24</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tprocess (°C)</td>
<td>586</td>
<td>805</td>
<td>920</td>
<td>950</td>
<td>976</td>
<td>972</td>
<td>937</td>
<td>898</td>
</tr>
<tr>
<td>Tgas (°C)</td>
<td>660</td>
<td>832</td>
<td>903</td>
<td>944</td>
<td>930</td>
<td>942</td>
<td>920</td>
<td>910</td>
</tr>
<tr>
<td>Tbrick (°C)</td>
<td>641</td>
<td>802</td>
<td>876</td>
<td>934</td>
<td>910</td>
<td>930</td>
<td>945</td>
<td>930</td>
</tr>
</tbody>
</table>

Process and estimated gas temperature

Gas and brick temperature
Optimal kiln operation

Problem formulation

\[
\begin{align*}
\min_{F_{f,j}} & \sum_{i=1}^{i=N_j} F_{f,j} \\
\text{s.t.} & \mu \leq T_{gas,j} - T_{sp,j} \leq M \\
& T_{b,j} - T_{gas,j} \leq \Delta T_{max} \\
& C_{CO2,i} \leq \Delta C_{max}
\end{align*}
\]

Optimization variables

- The mass flowrate of the fuel in each column, \( F_{f,j} \)
- The mass flowrate of the secondary air in each column, \( F_{s,j} \)
- The mass flowrate of the air coming from the cooling zone, \( F_{c} \)

Optimization problem

- Optimization variables, 109
- Equations, 2258
- Dynamic variables, 216
- Computation time, 653sec
Optimal kiln operation

### Massflowrate results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet air mass flux (kg/m²s)</td>
<td>0.85</td>
</tr>
<tr>
<td>Outlet air mass flux (kg/m²s)</td>
<td>1.17</td>
</tr>
<tr>
<td>Total fuel consumption (kg/kg brick)</td>
<td>0.013</td>
</tr>
<tr>
<td>Total secondary air (kg/m²s)</td>
<td>0.2</td>
</tr>
<tr>
<td>Secondary air temperature (°C)</td>
<td>600</td>
</tr>
<tr>
<td>Outlet CO₂ mass fraction</td>
<td>2.9%</td>
</tr>
</tbody>
</table>

### Process and optimal gas temperature

![Graph of process and optimal gas temperature](image)

### Optimal gas and brick temperature

![Graph of optimal gas and brick temperature](image)
PI Controller Design

**PI controller expression**

\[ U_f(t) = U_{f0} + K_C \left( e(t) + \frac{1}{\tau_i} \int_0^t e(\tau) d\tau \right) \]

*Manipulated variables*: fuel consumption, gas mass flowrate

*Control variables*: gas temperature

**Process and optimal gas temperature**

**Optimal gas and brick temperature**
Conclusions

- Dynamic mathematical modelling of the tunnel kiln
- Model validation through process data
- Design of a PI controller to follow the temperature profile

Future Work

- 2-D dynamic mathematical model based on first principles
- Design a model based controller
- Design mathematical model for the preheating and cooling phase