• Introduction & motivation

• Discussion of constraints as seen in a zero-dimensional model

• How to practically distinguish between a thermal and a chemical constraint? (Zero-dimensional analysis of real furnaces)

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• An extended conclusion: Quo vadis glass melting process?
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Glass Production World 124MM t/a (Germany 7MM t/a)

production capacities:
1/3 Asia
1/3 America (North & South)
1/3 Europe (West & East), Russia
physical limits

energy benchmark analysis for > 100 container glass tanks

H. van Limpt, TNO Eindhoven, 2003
Analysis in terms of a log-normal distribution

- H₅₀ = 1349 kWh/t
- H₁₀ = 1181 kWh/t

- H₅₀ = 1726 kWh/t
- H₁₀ = 1587 kWh/t
typical measures:
• combustion space
  - increasing flame emissivity
  - new burner concepts (top burners, FLOX burners)
  - staged combustion
  - larger combustion space
• heat recovery
  - regeneratio, recuperation; thermochemical recuperator (\(\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 4 \text{H}_2\) at \(T > 900\) °C)
  - batch pre-heating
  - pinch analysis of all heat flows
• new furnace concepts
  - larger furnaces
  - submerged combustion
  - segmented melters
  - all-electric melters
• chemical boosting
  - low-enthalpy batches
  - tailored fast conversion batches
  - in-flight technology
• indirect measures
  - light weight containers

\[
\begin{align*}
\text{Hin kWh per m}^3 \text{ CH}_4 & = H_{\text{NCV}}(\text{CH}_4) + \Delta H_f(\text{products}) \\
\lambda & = 1.05 \\
\text{adiabatic flame temperature, air: 25 °C}
\end{align*}
\]
\[ T_{\text{set}} = 2257 \, \text{K} + 0.67 \cdot \Delta T_{\text{re}} \]

Temperature \( T_{\text{re}} \) of pre-heated air, \( \lambda = 1.05 \),

\[ \Delta T_{\text{re}} = T_{\text{re}} - 25 \, ^\circ\text{C} \]

\[ \Delta H_i(\text{products}) \]

\[ H_{\text{NCV}}(\text{CH}_4) \]

\[ 1300 \, ^\circ\text{C} \]

\[ 1200 \]

\[ 1100 \]

\[ 1000 \]

Temperature \( T_{\text{in}} \) in \( ^\circ\text{C} \)

\[ 1800 \quad 2000 \quad 2200 \quad 2400 \quad 2600 \quad 2800 \quad 3000 \]

\( \log \text{m}^3 \quad 1.0 \quad 0.6 \quad 0.2 \quad 0 \quad -0.2 \quad -0.5 \quad -1.0 \quad -1.5 \quad -2.0 \)

Educts: \( 1 \, \text{CH}_4 + 2.1 \, \text{O}_2 \) (oxyfuel)
**staged combustion**

- a.
- b.
- c.
- d.
- e.

Secondary gas:
- a. none (reference case)
- b. burner side
- c. flue gas side
- d. both sides
- e. undershooting

**NO\textsubscript{x} distribution**

- a.
- b.
- c.
- d.
- e.

Secondary gas:
- a. none (reference case)
- b. burner side
- c. flue gas side
- d. both sides
- e. undershooting
**CO distribution**

- a. none (reference case)
- b. burner side
- c. flue gas side
- d. both sides
- e. undershooting

**Secondary Gas**

- a. none (reference case)
- b. burner side
- c. flue gas side
- d. both sides
- e. undershooting

**CO Distribution**

- case 1 (reference): pull 455 t/d
- case 2: zero port boost pull + 10 % (455 t/d)
- case 3: 3 top burners pull + 10 % (455 t/d)
- case 4: 5 top burners pull + 20 % (550 t/d)

Air fuel float glass furnace Ford Nashville; tinted glass 0.6 wt. % Fe₂O₃; 50 % cullet; boost and top burners: oxy-fuel  
(by A. Richardson, BOC, Karlovivary 2005)
<table>
<thead>
<tr>
<th>Case</th>
<th>Production (in t/d)</th>
<th>L(hot spot) (in m)</th>
<th>L(batch) (in m)</th>
<th>NOx/kg per t</th>
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<tr>
<td>Case 1 (reference)</td>
<td>455</td>
<td>14.00</td>
<td>13.36</td>
<td>7.34</td>
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<tr>
<td>Case 2 *)</td>
<td>500</td>
<td>14.00</td>
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<td>Case 4</td>
<td>550</td>
<td>14.15</td>
<td>13.36</td>
<td>4.95</td>
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</table>

*) Glas quality not maintained

Case 1 (Reference): Pull 455 t/d
Case 2: Zero port boost pull + 10% (455 t/d)
Case 3: 3 top burners pull + 10% (455 t/d)
Case 4: 5 top burners pull + 20% (550 t/d)

Conventional flame:
- Refractory wall
- Offgas
- Recuperator
- Fuel
- Pre-heated air
- Flame

FLOX® technology:
- Refractory wall
- Offgas
- Pre-heated air
- Reaction zone
**FLOX®**

- **no reaction**
- **instable flame**
- **conventional flame**
- **no reaction**

### Temperature in °C
- **CH₄ + 2O₂ \rightarrow CO₂ + 2H₂O** - 8.99 kWh/m³
- **CH₄ + H₂O \rightarrow CO + 3H₂** +2.31 kWh/m³
- **CO + 1/2O₂ \rightarrow CO₂** - 3.17 kWh/m³
- **3H₂ + 3/2O₂ \rightarrow 3H₂O** - 8.13 kWh/m³

### Thermochemical recuperator

- **CH₄ + H₂O**
- **flue gas**

- **CH₂H₂O**

- **H₂**
- **CO**
- **H₂O**
- **CO₂**

- **m³**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Efficiency (kWh/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄ + 2O₂ \rightarrow CO₂ + 2H₂O</td>
<td>8.99</td>
</tr>
<tr>
<td>CH₄ + H₂O \rightarrow CO + 3H₂</td>
<td>2.31</td>
</tr>
<tr>
<td>CO + 1/2O₂ \rightarrow CO₂</td>
<td>3.17</td>
</tr>
<tr>
<td>3H₂ + 3/2O₂ \rightarrow 3H₂O</td>
<td>8.13</td>
</tr>
</tbody>
</table>

\[ \begin{align*}
\text{Total Efficiency} & = 8.99 + 2.31 + 3.17 + 8.13 \\
& = 22.60 \text{ kWh/m³}
\end{align*} \]
BATCH PREHEATER

Sketch of a float glass production

- Melting tank, regenerators
- Refiner
- Float chamber
- Cooling lehr

Mass flow heated up:

Mass flow cooled down:
Pinch-Analyse

cold stream

hot stream

gas + pre-heated air → offgas

batch → melt + batch gases

Pinch-Analyse
Pinch-Analyse

- Advantages: high pull, high flexibility, melting of high liquidus glasses
- Disadvantages: relatively high energy demand, no established demonstrators yet

Submerged combustion

Advantages: high pull, high flexibility, melting of high liquidus glasses
Disadvantages: relatively high energy demand, no established demonstrators yet
concept of the „Flex Melter“: segmented melting

- internal batch pre-heater
- fossil fuel melter
- batch melter
- flames
- shallow finer
- deep refiner
- feeder
- electrodes
- bubblers
- 1000 °C
- 1200 °C
- 1300 °C
- 1500 °C
- 1350 °C
- 1400 °C
- 1600 °C
- 1200 °C
- pull

batch
pre-heating
batch melting
quartz
dissolution
primary fining
refining
conditioning

all-electric melting

- suitable for all glass except E, ECR
- pull up to 2.7 t/(m²·d)
- production up to 220 t/d
- 700 to 1100 kWh/t
- low investment
- short tank lifetime
- short dwell times
- difficult quartz dissolution and fining

source: M. Lindig, Sorg Co.
power station and heat exchanger

- heat recovery
- wall losses
- combustion space
- hot stream through combustion space
- offgas
- melt
- wall losses
- tank
- fuel
- air
- batch

chemical reactor

- batch 25 °C
- melt 1300 °C
- tank

radiative heat exchange

- crown
- clear melt
- batch
- flame
- radiation
- reflection
- transferred
- transferred

float glass tank,
melter 1.2 × 10 × 30 m³,
600 - 650 t/d
8 burner pairs,
air-gas fired,
regenerative heat recovery,
chambers not separated
burner no. 1: 1001 m³/h (9000 kW) + boosting; batch melting & carry-over
burner no. 2: 1040 m³/h (9350 kW) batch melting & carry-over
burner no. 3: 1080 m³/h (9710 kW) carry-over
burner no. 4: {1080 m³, 9710 kW}
burner no. 5: 1103 m³/h (9917 kW) clear melt surface
burner no. 6: {815 m³, 7330 kW} clear melt surface
burner no. 7: {723 m³, 6500 kW} clear melt surface
burner no. 8: 101 m³/h (980 kW) clear melt surface, perspirating chamber

power distribution along the furnace axis
isotherms (average between hot and cold cycle):

- 1000 °C
- 1100 °C
- 900 °C
- 800 °C
- 1200 °C

Chamber height in m:

- 0
- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Chamber no.:

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8

Combustion space:

- 6.875 m

Heat flux to tank:

- 130 kW/m²
- 110 kW/m²
- 60 kW/m²
- 10 kW/m²
- 5 kW/m²
- -5 kW/m²
- -10 kW/m²

Flow and temperatures, melt surface:

- 900 °C
- 1550 °C
- 1400 °C
- 1200 °C
- 1050 °C

-10 kW/m²
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• Discussion of constraints as seen in a zero-dimensional model (a)

• How to practically distinguish between a thermal and a chemical constraint? (Zero-dimensional analysis of real furnaces)

• Industrial experience with a fast conversion batch

• An extended conclusion: *Quo vadis* glass melting process?
chemical conversion: \((1 - y_C) \cdot \Delta H^0_{\text{chem}}\)

made available at pull temperature:
\[H_{\text{melt}}(T_x) - H_{\text{glass}}(T_0)\]

Carnot type availability (reversibl; \(\infty\) slow)

finite time heat transfer

\(H_{\text{init.}}\)

real installation; market driven pull

optimal technical realization; optimal pull

glass quality requires longer residence times; hence, higher wall losses

theoretical lower limit \(H_{\text{therm}}\)

thermal

chemical

optimal technical realization; optimal pull

longer residence times; hence, higher wall losses

the success of optimization strategies essentially depends on the nature of the constraint which has to be overcome

melting behavior
= heat demand
⊕ quartz dissolution rate
⊕ gas release rate

furnace performance
= heat transfer
⊕ dwell time characteristics
• Introduction & motivation

• Discussion of constraints as seen in a zero-dimensional model (b)

• How to practically distinguish between a thermal and a chemical constraint? (Zero-dimensional analysis of real furnaces)

• Industrial experience with a fast conversion batch

• An extended conclusion: Quo vadis glass melting process?
boundary conditions:
- $\dot{m}_H$ and $\dot{m}_L$ can be selected independently
- the cold stream has to reach a fixed temperature $T_{ex}$

problems:
- an imbalance of heat capacity flows, given by the ratio $\frac{\dot{m}_H \cdot c_H}{\dot{m}_L \cdot c_L}$
- a thermal constraint: $\frac{c_{ht} \cdot A}{\dot{m}_L \cdot c_L} = 1$ puts an upper limit to $\dot{m}_L$
- chemical constraint is an intrinsic limit of the cold stream: $\dot{m}_L \leq \dot{m}_{fr}$

in the glass furnace itself:
$$\dot{m}_H \cdot c_H \cdot \Delta T_{ad} = \dot{m}_L \cdot c_L \cdot \Delta T_{ex} = \left(1 - y_C\right) \cdot \Delta H^0_{chem} + \Delta H(T_{ex})$$

define the “ideal furnace”:
- perfect match between heat capacity flows: $\dot{m}_H \cdot c_H = \dot{m}_L \cdot c_L$
- infinitely fast heat transition; $\alpha_{ht} \to \infty$;
- no chemical constraints.

$\dot{m}_H \cdot c_H \cdot \Delta T_{ad} = P_{in} + P_{re} \Rightarrow \eta_{ex} = \frac{H_{ex}}{H_{in}} = \frac{\Delta T_{ex} \cdot (1 + f)}{\Delta T_{ad}} \approx 75\%$
boundary conditions:
- \( \dot{m}_h \) and \( \dot{m}_L \) can be selected independently
- the cold stream has to reach a fixed temperature \( T_{ex} \)

problems:
- an imbalance of heat capacity flows, given by the ratio \( \frac{\dot{m}_H \cdot c_H}{\dot{m}_L \cdot c_L} \)
- a thermal constraint: \( \frac{c_H \cdot A}{\dot{m}_L \cdot c_L} = 1 \) puts an upper limit to \( \dot{m}_L \)
- chemical constraint is an intrinsic limit of the cold stream: \( \dot{m}_L \leq \dot{m}_{fr} \)

What is an imbalance of heat capacity flows?
boundary conditions:
- $\dot{m}_H$ and $\dot{m}_L$ can be selected independently
- the cold stream has to reach a fixed temperature $T_{ex}$

problems:
- a mismatch of heat capacity flows, given by the ratio \( \frac{\dot{m}_H \cdot c_H}{\dot{m}_L \cdot c_L} \)
- a thermal constraint: \( \frac{\alpha_{int} \cdot A}{\dot{m}_L \cdot c_L} = 1 \) puts an upper limit to $\dot{m}_L$
- chemical constraint is an intrinsic limit of the cold stream: $\dot{m}_L \leq \dot{m}_H$

in the glass furnace itself:
- $P_{ex} = \dot{m}_L \cdot c_L \cdot \Delta T_{ex}$
- $H_{ex} = (1 - y_c) \cdot \Delta T_{ex}$

Define the “ideal furnace”:
- perfect match between heat capacity flows: $\dot{m}_H \cdot c_H = \dot{m}_L \cdot c_L$
- infinitely fast heat transition; $\alpha_{int} \rightarrow \infty$
- no chemical constraints.

$\dot{m}_H \cdot c_H \cdot \Delta T_{ad} = P_{in} + P_{re}$

How to derive a realistic value for $\alpha_{int}$?
\[ q_1 = \text{flux from glass} \]
\[ q_2 = \text{flux to glass} \]
\[ q_3 = \text{flux from crown} \]
\[ q_4 = \text{flux to crown} \]
\[ \Rightarrow q_2 - q_1 = q_{ht} = \text{flux transferred} \]

**Approach by M. Lindig adopted**

\[ q_1 = \text{flux from glass} \]
\[ q_2 = \text{flux to glass} \]
\[ q_3 = \text{flux from crown} \]
\[ q_4 = \text{flux to crown} \]
\[ \Rightarrow q_2 - q_1 = q_{ht} = \text{flux transferred} \]

1. \[ q_1 = \text{flux from glass} \]
2. \[ q_2 = \text{flux to glass} \]
3. \[ q_3 = \text{flux from crown} \]
4. \[ q_4 = \text{flux to crown} \]

\[ q_1 = C_s \epsilon_{\text{glass}} T_{\text{glass}}^4 + (1 - \epsilon_{\text{glass}}) \]  \( q_2 \)
\[ q_2 = C_s \epsilon_{\text{gas}} T_{\text{gas}}^4 + (1 - \epsilon_{\text{gas}}) \]  \( q_3 \)
\[ q_3 = C_s \epsilon_{\text{wo}} T_{\text{wo}}^4 + (1 - \epsilon_{\text{wo}}) \]  \( q_4 \)
\[ q_4 = C_s \epsilon_{\text{gas}} T_{\text{gas}}^4 + (1 - \epsilon_{\text{gas}}) \]  \( q_1 \)

\[ \)  \]

*) first term: radiation; second term: reflection; reflectivity = 1 – emissivity
\( q_1 = \text{flux from glass} \)
\( q_2 = \text{flux to glass} \)
\( q_3 = \text{flux from crown} \)
\( q_4 = \text{flux to crown} \)

\[ \Rightarrow q_2 - q_1 = q_{ht} = \text{flux transferred} \]

\[
q_{ht} = C_S \cdot [A \left( T_{gas}^4 - T_{glass}^4 \right) + B \left( T_{wo}^4 - T_{glass}^4 \right)]
\]

\( C_S = 57.7 \text{ kW/m}^2; \ T \text{ in 1000 K}; \ A, B = \text{dimensionless functions of } \varepsilon_{gas}, \varepsilon_{glass}, \varepsilon_{wo}. \)

**EXAMPLE:**

\( \varepsilon_{gas} = 0.25, \varepsilon_{glass} = 0.8, \varepsilon_{wo} = 0.5; \)
\( T_{gas} = 1650 \text{ °C}, T_{glass} = 1500 \text{ °C}, T_{wo} = 1580 \text{ °C}; \)

\( q_{ht} = 106 \text{ kW/m}^2 \)

This may constitute a thermal constraint for glass melting.

\( \Rightarrow q_{ht} = 106 \text{ kW/m}^2 \)

**EXAMPLE:**

\( \varepsilon_{gas} = 0.25, \varepsilon_{glass} = 0.8, \varepsilon_{wo} = 0.5; \)
\( T_{gas} = 1650 \text{ °C}, T_{glass} = 1500 \text{ °C}, T_{wo} = 1580 \text{ °C}; \)

\( q_{ex} = H_{ex} \cdot r = 74 \text{ kW/m}^2 \)

\( \Rightarrow q_{ex} = H_{ex} \cdot r = 74 \text{ kW/m}^2 \)
What is a "chemical constraint"?

- the cold stream has to reach a fixed temperature $T_{\text{ex}}$
- for a given temperature, the conversion reactions cannot support any pull $p > p_R$
- inspite of many known details, it is not well understood yet
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• An extended conclusion: Quo vadis glass melting process?

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>p (kg/m²)</th>
<th>T₀₁ (°C)</th>
<th>T₀₃ (°C)</th>
<th>T₀₅ (°C)</th>
<th>B₁ (Nm³/h)</th>
<th>B₂ (Nm³/h)</th>
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<tbody>
<tr>
<td>0.00</td>
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<td>255.3</td>
<td>63.9</td>
<td>219.6</td>
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</tbody>
</table>
Furnace data, collected over 6 weeks; melting area = 40 m²

<table>
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<th>date</th>
<th>r</th>
<th>t</th>
<th>g</th>
<th>M</th>
<th>H</th>
<th>1/r</th>
<th>q</th>
<th>T</th>
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<tbody>
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<td>Nm³/h</td>
<td>Nm³/d</td>
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</table>

**Diagram:**

Production p in t/d

**Legend:**

- Production p in t/d
- Days in 0 to 45 range
- Production trend over time
gas consumption in m³ per h

energy input H(in) in kWh per t of glass
energy input $H(\text{in})$ in kWh per t of glass

gas consumption in m³ per h

$H(\text{in}) \cdot r = q(\text{in}) \propto r$

e = 0.0427,
f = 0.7164,
r² = 0.84
dq = ±0.0031
Even without any model scenario, the linear relationship between power and pull is well substantiated. A retrospective long-term evaluation of furnace data yields a most valuable basis for optimization.
Hex = 847±5 kWh/t

P_{in} = a + b \cdot p
a = 1057 kW
b = 1094 kWh/t
r^2 = 0.95

P_{loss} = P_{in} - P_{ex} = a + (b - Hex) \cdot p
P_{ex} = Hex \cdot p

P_{loss} = 581±5 kWh
By statistical evaluation of furnace data over an extended period of time:
\[ P_{in} = a + b \cdot p \]

By thermodynamic calculation *) from the batch; by evaluation \( T_{ex} \) data:
\[ P_{ex} = H_{ex} \cdot p; \quad H_{ex} = (1 - \gamma_C) \cdot \Delta H^0_{chem} + c_{P,melt} \cdot \Delta T_{ex} \]

By difference, the cumulative loss is obtained:
\[ P_{loss} = P_{in} - P_{ex} = a + (b - H_{ex}) \cdot p > 0 \]
\[ = P_{wu} + P_{wo} + P_{wx} + P_{stack} \quad \text{independent of } p \]
\[ \quad \text{has the same slope as } P_{loss}: \text{slope} = (b - H_{ex}) \]

Evaluating \( P_{in} \) according to the heat balance yields:
\[ P_{in} = P_{ex} + P_{wu} + P_{wo} + P_{wx} + P_{stack} \Rightarrow P_{in} - P_{ht} = P_{loss-fire} \]
\[ P_{ht} \quad \text{same slope as } P_{loss} \]

What is left to do is to derive a threshold of \( P_{ht,\text{MAX}} \), to determine the slope of \( P_{in} - P_{ht,\text{MAX}} \), and to compare it to the slope of \( P_{loss} \).
In order to assess $P_{ht}$, let us introduce the following abbreviations:

- $f_{HL} = \frac{m_H \cdot c_H}{m_L \cdot c_L}$: the imbalance ratio between hot and cold stream,
- $z_j = \frac{c_j \cdot V_j / V_{fuel}}{H_{NCV}}$: a reciprocal ref. temperature for $j = \text{off, oxy-off, and air}$

According to the theory of heat exchangers (co-current mode), the maximum transferred power at infinitely high $\alpha_{ht}$ is given by

$$P_{ht-MAX} = \frac{1}{1 + f_{HL}} \cdot z_{off} \cdot \Delta T_{ad} \cdot P_{in} \propto x \cdot b \cdot p \leq \frac{1}{2} \approx 1 \Rightarrow \text{factor } x \leq \frac{1}{2}$$

A thermal constraint is reached if the slope of the losses $P_{loss} \cdot (b - H_{in})$ exceeds $(1-x) \cdot b = b_{imb}$.

As long as $0 < (b - H_{in}) < b_{imb}$, the only constraint is due to the imbalance of cold and hot stream heat capacity flows.
### Table

<table>
<thead>
<tr>
<th>Case</th>
<th>Threshold of Slope</th>
<th>Principal Constraint Involved</th>
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</thead>
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<tr>
<td>A</td>
<td>( b - H_{ex} = 0 )</td>
<td>( P_{stack} ) independent of pull ( p ) (does not increase with increasing power input ( P_{in} )); heat transferred to the tank just follows the pull; no thermal constraint involved; <strong>chemical constraint</strong></td>
</tr>
<tr>
<td>B</td>
<td>( 0 &lt; b - H_{ex} \leq b_{imb} )</td>
<td>( P_{stack} ) increases with ( P_{in} ); an increasing portion of ( P_{in} ) cannot be transferred to the tank due to flow imbalance only; ( \alpha_{ht} ) not constrained; at prevailing flow imbalance: <strong>chemical constraint</strong></td>
</tr>
<tr>
<td>C</td>
<td>( b - H_{ex} &gt; b_{imb} )</td>
<td>( P_{stack} ) increases with ( P_{in} ); an increasing portion of ( P_{in} ) cannot be transferred to the tank due to a constrained ( \alpha_{ht} ); <strong>thermal constraint</strong></td>
</tr>
</tbody>
</table>

### Graph

- **Equations:**
  - \( P_{in} = a + b \cdot p \)
  - \( a = 1057 \text{ kW} \)
  - \( b = 1094 \text{ kWh/t} \)
  - \( r^2 = 0.95 \)
  - \( H_{ex} = 847 \pm 5 \text{ kWh/t} \)
  - \( P_{loss} = P_{in} - P_{ex} = a + (b - H_{ex}) \cdot p \)
  - \( P_{ex} = H_{ex} \cdot p \)

- **Graph Notes:**
  - \( P_{loss, min} \)
  - 180 days, 70 data sets
two “practically identical” horseshoe flame container glass furnaces
40 m², large regenerator 40.5 m², medium size regenerator

\[ P_{\text{in}} = P_{\text{ex}} + P_{\text{loss}} \]

\[ P_{\text{loss}} = \min \left( P_{\text{in}} - P_{\text{ex}} \right) \]

Energy consumption in kWh per kg glass

Pull rate \( r \) in t/(m²·d)

dolomite
half-burnt dolomite
The combustion space responds very well; all heat required can be actually made available to the basin (lines converge).

The case study: tank 5.

Too much of the heat conveyed to the basin is lost through the periphery.
• Introduction & motivation

• Discussion of constraints as seen in a zero-dimensional model

• How to practically distinguish between a thermal and a chemical constraint? (Zero-dimensional analysis of real furnaces)

• Industrial experience with a fast conversion batch

• An extended conclusion: *Quo vadis* glass melting process?
Due to the manager’s impatience, no significant difference was found ...

... although the new batch quickly makes the furnace more stable.
Same type of batches in a different factory.

This time, an energy savings effect was found, however, statistically blurred. The furnace seems to run in a less stable way.

Evaluating the mass and power pulled from the furnace speaks a different language!

\[ Q_T = \Delta H(T_{es}) \cdot p \]
... but nobody noticed that $T_{\text{ex}}$ was unnecessarily high. So the energy savings effect was much smaller than it could have been.

Intermediate conclusion:

Enhancing glass melting by overcoming chemical constraints (i.e., by speeding up the conversion processes) seems to have an especially high and widely unexploited potential for optimization.
• Introduction & motivation

• Discussion of constraints as seen in a zero-dimensional model

• How to practically distinguish between a thermal and a chemical constraint? (Zero-dimensional analysis of real furnaces)

• Industrial experience with a fast conversion batch

• An extended conclusion: Quo vadis glass melting process?
\[ \text{Na}_2\text{CO}_3 + \text{SiO}_2 \rightarrow \text{Na}_2\text{SiO}_3 + \text{CO}_2 \]
\[ T_{\text{eq}} = 287 \, ^\circ\text{C}, \Delta H_{\text{chem}} = 185 \, \text{kWh/t} \]
\[ \text{Na}_2\text{CO}_3 + 2\text{SiO}_2 \rightarrow \text{Na}_2\text{Si}_2\text{O}_5 + \text{CO}_2 \]
\[ T_{\text{eq}} = 256 \, ^\circ\text{C}, \Delta H_{\text{chem}} = 127 \, \text{kWh/t} \]
\[ 2\text{Na}_2\text{CO}_3 + \text{CaCO}_3 + 3\text{SiO}_2 \rightarrow \text{N}_2\text{CS}_3 + 3\text{CO}_2 \]
\[ T_{\text{eq}} = 281 \, ^\circ\text{C}, \Delta H_{\text{chem}} = 191 \, \text{kWh/t} \]
\[ \text{Na}_2\text{CO}_3 + 3\text{CaCO}_3 + 6\text{SiO}_2 \rightarrow \text{NC}_3\text{S}_6 + 4\text{CO}_2 \]
\[ T_{\text{eq}} = 152 \, ^\circ\text{C}, \Delta H_{\text{chem}} = 128 \, \text{kWh/t} \]

860 °C  Tm of Na2CO3
eutectic Na2-Ca-CO3 785 °C
eutectic S-NC3S6-NS2 760 °C
< 0.4 %
< 2 %
60 %

Kröger 1957
\[
\begin{align*}
\text{Na}_2\text{CO}_3 + \text{SiO}_2 & \rightarrow \text{Na}_2\text{SiO}_3 + \text{CO}_2 \\
T_{\text{eq}} &= 287\,^\circ\text{C}, \Delta H_{\text{chem}} = 185\,\text{kWh/t} \\
\text{Na}_2\text{CO}_3 + 2\text{SiO}_2 & \rightarrow 2\text{Na}_2\text{SiO}_3 + \text{CO}_2 \\
T_{\text{eq}} &= 256\,^\circ\text{C}, \Delta H_{\text{chem}} = 127\,\text{kWh/t} \\
2\text{Na}_2\text{CO}_3 + \text{CaCO}_3 + 3\text{SiO}_2 & \rightarrow \text{N}_2\text{CS}_3 + 3\text{CO}_2 \\
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\text{Na}_2\text{CO}_3 + 3\text{CaCO}_3 + 6\text{SiO}_2 & \rightarrow \text{NC}_3\text{S}_6 + 4\text{CO}_2 \\
T_{\text{eq}} &= 152\,^\circ\text{C}, \Delta H_{\text{chem}} = 128\,\text{kWh/t}
\end{align*}
\]
\[
\begin{align*}
Na_2CO_3 + SiO_2 & \rightarrow Na_2SiO_3 + CO_2 \\
T_{eq} = 287 \, ^\circ C, \Delta H_{chem} = 185 \, \text{kWh/t}
\end{align*}
\]
\[
\begin{align*}
Na_2CO_3 + 2SiO_2 & \rightarrow Na_2Si_2O_5 + CO_2 \\
T_{eq} = 256 \, ^\circ C, \Delta H_{chem} = 127 \, \text{kWh/t}
\end{align*}
\]
\[
\begin{align*}
2Na_2CO_3 + CaCO_3 + 3SiO_2 & \rightarrow 2Na_2Si_2O_5 + 3CO_2 \\
T_{eq} = 281 \, ^\circ C, \Delta H_{chem} = 191 \, \text{kWh/t}
\end{align*}
\]
\[
\begin{align*}
Na_2CO_3 + 3CaCO_3 + 6SiO_2 & \rightarrow Na_2Si_5O_9 + 4CO_2 \\
T_{eq} = 152 \, ^\circ C, \Delta H_{chem} = 128 \, \text{kWh/t}
\end{align*}
\]

- options for the optimization of the steps taking place prior to the high-T melting process:
  - option 1: developing "instant coffee" batches
  - option 2: developing a prototype of a combined mixer & grider & pre-heater reactor unit working under hydrothermal conditions and exploiting heat at T levels < 300 °C

---

**thumb movie:**

limestone + soda ash + sand

(not activated)
sand  limestone  soda ash  sand  limestone

Temperature: 1085°C
Heating rate: 10 K/min
25.04.2008  13:12:51 h

sand  limestone  soda ash  sand  limestone

Temperature: 1320°C
Heating rate: 10 K/min
25.04.2008  13:38:21 h
sand limestone soda ash sand limestone

Temperature: 1350°C
Aufheizrate: 10 K/min

sample 1
medium temperature range (25-1200 °C) DTA-TG, calibrated against CuSO₄·5H₂O

sample 2

DTA signal in µV

TG signal in mg

Sample 1:
- Onset: 399 °C
- Peak height: 3.47 µV\text{mg}^{-1}
- 473 °C: 5.0%
- 712 °C: 20.5%
- 967 °C: 0.3%

Sample 2:
- Onset: 399 °C
- Peak height: 4.08 µV\text{mg}^{-1}
- 481 °C: 3.8%
- 699 °C: 20.5%
- 111 °C: 1.1%
experimental parameters:

- $T_{\text{melt}} = 1400 \, ^\circ\text{C}$
- $t_{\text{hold}} = 10$ und $15$ min
- $T_{\text{anneal}} = 550 \, ^\circ\text{C}$
- $q_{\text{cool}} = -2$ K/min

modified Batch-Free-Time test

batch-free time experiments
batch-free time tests
black-white contrast;
black = clear melt

re-evaluation of free surface by black-white contrast image analysis;
calibration area = 100 %
∅ = 757 mm

T = const. or
L = const.
heating mode

batch heap (4 kg)

glass melt (7 kg)

1 ± 0.2 cm
step 1: retrospective analysis:
heat & power balance;
casting into a model

\[
\begin{bmatrix}
T_1 & T_2 & \ldots & T_n \\
m_1 & m_2 & \ldots & m_n \\
c_{P,1} & c_{P,2} & \ldots & c_{P,n} \\
\vdots & \vdots & \ddots & \vdots \\
H_1^0 & H_2^0 & \ldots & H_n^0
\end{bmatrix}
\]
step 2: retrospective analysis:
reactor (dwell time) behavior;
on-line actualization of model

\[
\begin{pmatrix}
T_1 & T_2 & \ldots & T_n \\
\dot{m}_1 & \dot{m}_2 & \ldots & \dot{m}_n \\
C_{P,1} & C_{P,2} & \ldots & C_{P,n} \\
\vdots & \vdots & \ddots & \vdots \\
H_0^1 & H_0^2 & \ldots & H_0^n
\end{pmatrix}
\]

lab

batch house

tank, hotstream

tank, coldstream

step 3: in-factory analysis of heat and mass flows;
data acquisition and formatting
step 4: comprehension and linking of data

\[
\begin{pmatrix}
T_1 & T_2 & \ldots & T_n \\
\bar{m}_1 & \bar{m}_2 & \ldots & \bar{m}_n \\
C_{P,1} & C_{P,2} & \ldots & C_{P,n} \\
\vdots & \vdots & \ddots & \vdots \\
H_1^0 & H_2^0 & \ldots & H_n^0
\end{pmatrix}
\]

data bank

step 5: realization: structuring of the processes

data & software architecture

step 6: factory test and evaluation
Thank you for your kind attention!