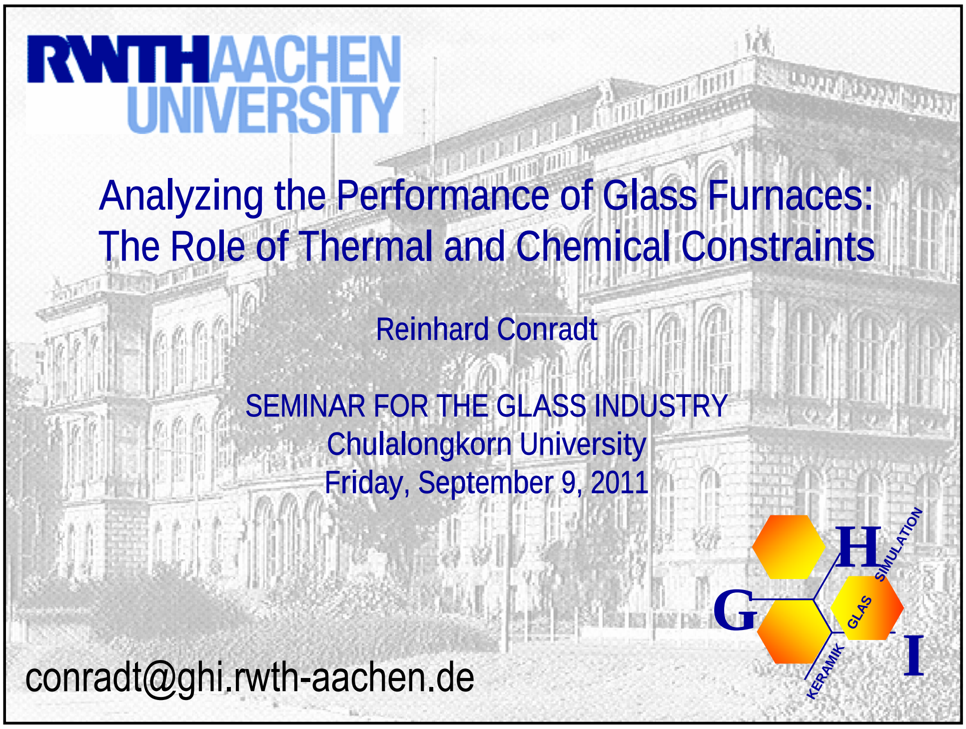

RWTH AACHEN UNIVERSITY

Analyzing the Performance of Glass Furnaces: The Role of Thermal and Chemical Constraints

Reinhard Conradt

SEMINAR FOR THE GLASS INDUSTRY
Chulalongkorn University
Friday, September 9, 2011

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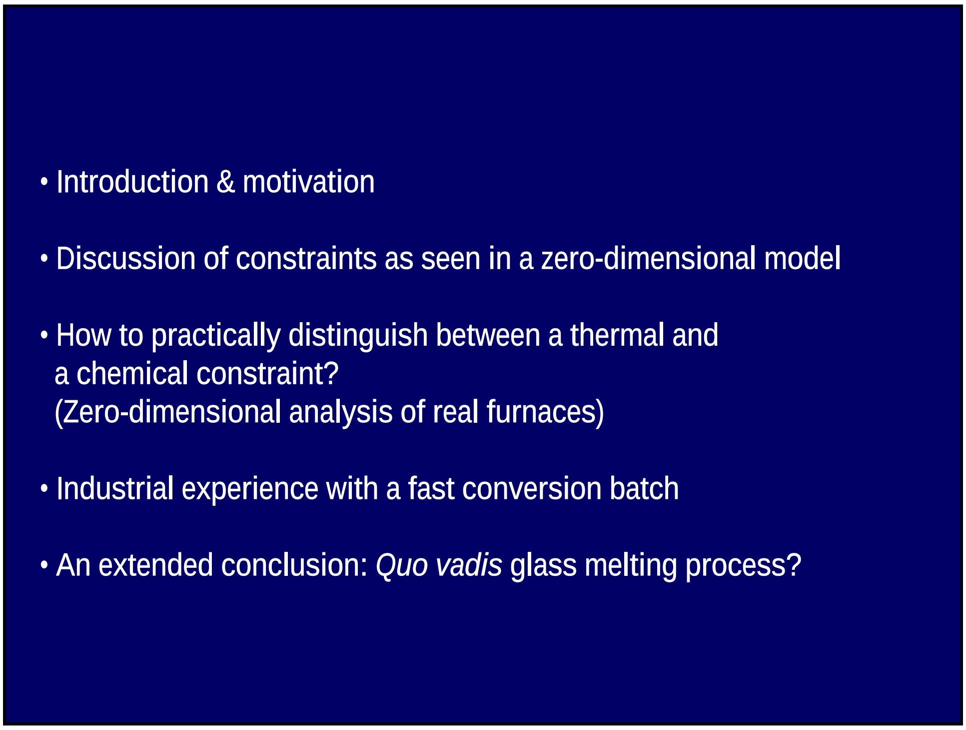

- Introduction & motivation
- Discussion of constraints as seen in a zero-dimensional model
- How to practically distinguish between a thermal and a chemical constraint? (Zero-dimensional analysis of real furnaces)
- Industrial experience with a fast conversion batch
- An extended conclusion: *Quo vadis* glass melting process?

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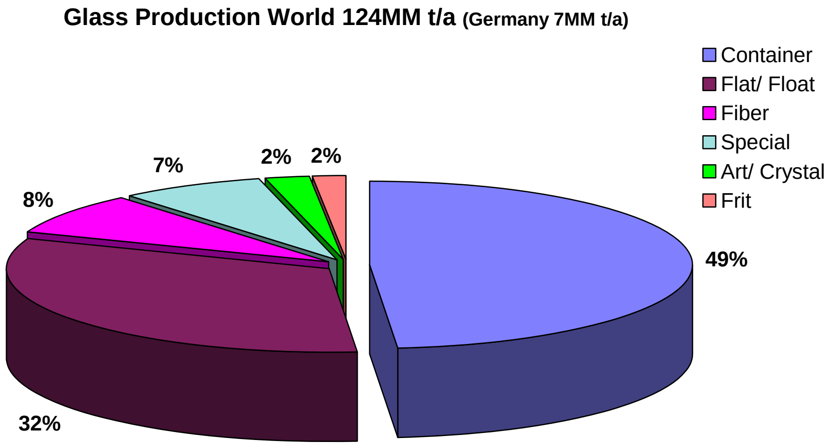
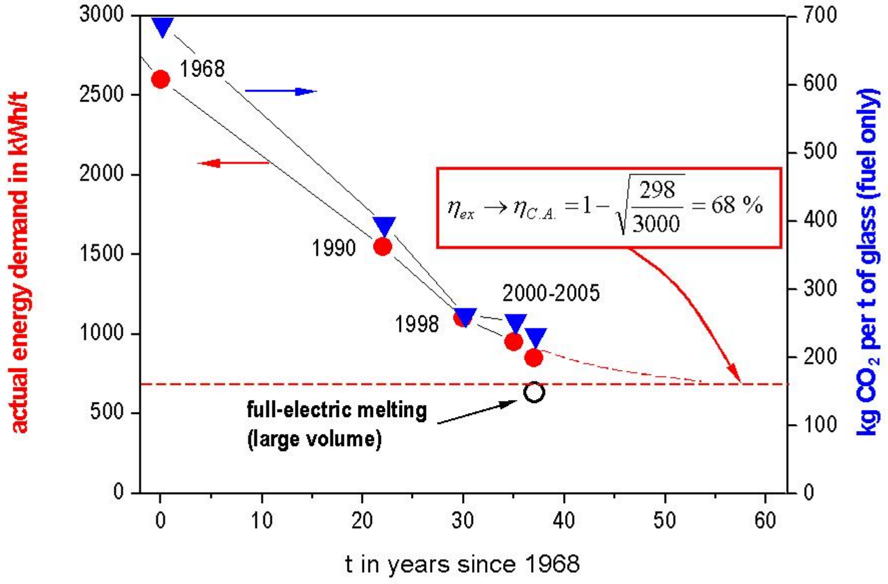
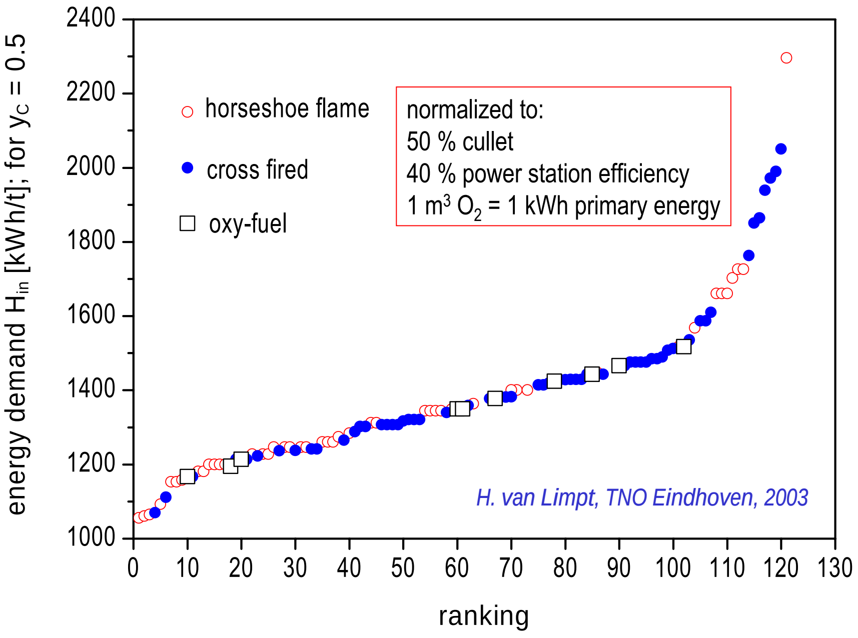

Glass Production World 124MM t/a (Germany 7MM t/a)

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

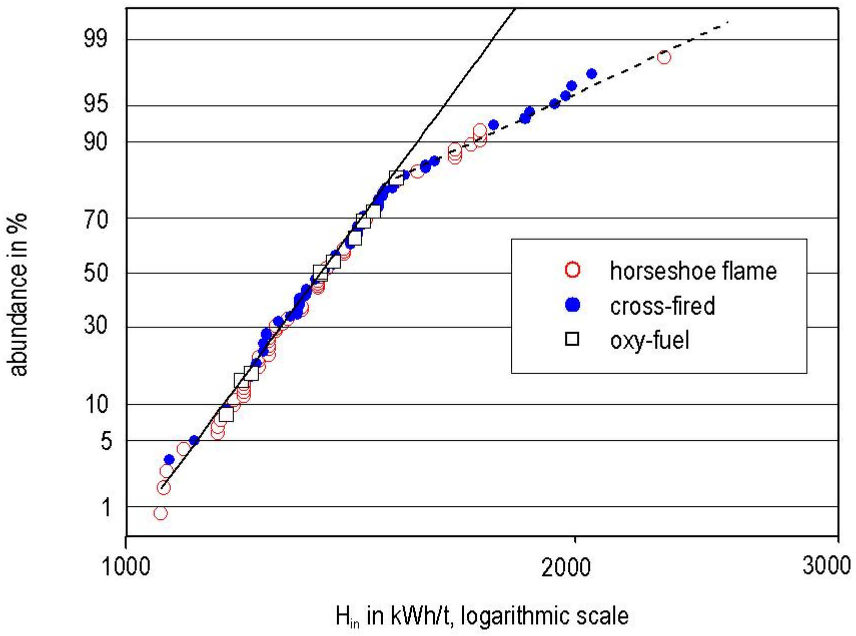
physical limits

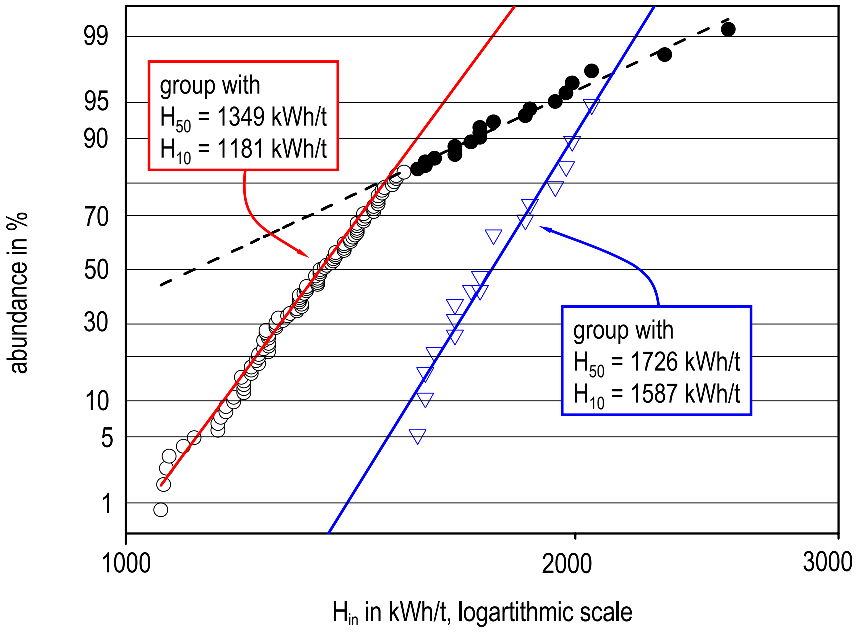


energy benchmark analysis for > 100 container glass tanks



analysis in terms of a log-normal distribution



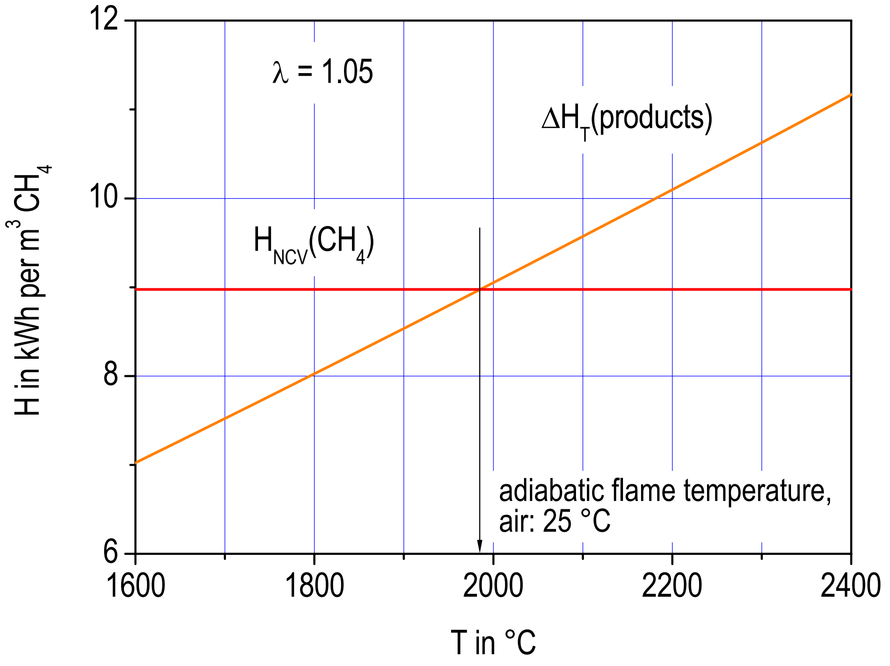


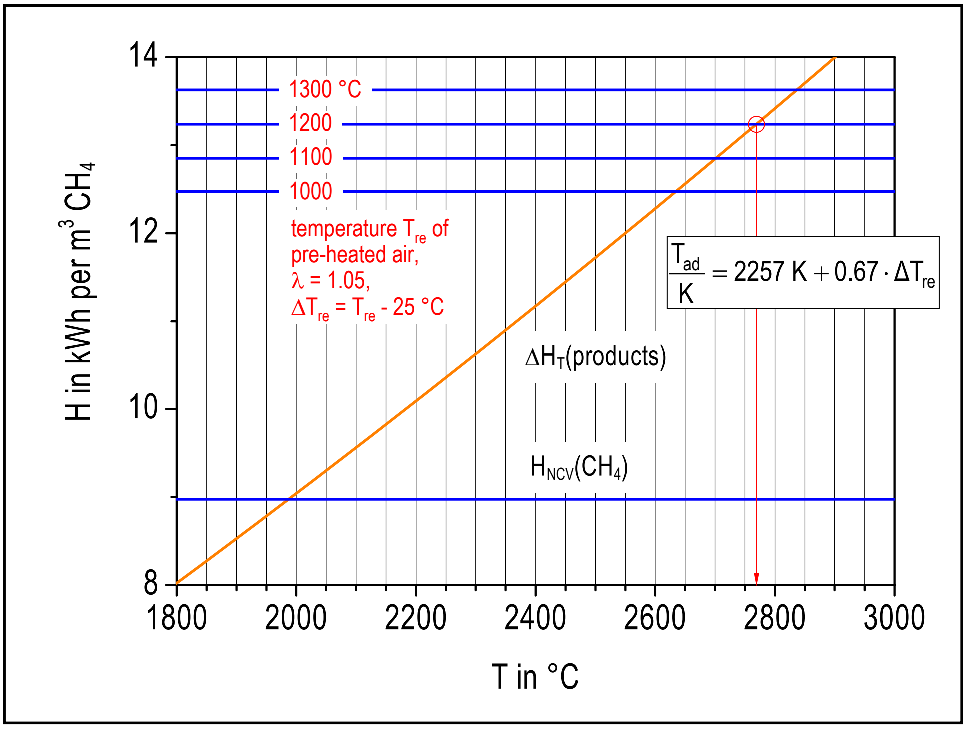
group with
H_{50} = 1349 kWh/t
H_{10} = 1181 kWh/t

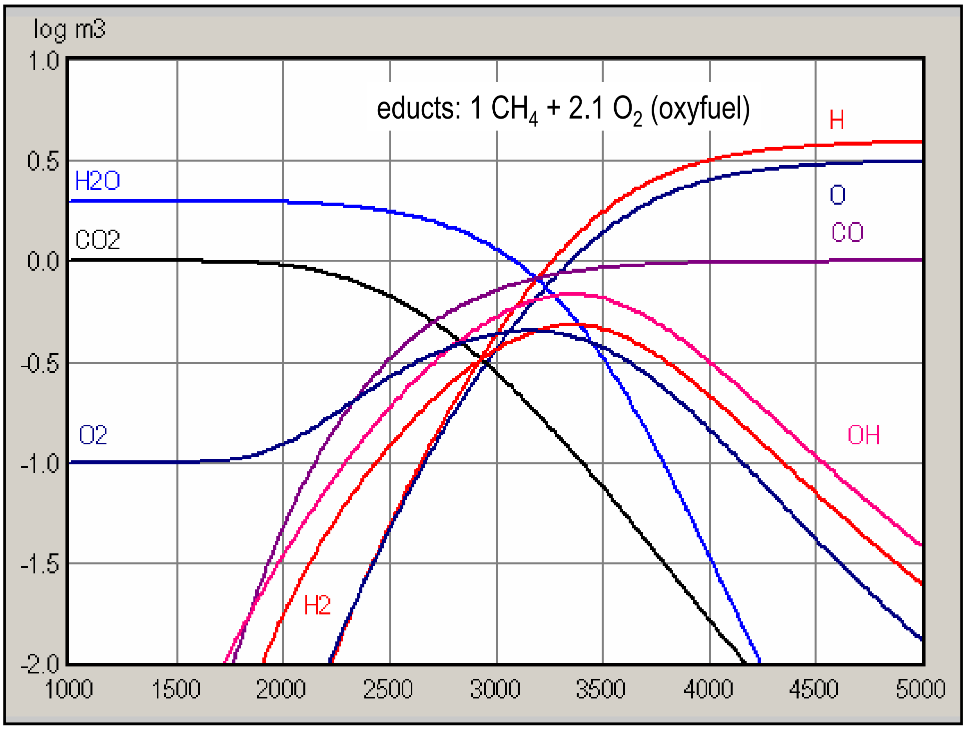
group with
H_{50} = 1726 kWh/t
H_{10} = 1587 kWh/t

typical measures:

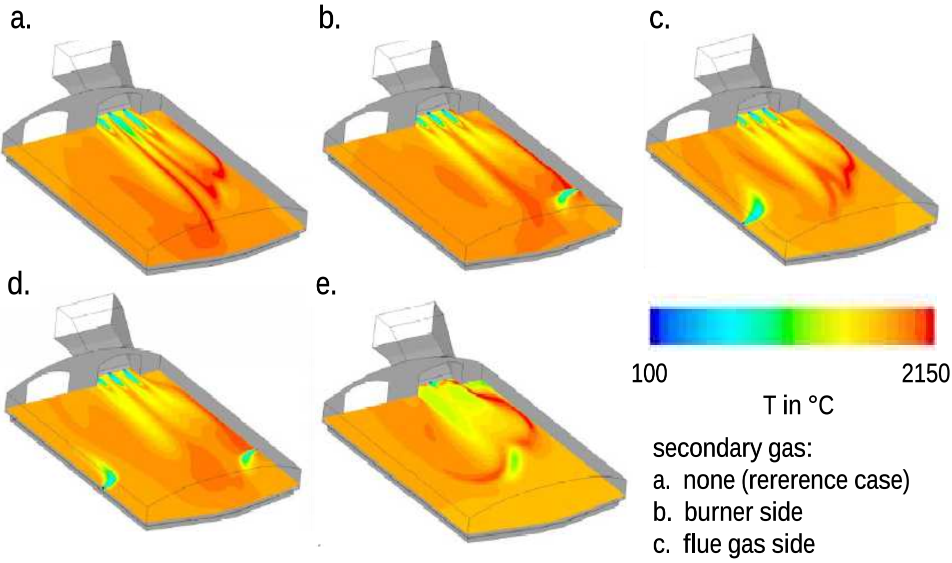
- combustion space
  - increasing flame emmissivity
  - new burner concepts (top burners, FLOX burners)
  - staged combustion
  - larger combustion space
- heat recovery
  - regeneratio, recuperation; thermochemical recuperator ($CH_4 + H_2O \rightarrow CO + 4\ H_2$ at T > 900 °C)
  - batch pre-heating
  - 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




H in kWh per m^3 CH_4
14
12
10
8
1800
2000
2200
2400
2600
2800
3000
T in °C
1300 °C
1200
1100
1000
temperature T_{re} of pre-heated air,
$\lambda = 1.05$,
$\Delta T_{re} = T_{re} - 25$ °C
$\frac{T_{ad}}{K} = 2257 K + 0.67 \cdot \Delta T_{re}$
ΔH_T(products)
$H_{NCV}(CH_4)$


log m3
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1000
1500
2000
2500
3000
3500
4000
4500
5000
educts: 1 CH_4 + 2.1 O_2 (oxyfuel)
H2O
CO2
O2
H2
H
O
CO
OH

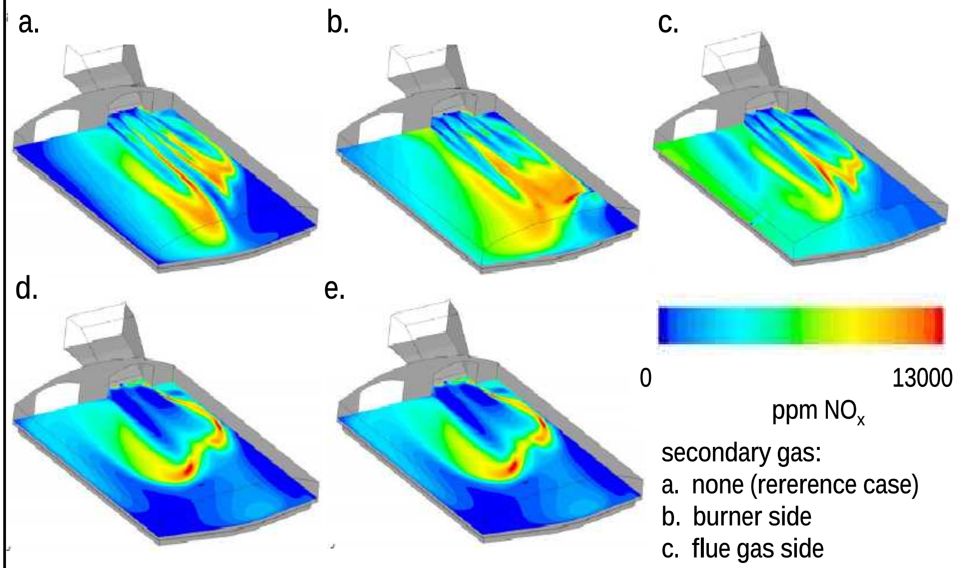
staged combustion



secondary gas:

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

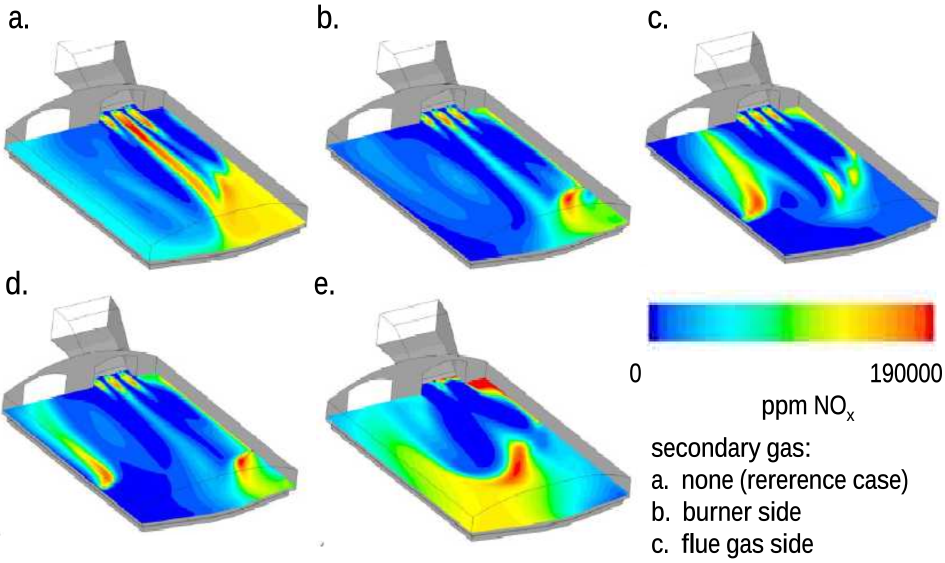
NO$_x$ distribution



secondary gas:

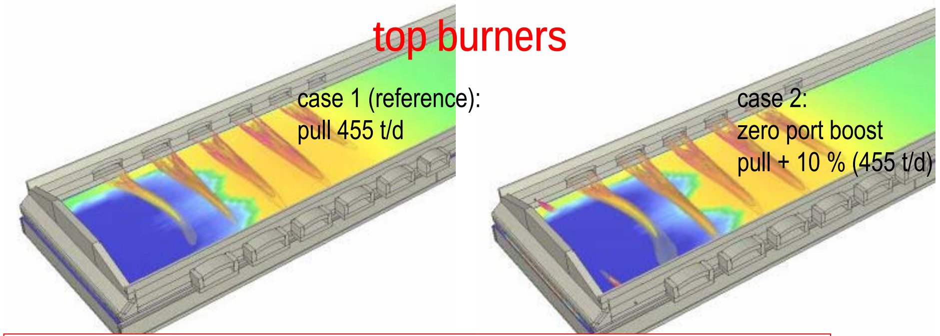
a. none (rererence case)
b. burner side
c. flue gas side
d. both sides
e. undershooting

CO distribution



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

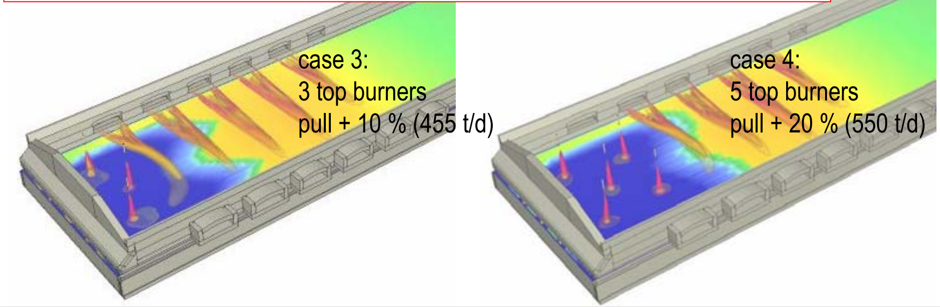
top burners



case 1 (reference):
pull 455 t/d

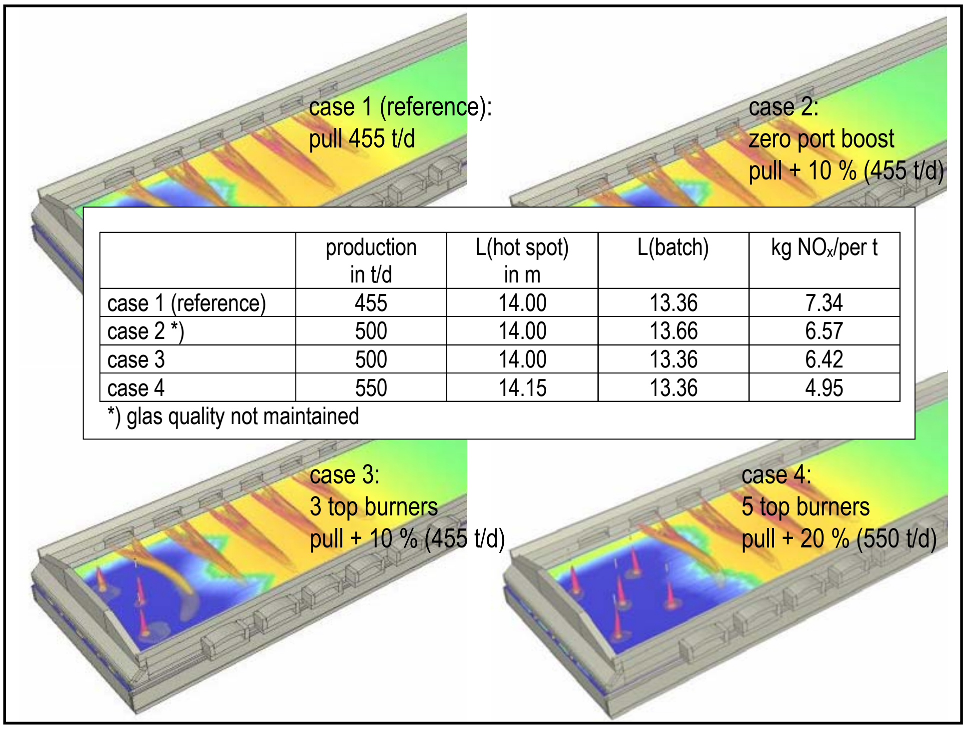
case 2:
zero port boost
pull + 10 % (455 t/d)

air fuel float glass furnace Ford Nashville; tinted glass 0.6 wt. % Fe_2O_3; 50 % culllet; boost and top burners: oxy-fuel (by A. Richardson, BOC, Karlovivary 2005)



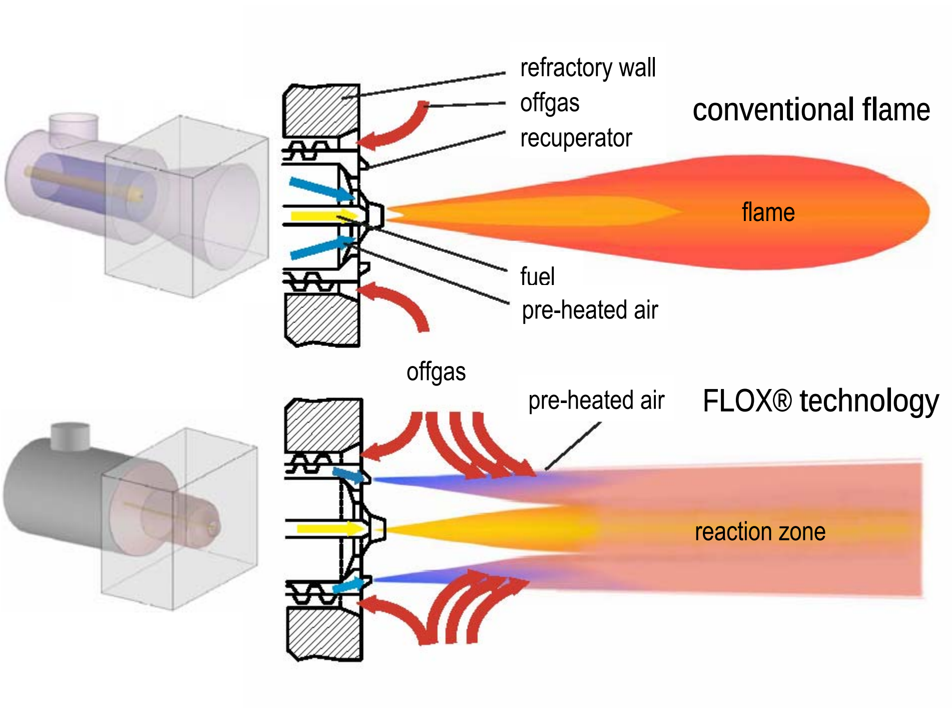
case 3:
3 top burners
pull + 10 % (455 t/d)

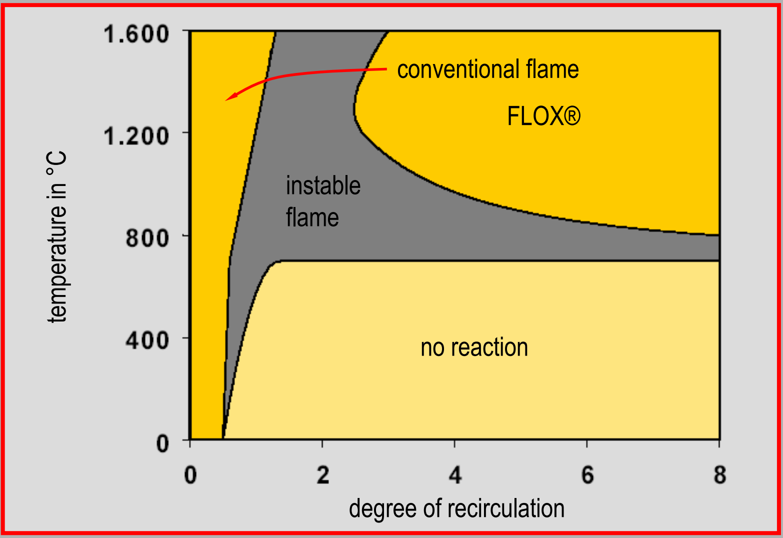
case 4:
5 top burners
pull + 20 % (550 t/d)



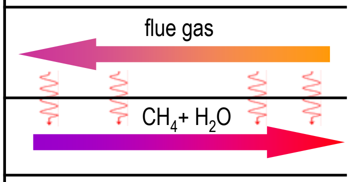
	production in t/d	L(hot spot) in m	L(batch)	kg NO_x/per t
case 1 (reference)	455	14.00	13.36	7.34
case 2 *)	500	14.00	13.66	6.57
case 3	500	14.00	13.36	6.42
case 4	550	14.15	13.36	4.95

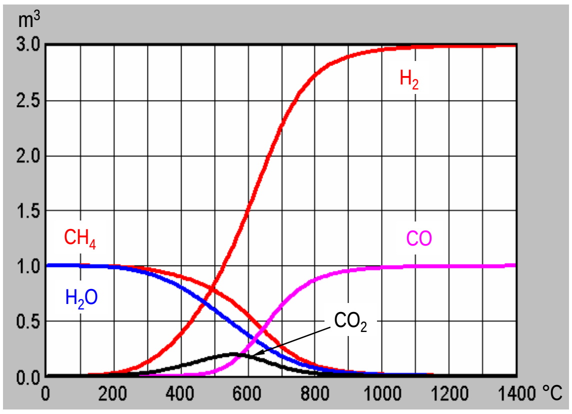
*) glas quality not maintained





thermochemical recuperator





$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ - 8.99 kWh/m^3

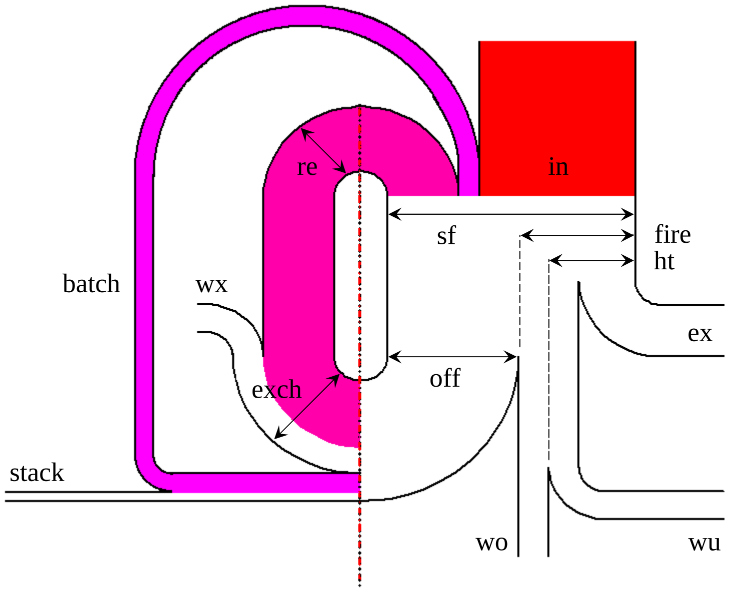
$CH_4 + H_2O \rightarrow CO + 3H_2$ +2.31 kWh/m^3

$CO + 1/2O_2 \rightarrow CO_2$ - 3.17 kWh/m^3

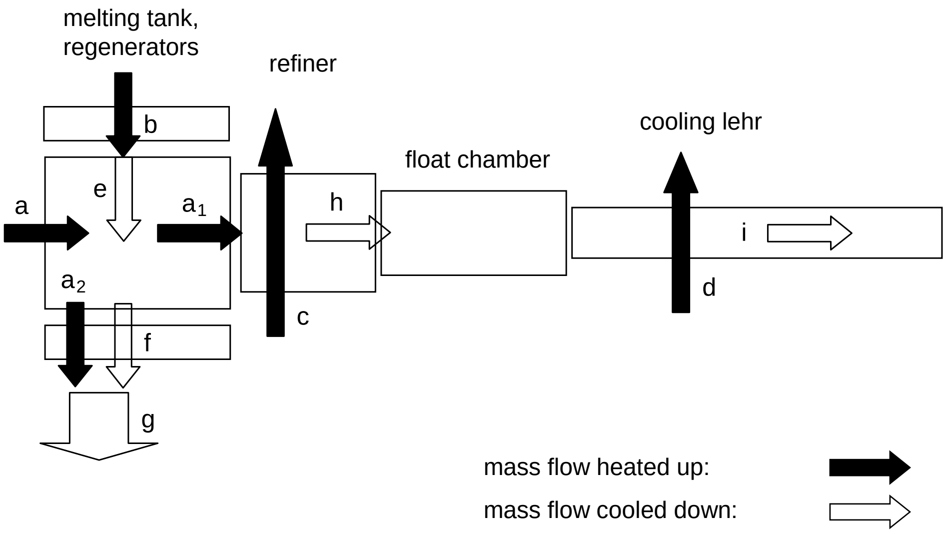
$3H_2 + 3/2O_2 \rightarrow 3H_2O$ - 8.13 kWh/m^3

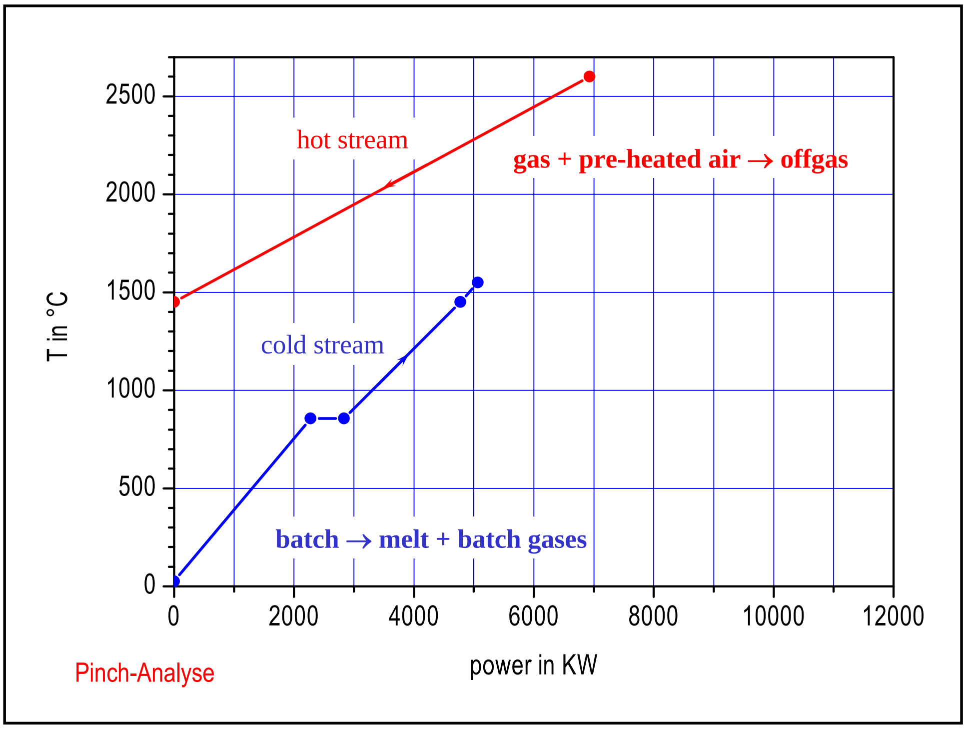
$\left.\begin{array}{l} - 3.17 \\ - 8.13 \end{array}\right\}$ - 11.30 kWh/m^3

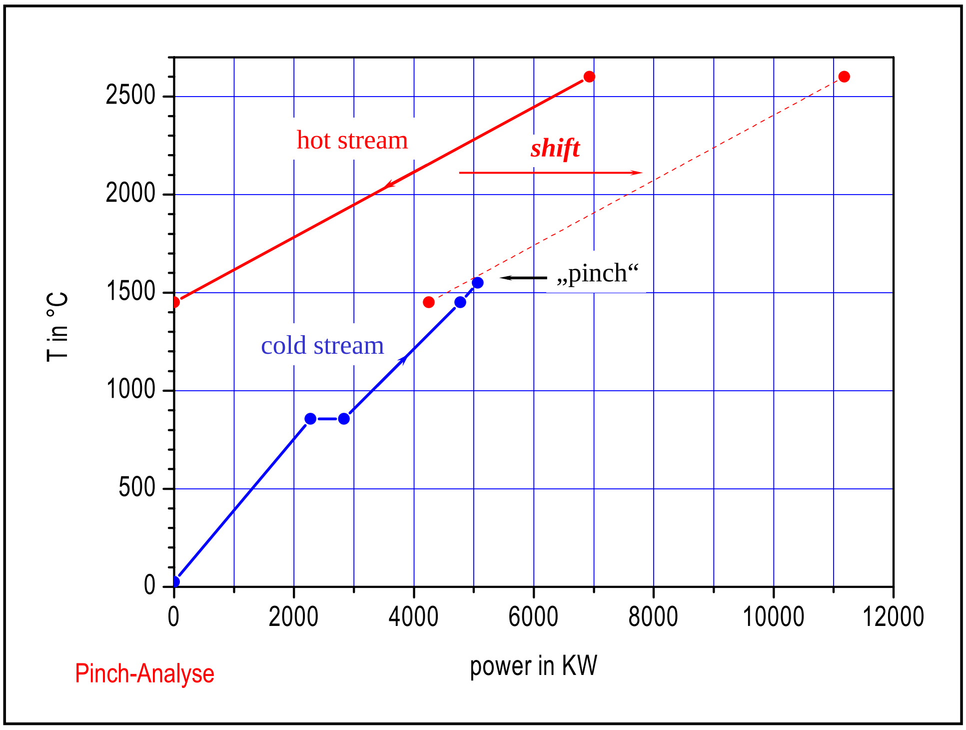
BATCH PREHEATER

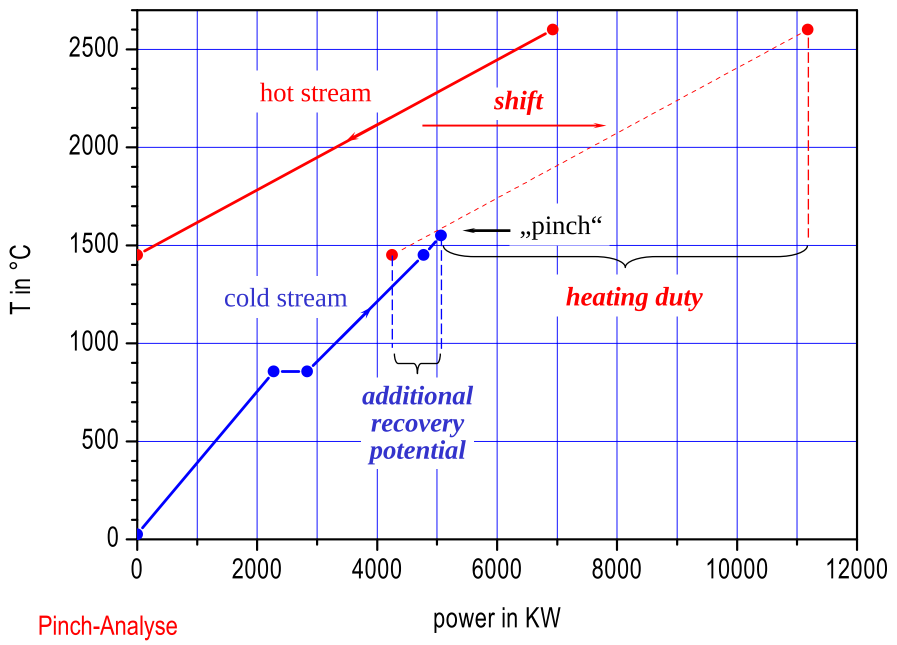


sketch of a float glass production

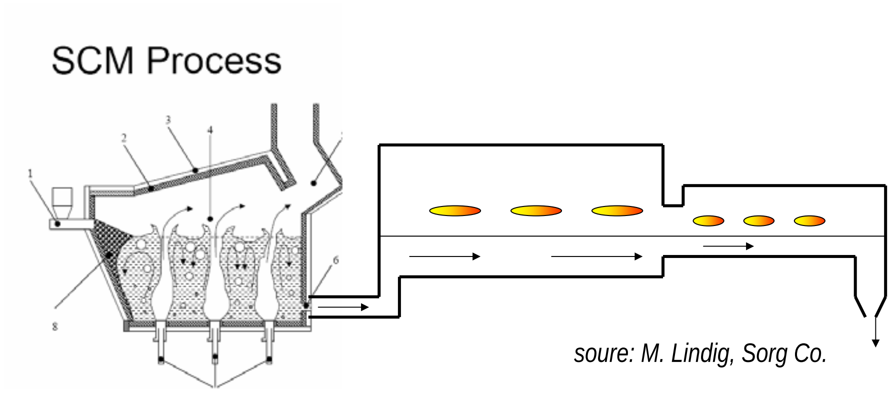



T in °C
2500
2000
1500
1000
500
0
0
2000
4000
6000
8000
10000
12000
power in KW
hot stream
gas + pre-heated air → offgas
cold stream
batch → melt + batch gases
Pinch-Analyse


T in °C
2500
2000
1500
1000
500
0
0
2000
4000
6000
8000
10000
12000
power in KW
hot stream
shift
„pinch“
cold stream
Pinch-Analyse

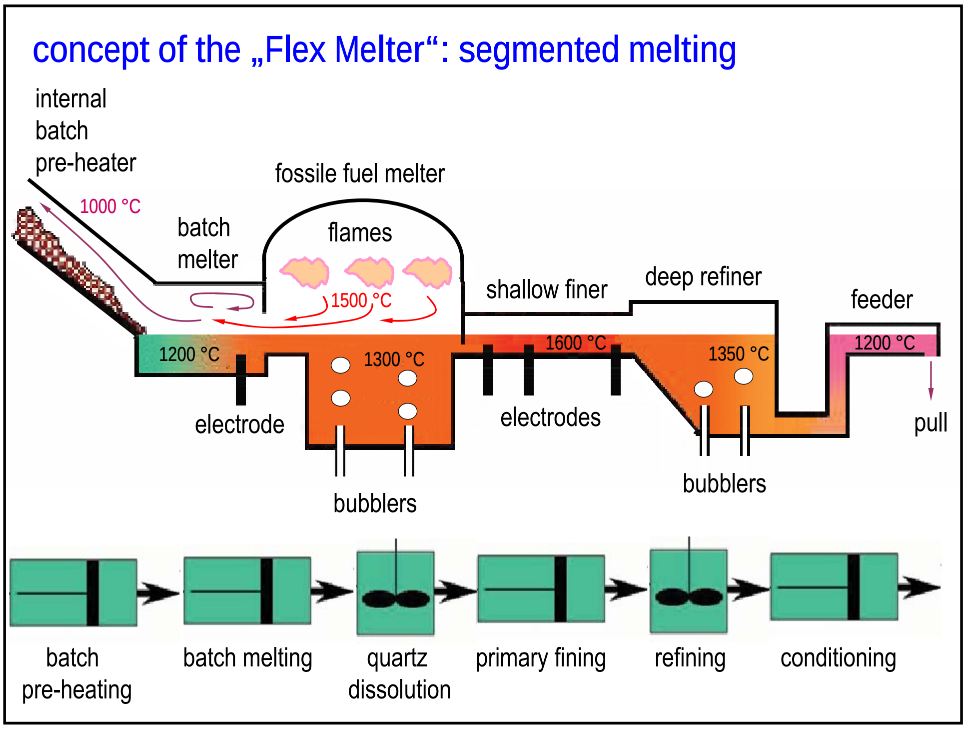


submerged combustion

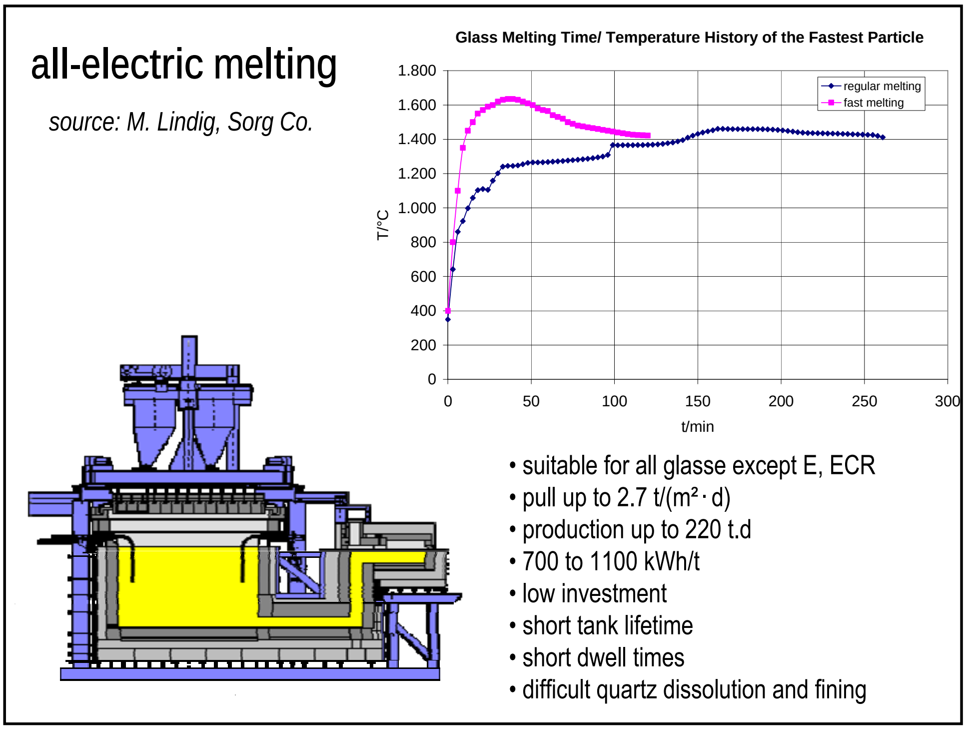


soure: M. Lindig, Sorg Co.

advantages:	high pull, high flexibility, melting of high liquidus glasses
disadvantages:	relatively high energy demand, no established demonstrators yet



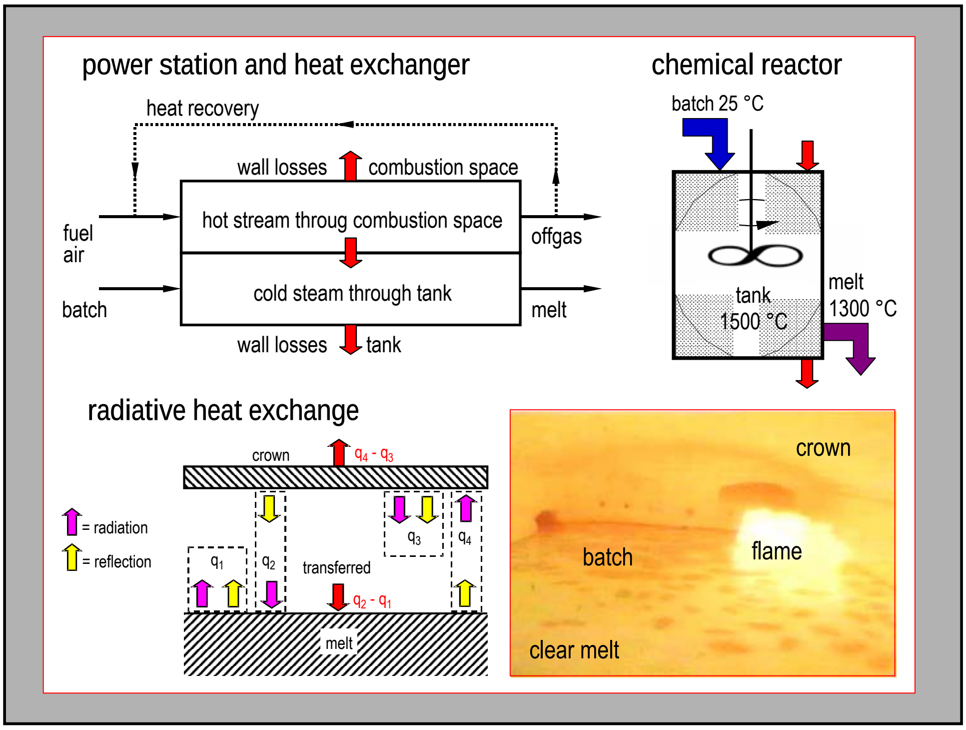
concept of the „Flex Melter“: segmented melting



all-electric melting

source: M. Lindig, Sorg Co.

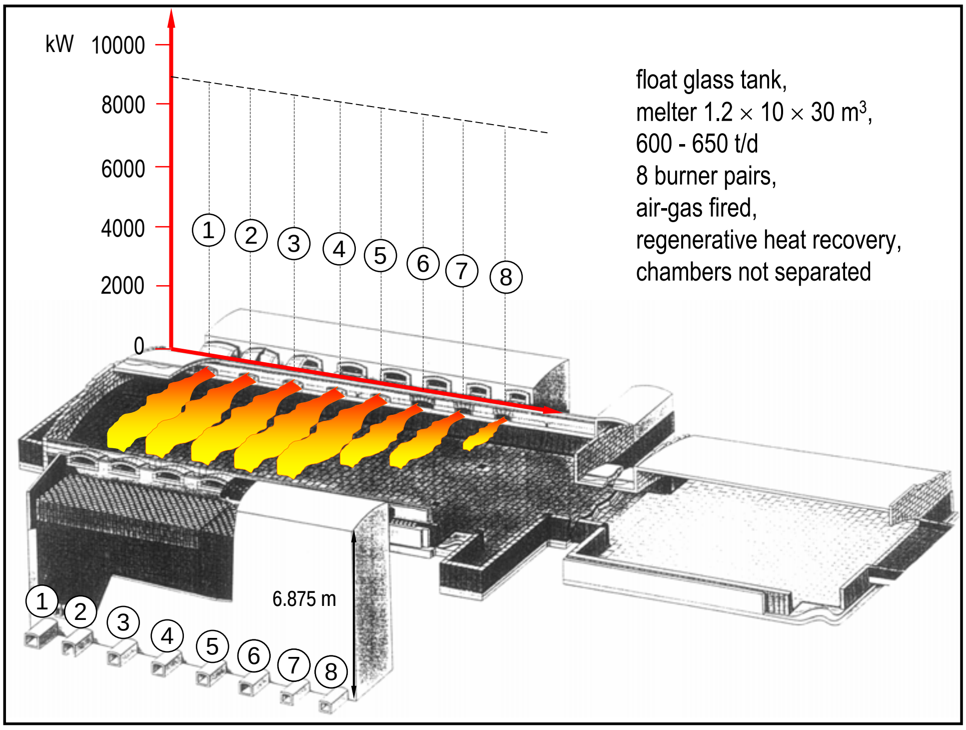
- suitable for all glasse except E, ECR
- pull up to 2.7 t/(m²·d)
- production up to 220 t.d
- 700 to 1100 kWh/t
- low investment
- short tank lifetime
- short dwell times
- difficult quartz dissolution and fining



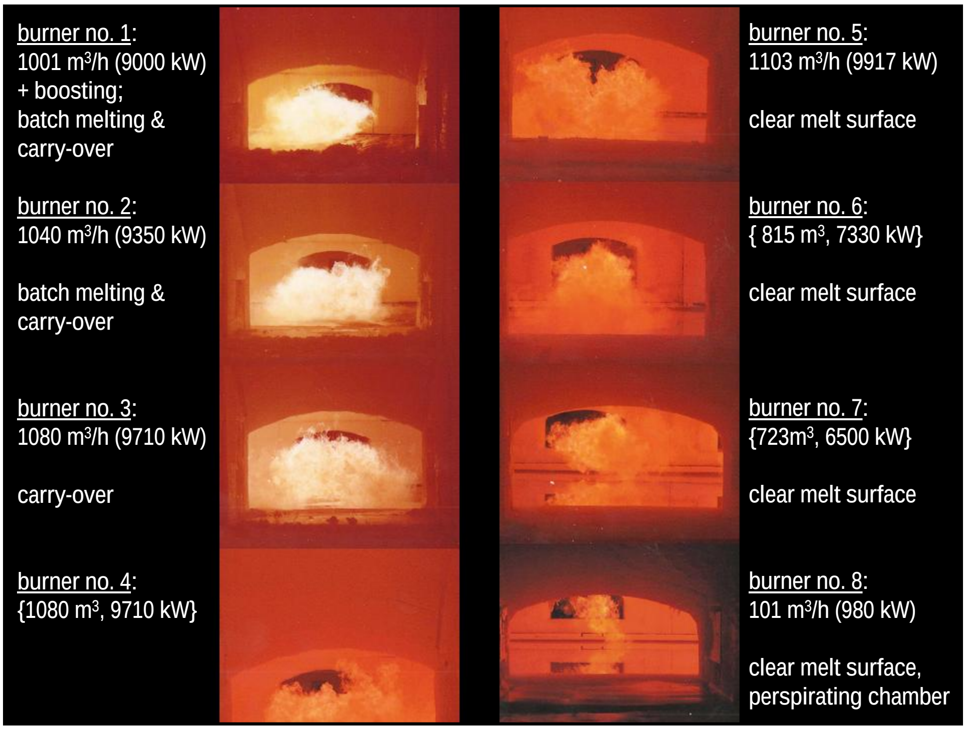
power station and heat exchanger

chemical reactor

radiative heat exchange



float glass tank,
melter 1.2 × 10 × 30 m^3,
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}

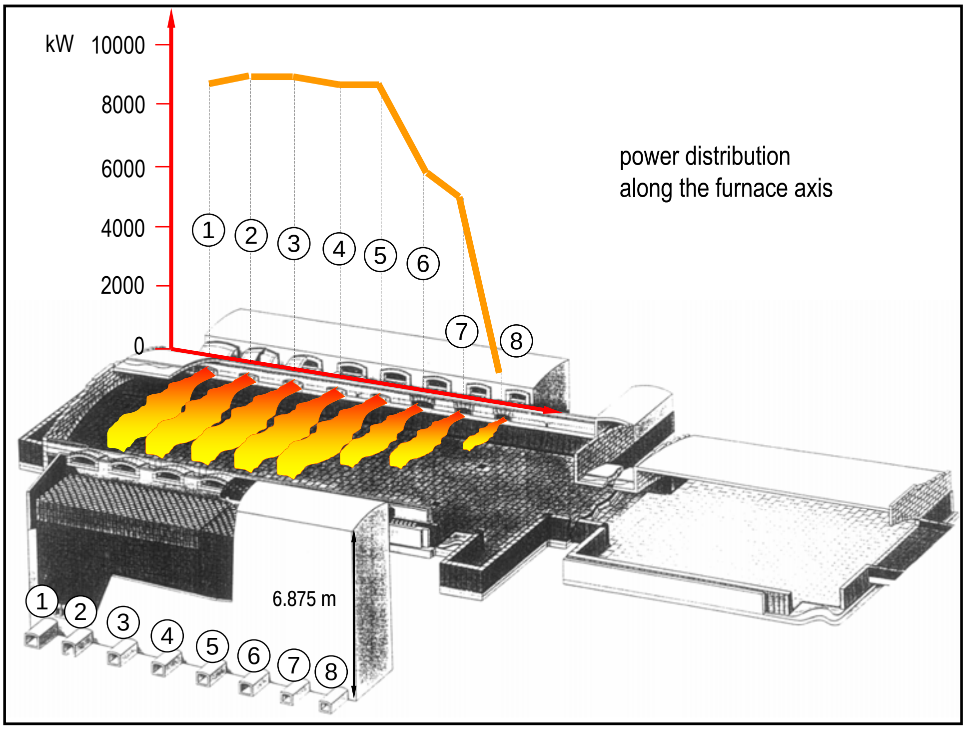
clear melt surface

burner no. 7:
{723m³, 6500 kW}

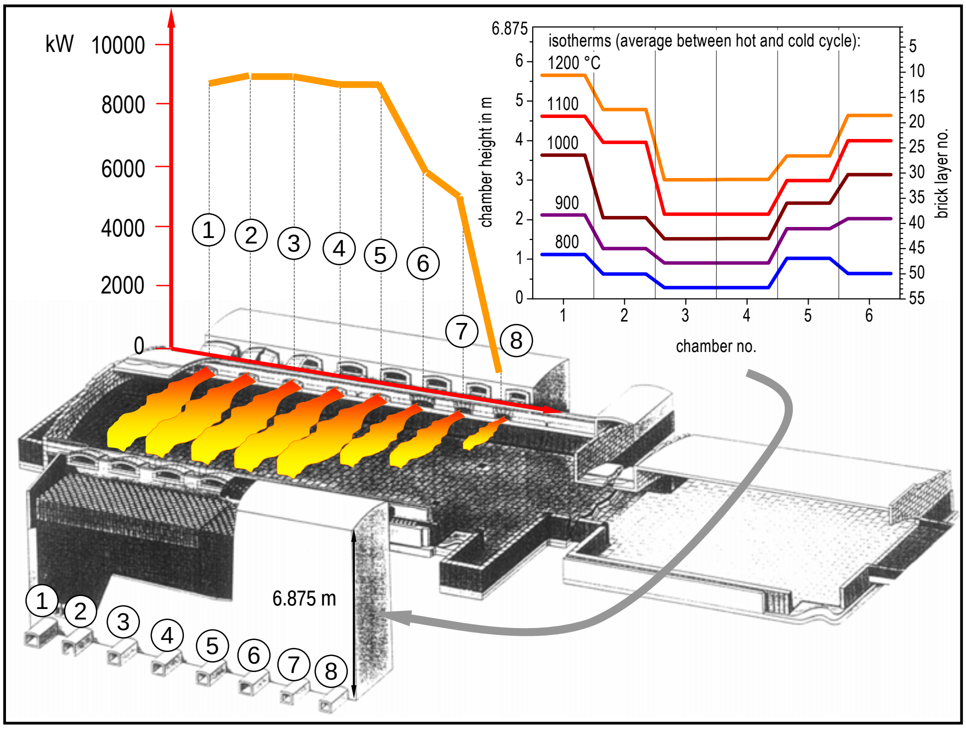
clear melt surface

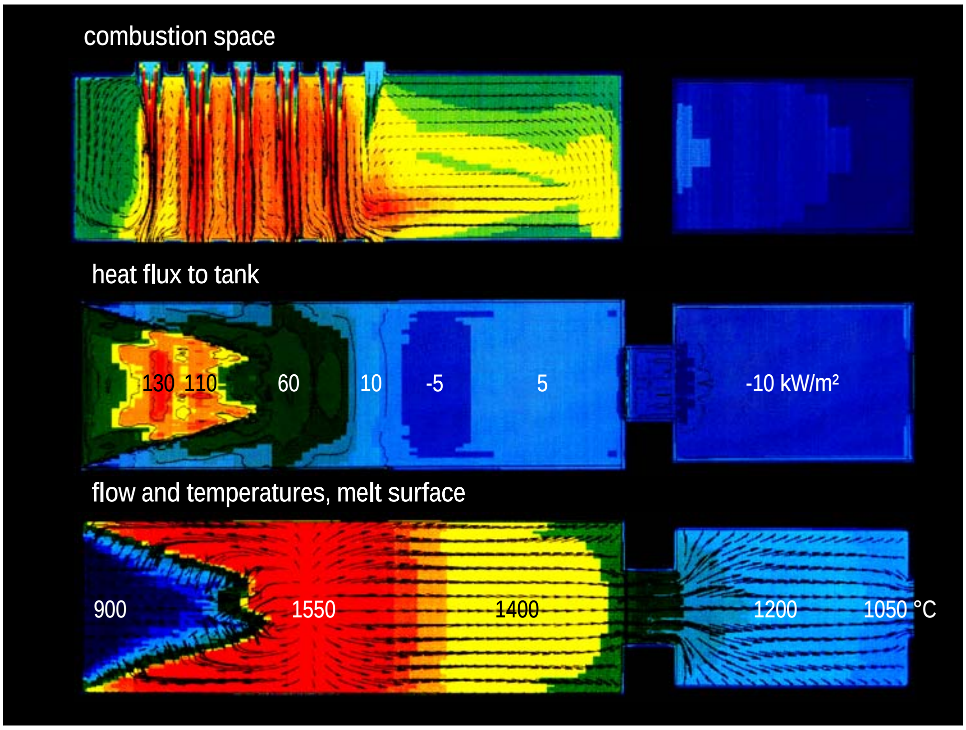
burner no. 8:
101 m³/h (980 kW)

clear melt surface,
perspirating chamber



power distribution
along the furnace axis


kW
10000
8000
6000
4000
2000
0
① ② ③ ④ ⑤ ⑥ ⑦ ⑧
6.875
6
5
4
3
2
1
0
chamber height in m
isotherms (average between hot and cold cycle):
1200 °C
1100
1000
900
800
1 2 3 4 5 6
chamber no.
5 10 15 20 25 30 35 40 45 50 55
brick layer no.
6.875 m
① ② ③ ④ ⑤ ⑥ ⑦ ⑧


combustion space
heat flux to tank
130 110 60 10 -5 5 -10 kW/m²
flow and temperatures, melt surface
900 1550 1400 1200 1050 °C

- Introduction & motivation
- Discussion of constraints as seen in a zero-dimensional model (a)
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  (Zero-dimensional analysis of real furnaces)
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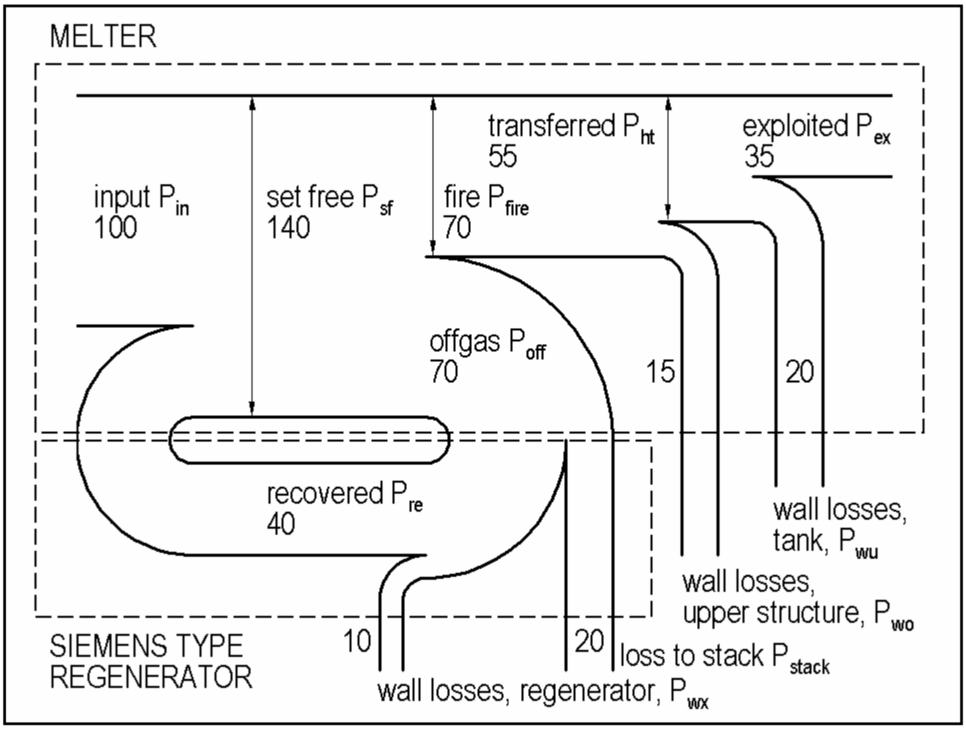
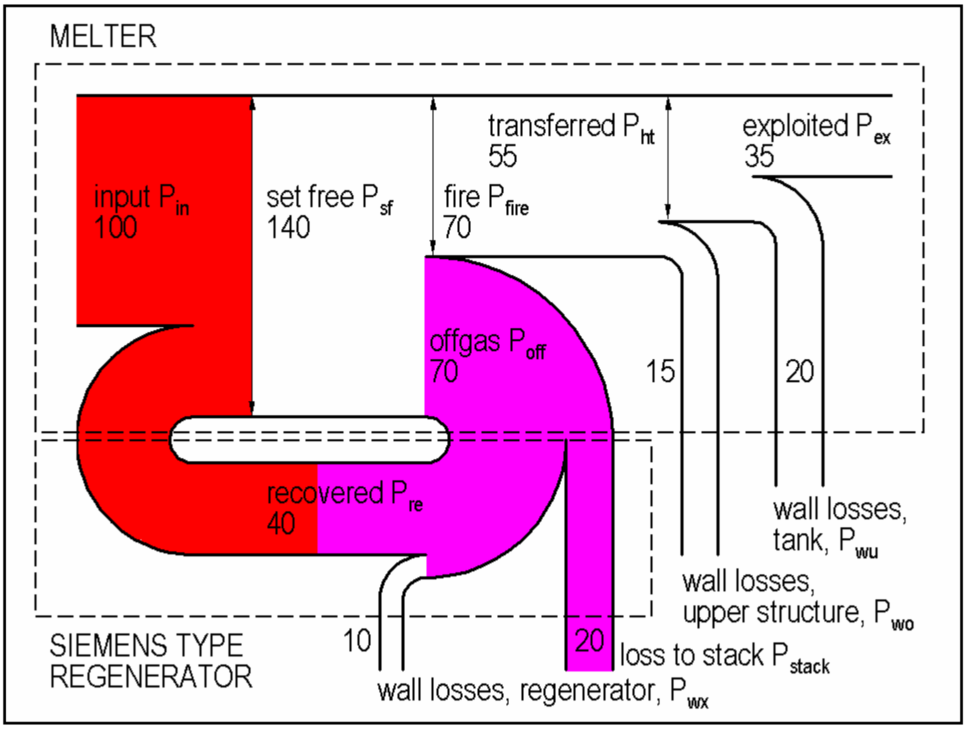
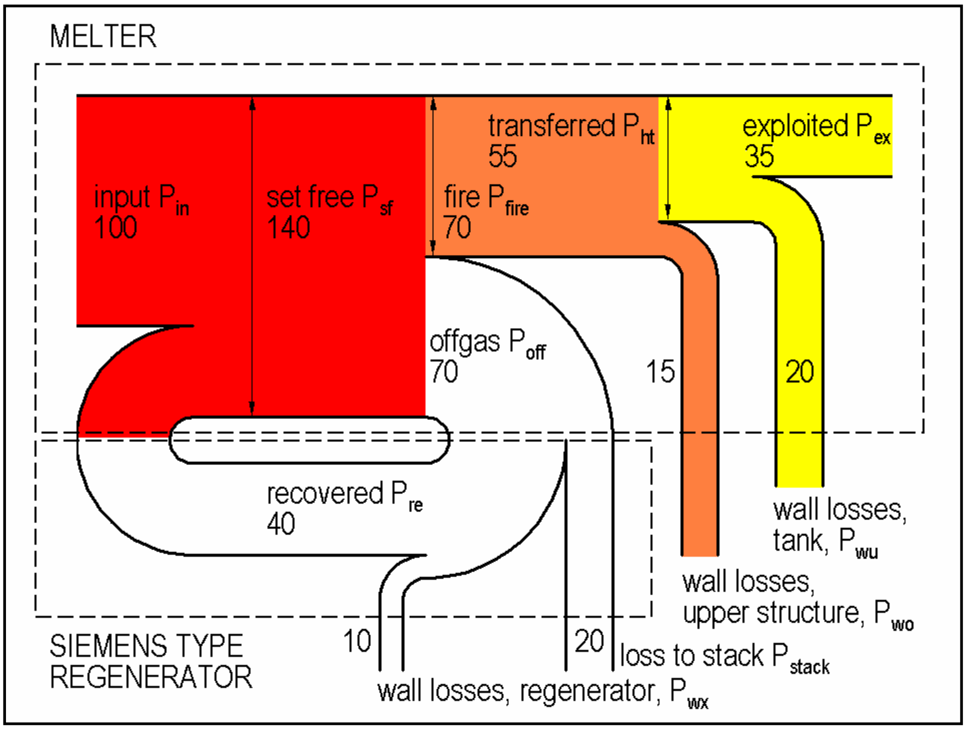
- An extended conclusion: *Quo vadis* glass melting process?




MELTER
input P_{in}
100
set free P_{sf}
140
fire P_{fire}
70
transferred P_{ht}
55
exploited P_{ex}
35
offgas P_{off}
70
15
20
recovered P_{re}
40
wall losses,
tank, P_{wu}
wall losses,
upper structure, P_{wo}
SIEMENS TYPE
REGENERATOR
10
20
loss to stack P_{stack}
wall losses, regenerator, P_{wx}


MELTER
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100
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140
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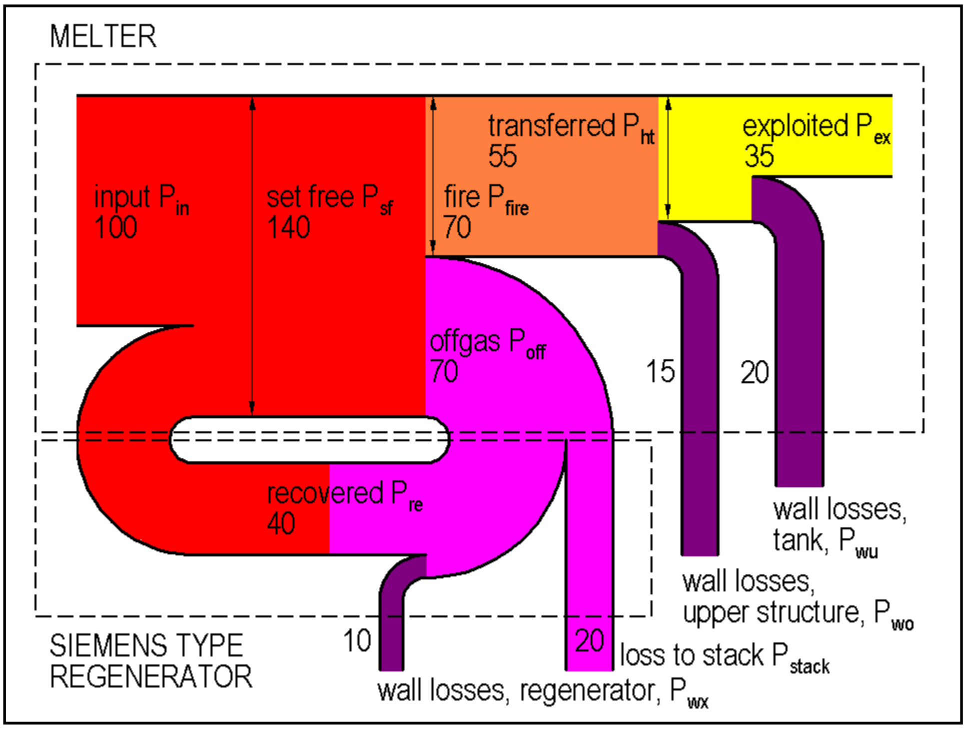
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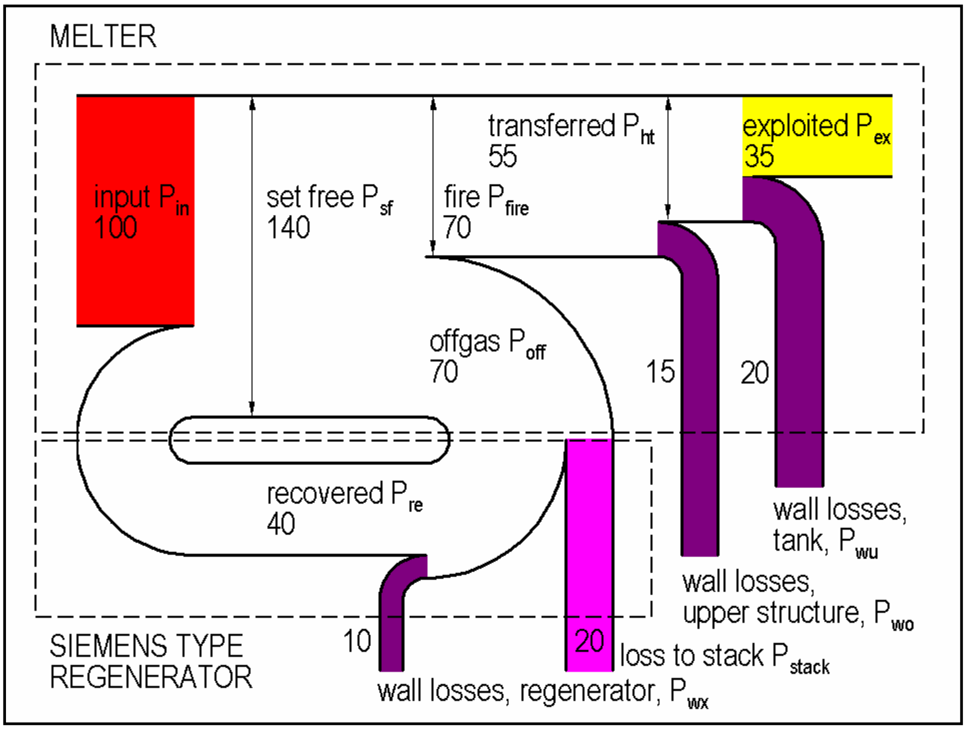
wall losses, regenerator, P_{wx}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100
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140
fire P_{fire}
70
transferred P_{ht}
55
exploited P_{ex}
35
offgas P_{off}
70
15
20
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40
wall losses,
tank, P_{wu}
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upper structure, P_{wo}
SIEMENS TYPE
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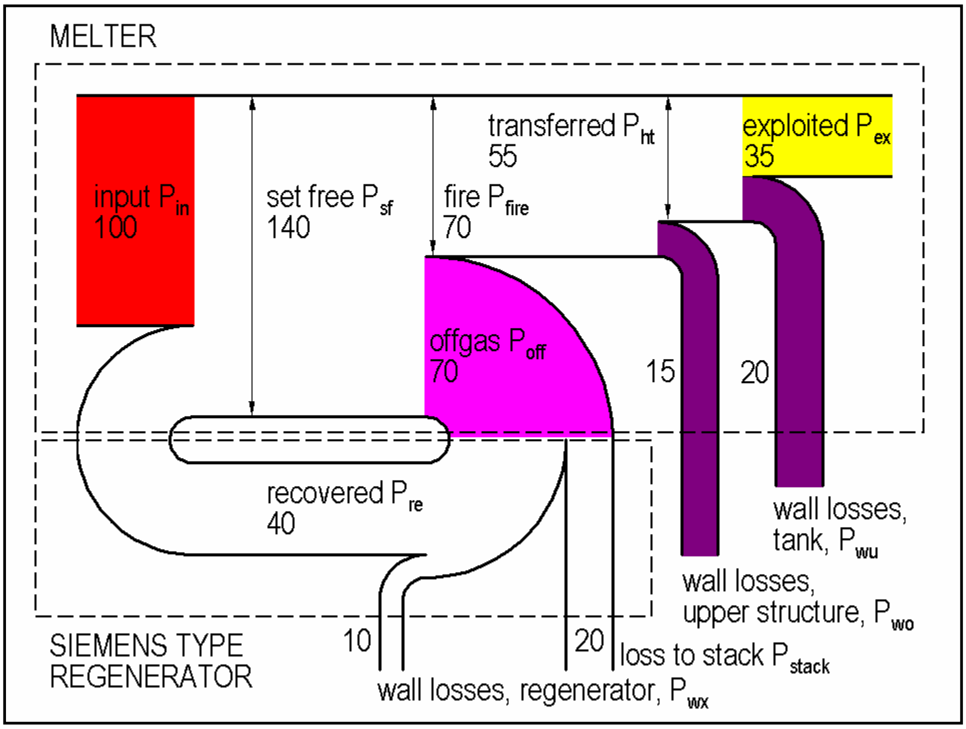
10
20
loss to stack P_{stack}
wall losses, regenerator, P_{wx}


MELTER
input P_{in}
100
set free P_{sf}
140
fire P_{fire}
70
transferred P_{ht}
55
exploited P_{ex}
35
offgas P_{off}
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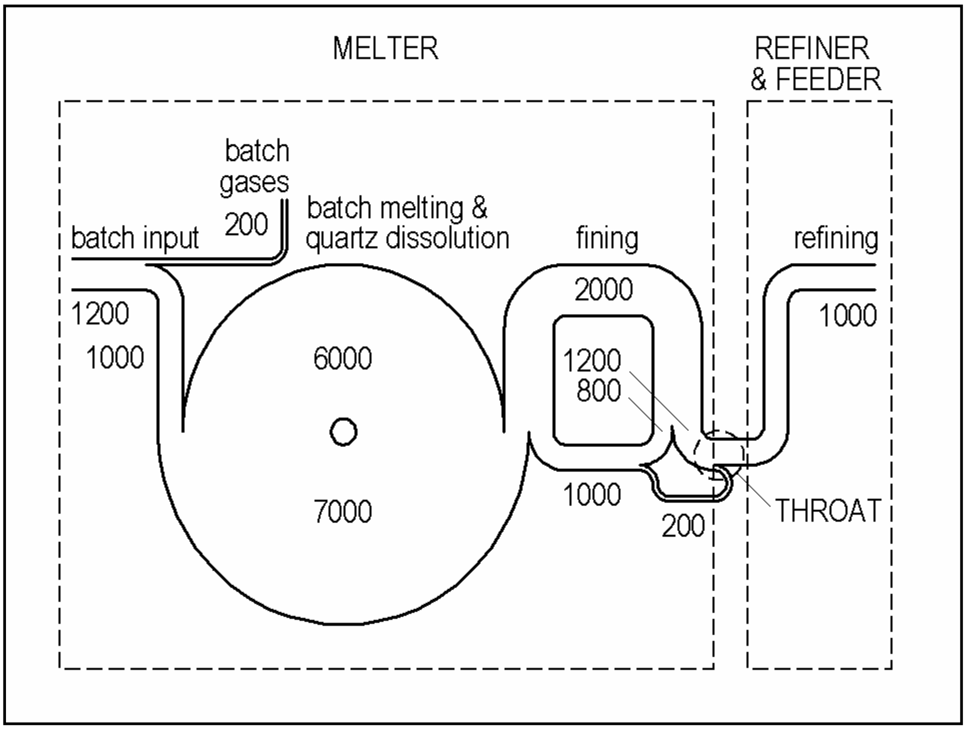
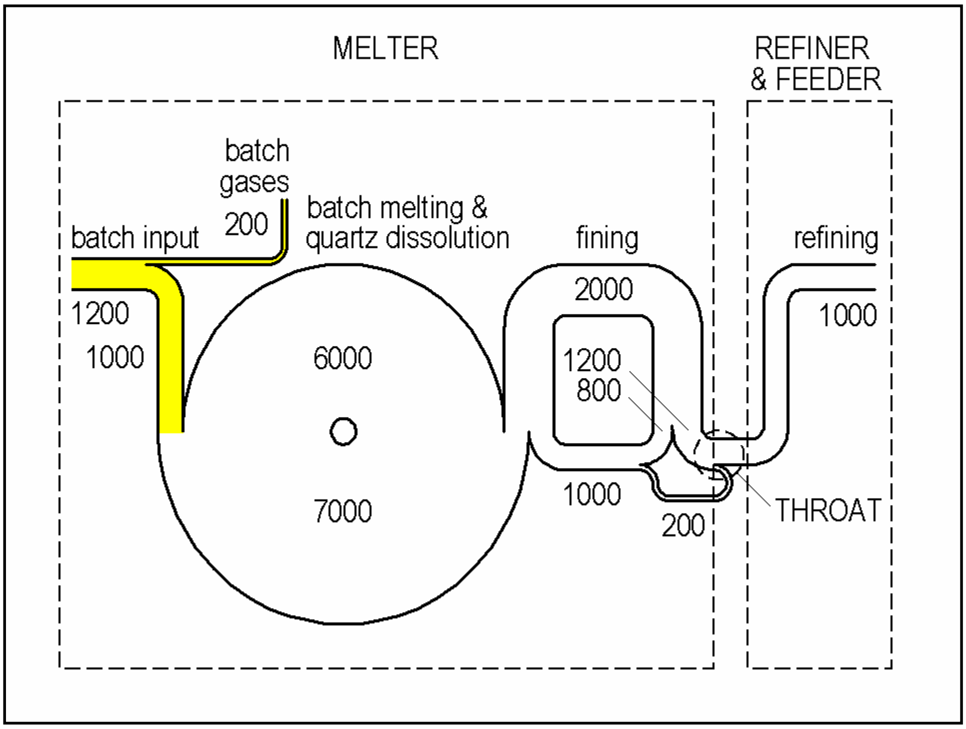
40
wall losses,
tank, P_{wu}
wall losses,
upper structure, P_{wo}
SIEMENS TYPE
REGENERATOR
10
20
loss to stack P_{stack}
wall losses, regenerator, P_{wx}


MELTER
REFINER
& FEEDER
batch
gases
200
batch input
batch melting &
quartz dissolution
fining
refining
1200
1000
6000
2000
1200
800
1000
7000
1000
200
THROAT


MELTER

REFINER
& FEEDER

batch
gases
200

batch input

batch melting &
quartz dissolution

fining

refining

1200
1000

6000

7000

2000

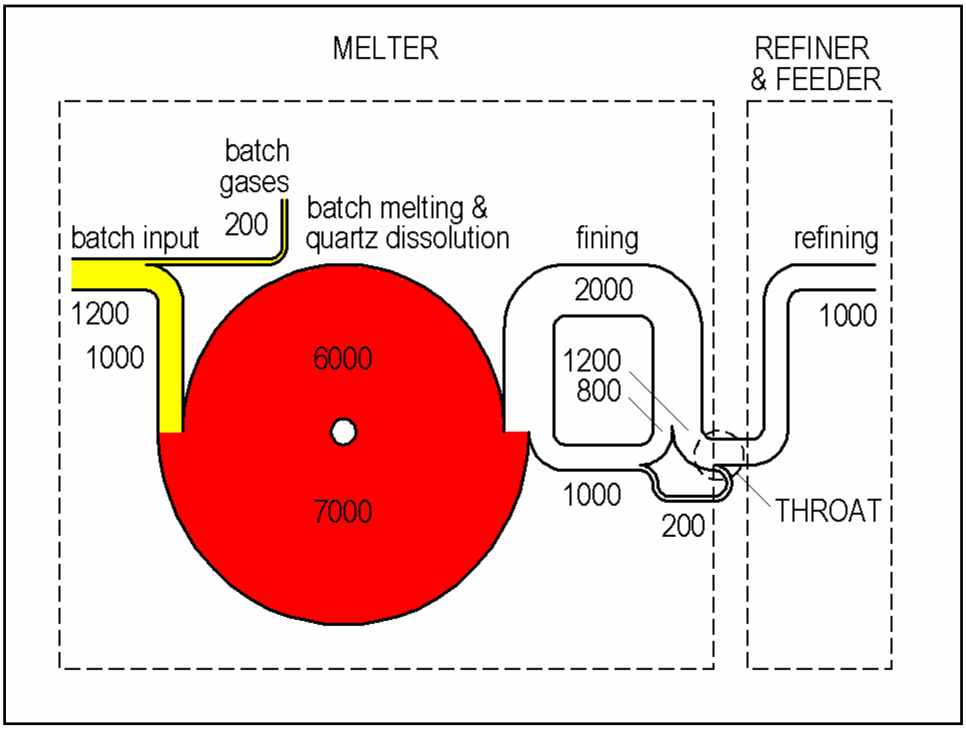
1200
800

1000

200

1000

THROAT


MELTER

REFINER
& FEEDER

batch
gases
200

batch input

batch melting &
quartz dissolution

fining

refining

1200
1000

6000

7000

2000

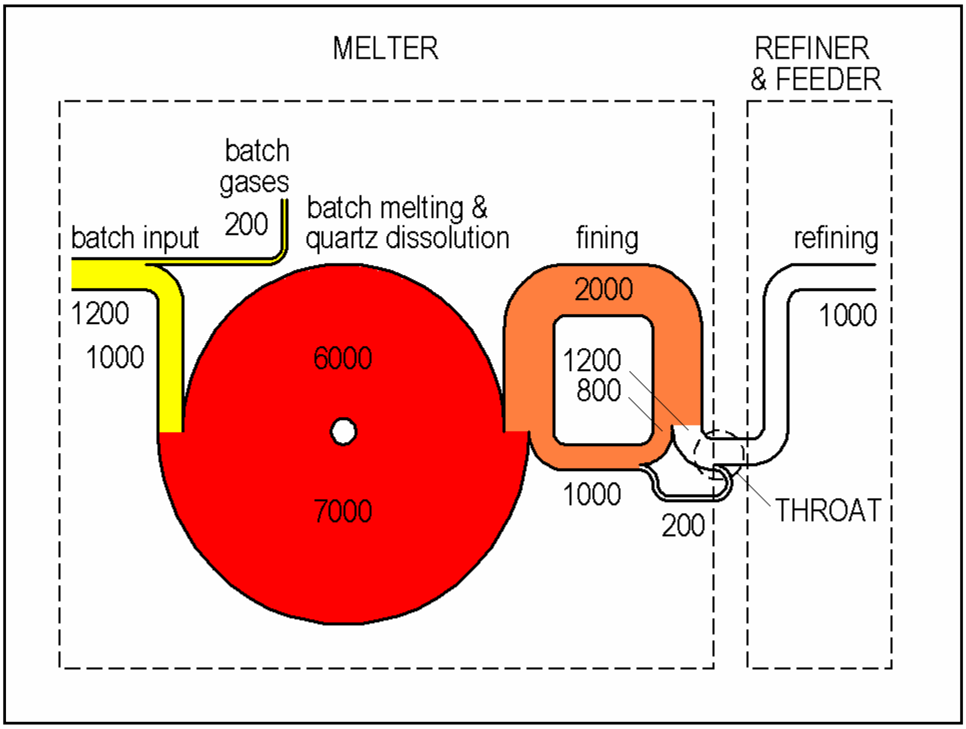
1200
800

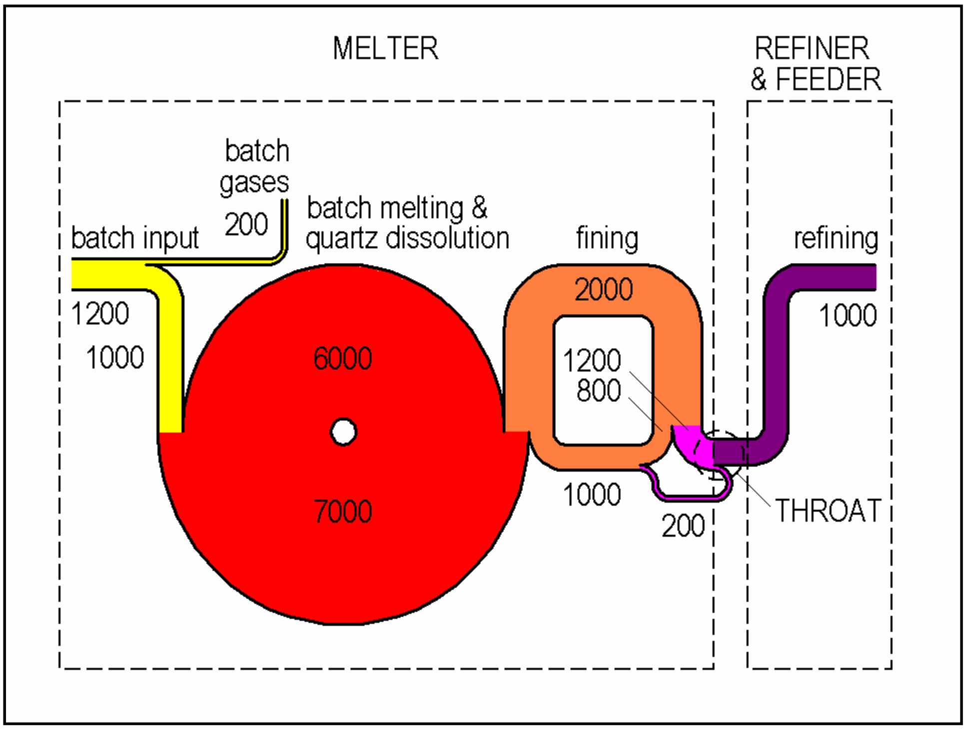
1000

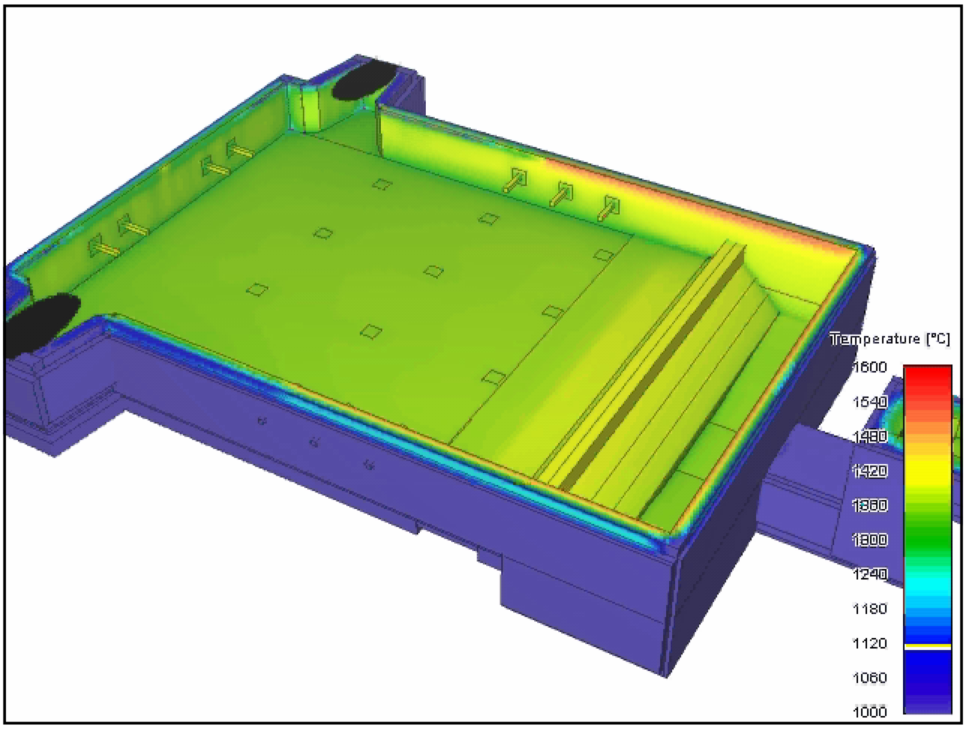
200

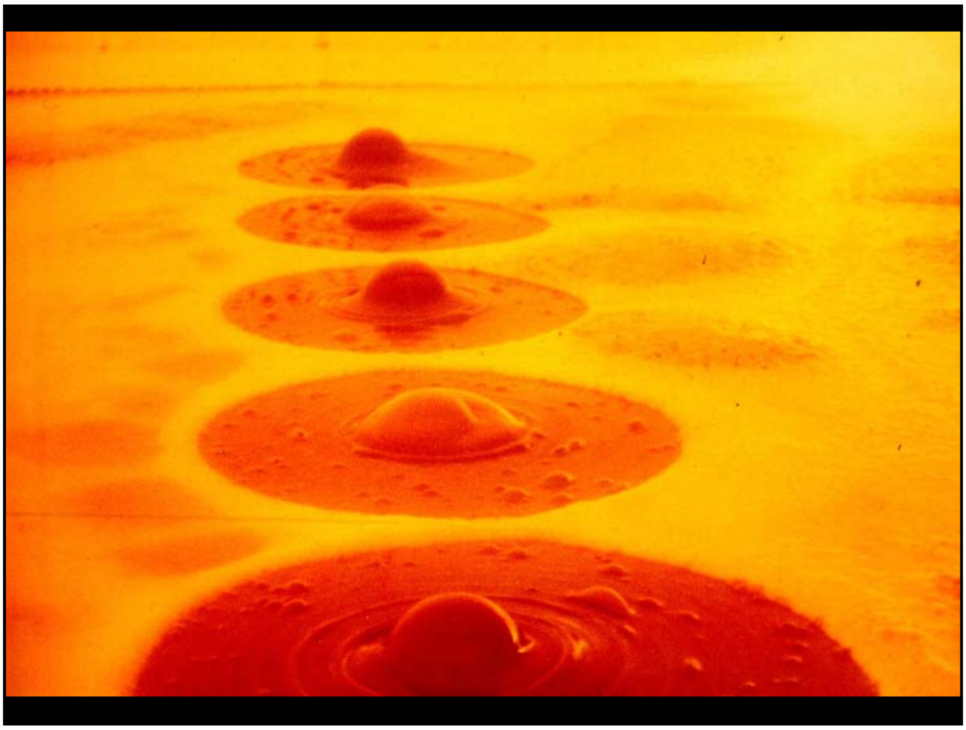
1000

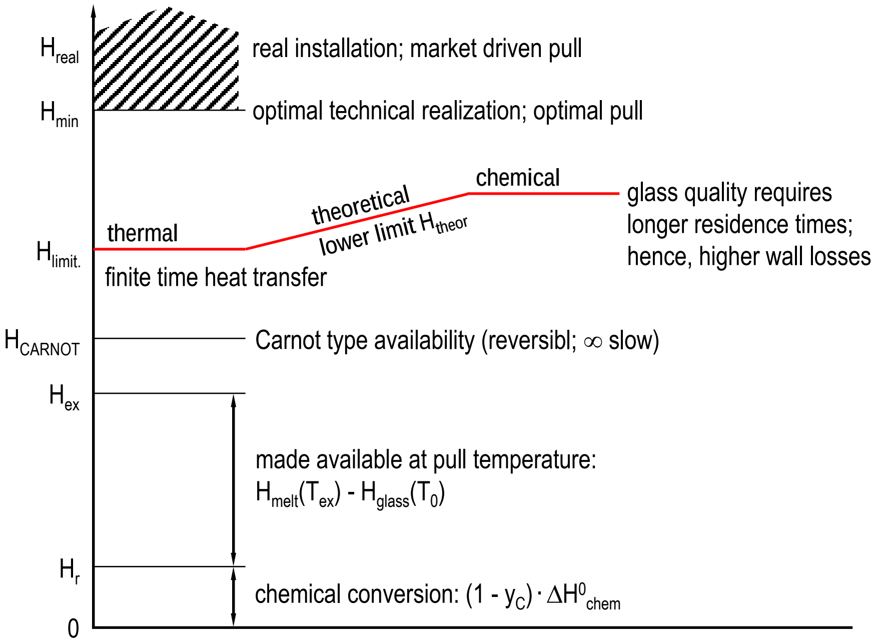
THROAT


MELTER
REFINER & FEEDER
batch gases
200
batch input
batch melting & quartz dissolution
fining
refining
2000
1200
1000
6000
1200
800
1000
7000
1000
200
THROAT


MELTER
REFINER & FEEDER
batch gases
200
batch input
batch melting & quartz dissolution
fining
refining
2000
1200
1000
6000
1200
800
1000
7000
1000
200
THROAT


Temperature [°C]
1600
1540
1480
1420
1360
1300
1240
1180
1120
1060
1000





H_{real}

real installation; market driven pull

H_{min}

optimal technical realization; optimal pull

thermal

theoretical lower limit H_{theor}

chemical

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

$H_{limit.}$

finite time heat transfer

H_{CARNOT}

Carnot type availability (reversibl; ∞ slow)

H_{ex}

made available at pull temperature:

$H_{melt}(T_{ex}) - H_{glass}(T_0)$

H_r

chemical conversion: $(1 - y_C) \cdot \Delta H^0_{chem}$

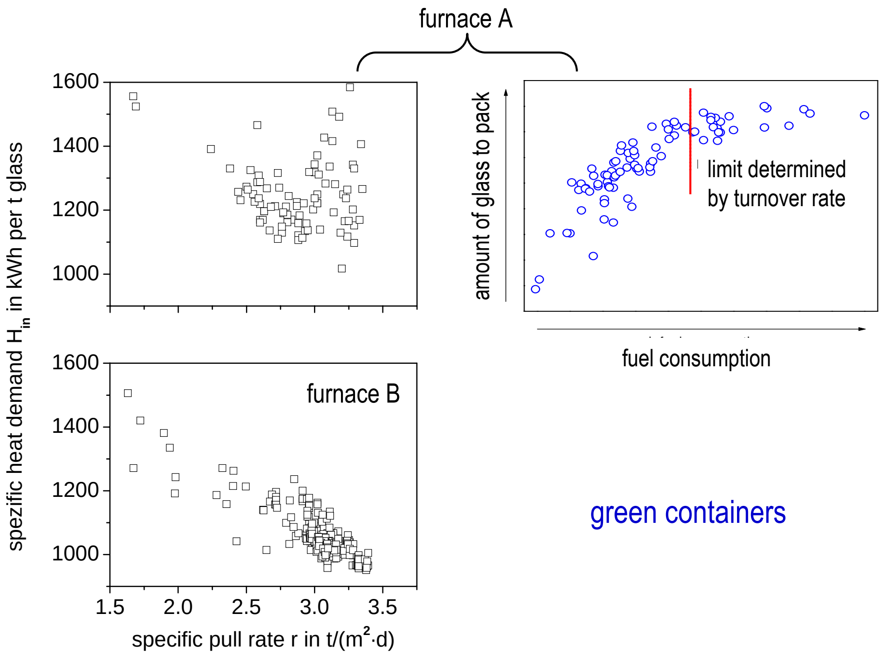
0

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

⇔

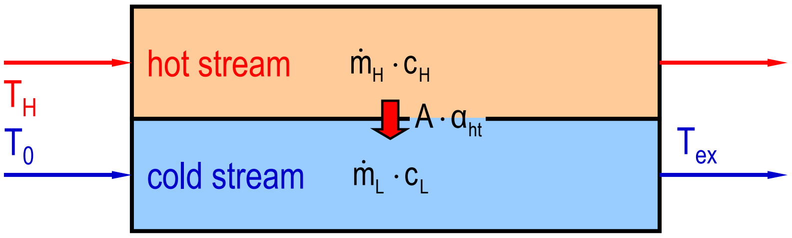
furnace performance
=
heat transfer
⊕
dwell time characteristics

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



green containers

- 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?

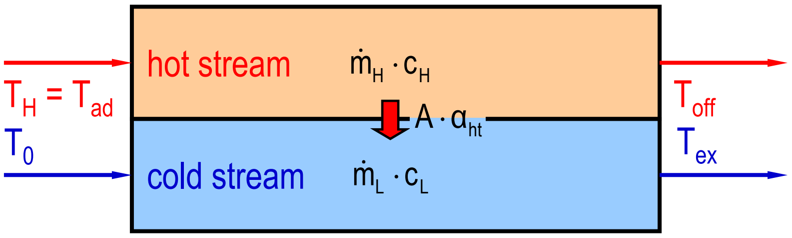


boundary conditions:

- $\dot m_H$ 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: $\frac{\alpha_{ht} \cdot A}{\dot m_L \cdot c_L} = 1$ puts an upper limit to $\dot m_L$
- chemical constraint is an intrinsic limit of the cold stream: $\dot m_L \le \dot m_{tr}$



$H_{ex} = (1 - y_C) \cdot \Delta H^0_{chem} + \Delta H(T_{ex})$

in the glass furnace itself:

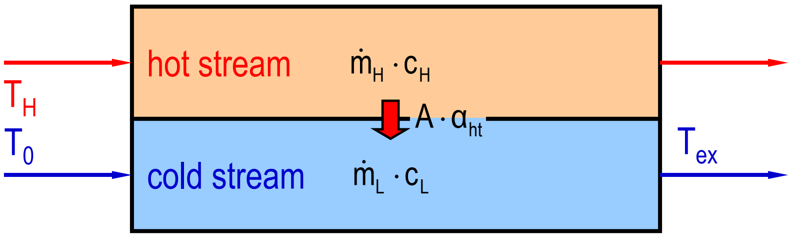
$P_{ex} = \dot m_L \cdot c_L \cdot \Delta T_{ex} = H_{ex} \cdot p;$ $\left[\frac{kWh}{t}\right] \cdot \left[\frac{t}{h}\right] = [kW]$

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.

V_{off} / V_{fuel}, η_{re}, ...

$$\dot m_H \cdot c_H \cdot \Delta T_{ad} = P_{in} + P_{re} \Rightarrow \eta_{ex} = \frac{H_{ex}}{H_{in}} = \frac{\Delta T_{ex}}{\Delta T_{ad}} \cdot (1 + f^*) \approx 75\ \%$$



boundary conditions:

- $\dot m_H$ and $\dot m_L$ can be selected independently
- the cold stream has to reach a fixed tem

What is an imbalance of heat capacity flows?

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: $\frac{\alpha_{ht} \cdot A}{\dot m_L \cdot c_L} = 1$ puts an upper limit to $\dot m_L$
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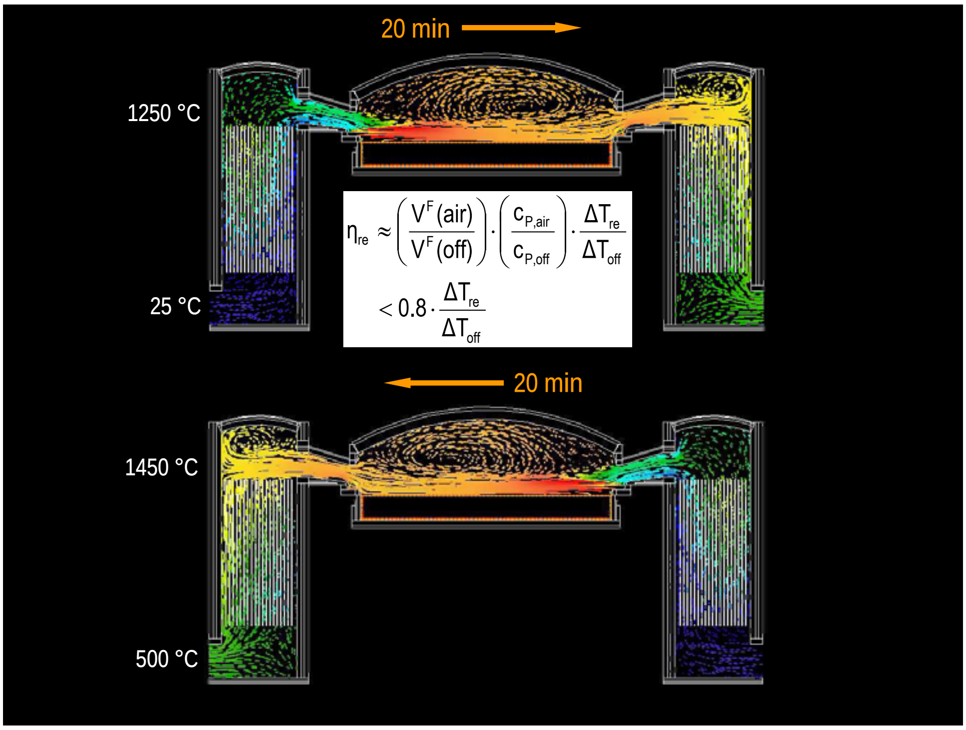
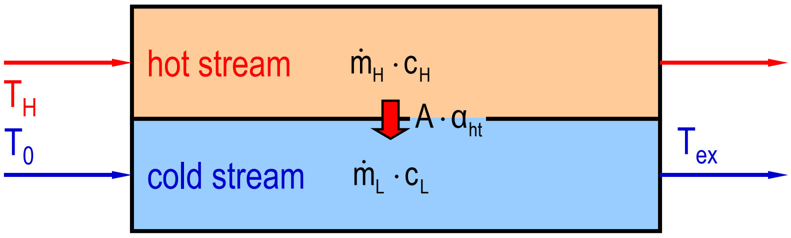


$$\eta_{re} \approx \left(\frac{V^F(\text{air})}{V^F(\text{off})}\right)\cdot\left(\frac{c_{P,air}}{c_{P,off}}\right)\cdot\frac{\Delta T_{re}}{\Delta T_{off}} < 0.8\cdot\frac{\Delta T_{re}}{\Delta T_{off}}$$



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 $\frac{\dot{m}_H \cdot c_H}{\dot{m}_L \cdot c_L}$
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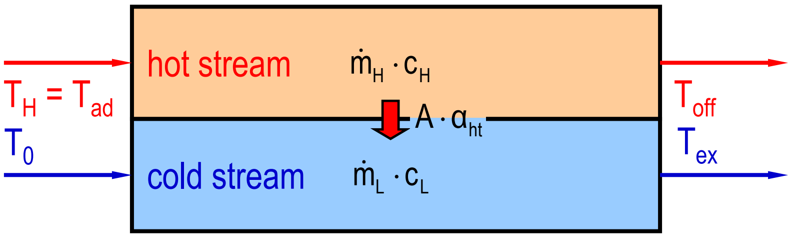

$H_{ex} = (1 - y_C) \cdot \Delta$

in the glass furnace itself:

$P_{ex} = \dot{m}_L \cdot c_L \cdot \Delta T_{ex} = H_{ex} \cdot p;$ $\left[\frac{kWh}{t}\right] \cdot \left[\frac{t}{h}\right] =$

How to derive a realistic value for α_{ht} ?

define the “ideal furnace”:

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- infinitely fast heat transition; $\alpha_{ht} \to \infty$;
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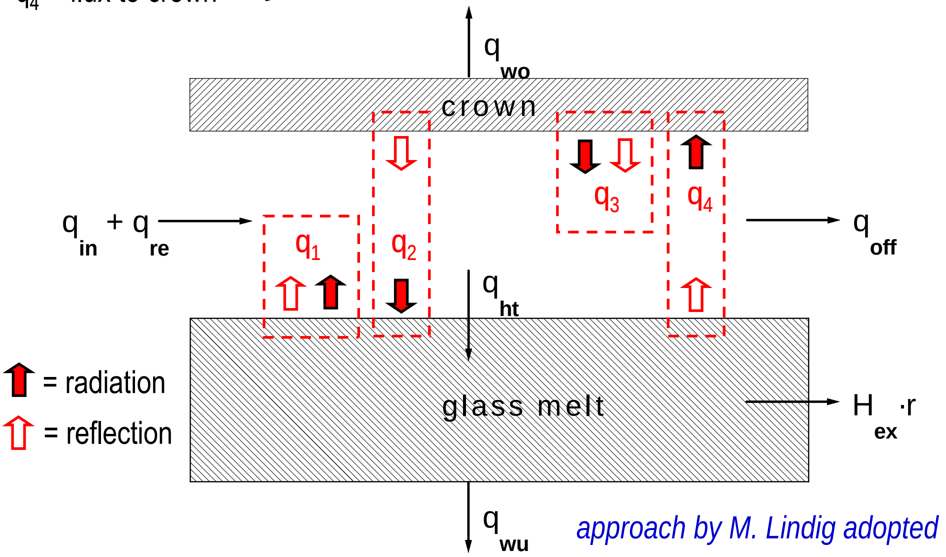
V_{off} / V_{fuel}, η_{re}, ...

$$\dot{m}_H \cdot c_H \cdot \Delta T_{ad} = P_{in} + P_{re} \Rightarrow \eta_{ex} = \frac{H_{ex}}{H_{in}} = \frac{\Delta T_{ex}}{\Delta T_{ad}} \cdot \left(1 + f^*\right) \approx 75\ \%$$

q_1 = flux from glass
q_2 = flux to glass
q_3 = flux from crown
q_4 = flux to crown

$\Rightarrow q_2 - q_1 = q_{ht}$ = flux transferred



approach by M. Lindig adopted

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q_1 = flux from glass
q_2 = flux to glass
q_3 = flux from crown
q_4 = flux to crown

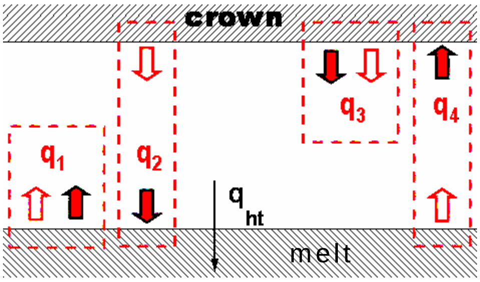
$\Rightarrow q_2 - q_1 = q_{ht}$ = flux transferred

$$q_1 = C_S \cdot \varepsilon_{glass} \cdot T^4_{glass} + (1 - \varepsilon_{glass}) \cdot q_2 \text{*)}$$

$$q_2 = C_S \cdot \varepsilon_{gas} \cdot T^4_{gas} + (1 - \varepsilon_{gas}) \cdot q_3$$

$$q_3 = C_S \cdot \varepsilon_{wo} \cdot T^4_{wo} + (1 - \varepsilon_{wo}) \cdot q_4$$

$$q_4 = C_S \cdot \varepsilon_{gas} \cdot T^4_{gas} + (1 - \varepsilon_{gas}) \cdot q_1$$



*) first term: radiation; second term: reflection; reflectivity = 1 – emissivity

q_1 = flux from glass
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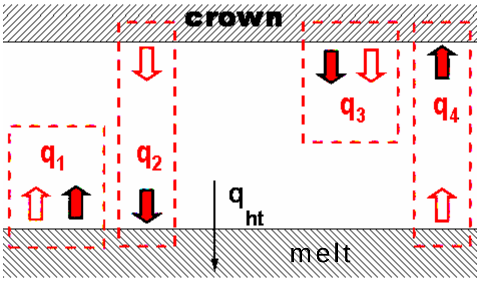

$$q_1 = C_S \cdot \varepsilon_{glass} \cdot T^4_{glass} + (1-\varepsilon_{glass}) \cdot q_2$$
$$q_2 = C_S \cdot \varepsilon_{gas} \cdot T^4_{gas} + (1-\varepsilon_{gas}) \cdot q_3$$
$$q_3 = C_S \cdot \varepsilon_{wo} \cdot T^4_{wo} + (1-\varepsilon_{wo}) \cdot q_4$$
$$q_4 = C_S \cdot \varepsilon_{gas} \cdot T^4_{gas} + (1-\varepsilon_{gas}) \cdot q_1$$

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

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

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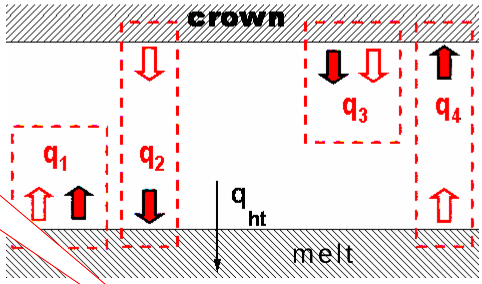
q_2 = flux to glass
q_3 = flux from crown
q_4 = flux to crown

$\Rightarrow q_2 - q_1 = q_{ht}$ = flux transferred

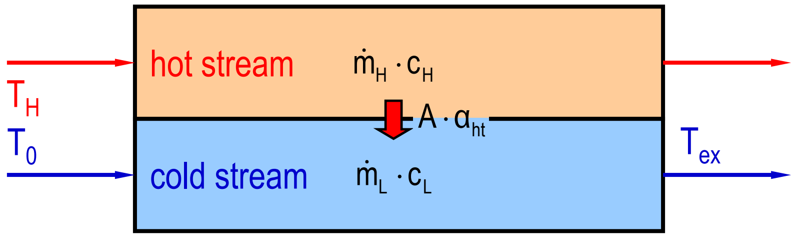


$q_1 = C_S \cdot \varepsilon$
$q_2 = C_S \cdot \varepsilon$
$q_3 = C_S \cdot \varepsilon$
$$q_4 = C_S \cdot \varepsilon_{gas} \cdot T^4_{gas} + (1-\varepsilon_{gas}) \cdot q_1$$

This may constitute a thermal constraint for glass melting.

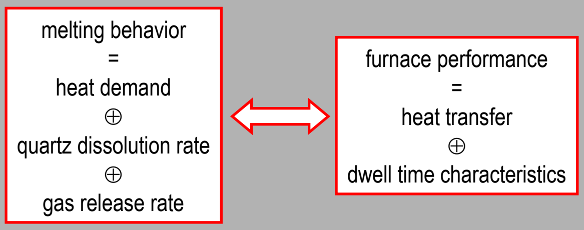
EXAMPLE:
ε_{gas} = 0.25, ε_{glass} = 0.8, ε_{wo} = 05;
T_{gas} = 1650 °C, T_{glass} = 1500 °C, T_{wo} = 1580 °C;
} q_{ht} = 106 kW/m^2

Compare to: H_{ex} = 590 kWh/t, r = 3 t / m$^2 \cdot$d) $\Rightarrow$ $q_{ex} = H_{ex} \cdot r$ = 74 kW/m^2



What is a "chemical constraint"?

- the cold stream has to reach a fixed temperature T_{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



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

furnace performance
=
heat transfer
⊕
dwell time characteristics

- Introduction & motivation
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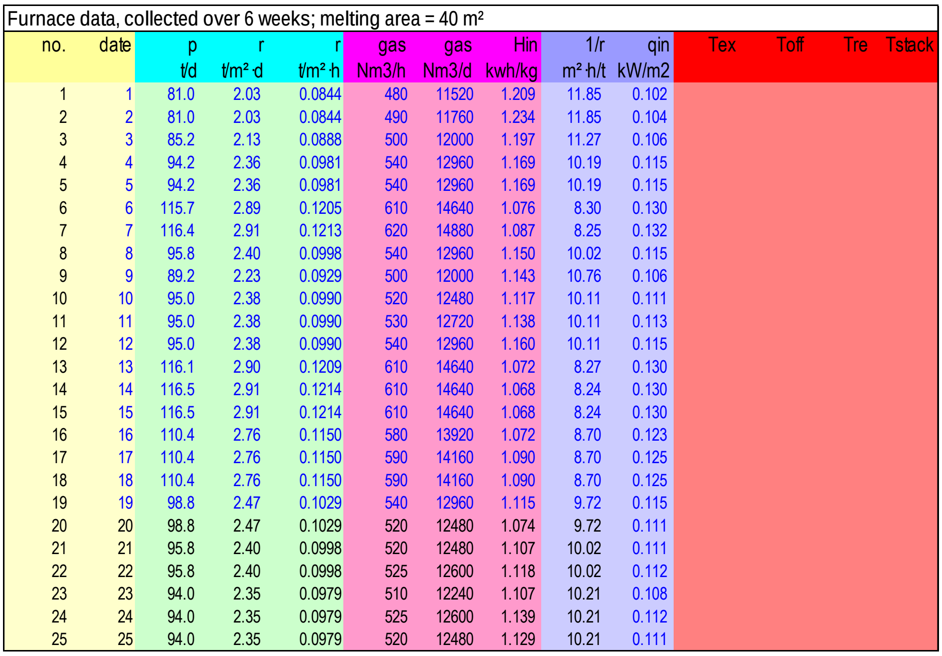
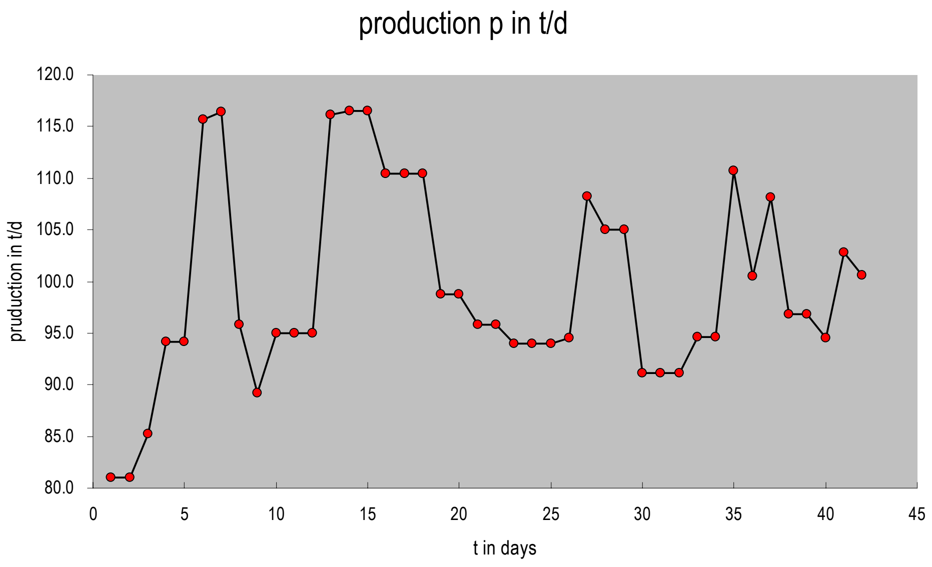
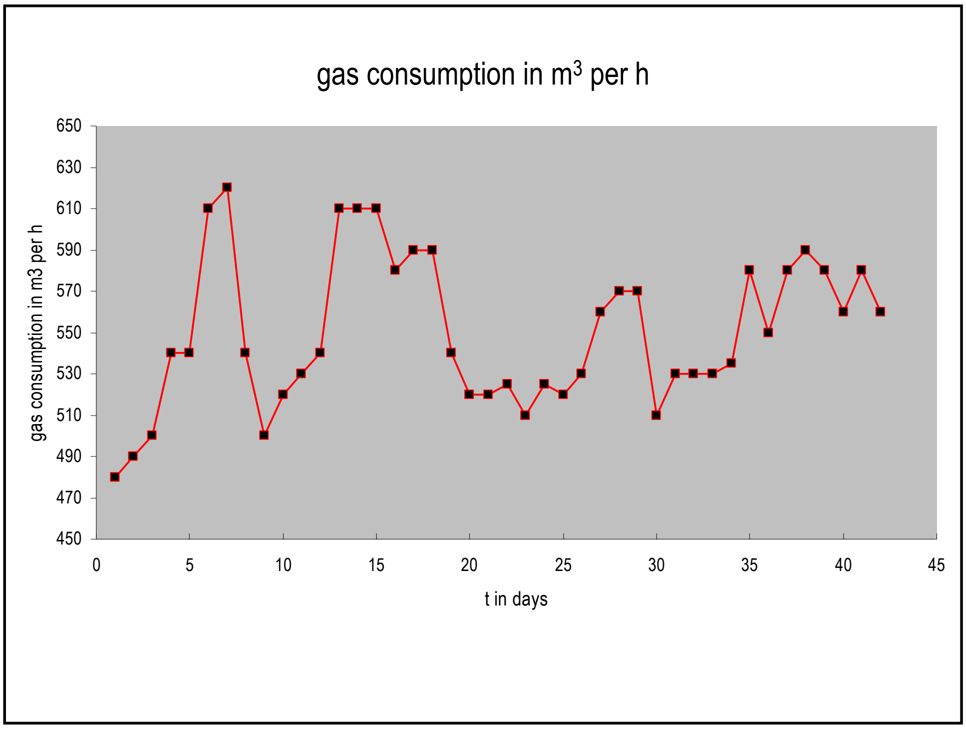
time d	p kg/h	T01 °C	T03 °C	T05 °C	B1 Nm3/h	B2 Nm3/h	B3 Nm3/h
0.00	5855.2	1444	1586	1629	261.6	65.2	225.0
0.25	5510.8	1445	1586	1624	260.8	65.2	224.4
0.50	5855.2	1441	1581	1619	260.3	65.3	223.8
0.75	6199.7	1442	1580	1619	260.5	65.2	224.1
1.00	5855.2	1443	1580	1619	261.7	65.1	225.0
1.25	6199.7	1448	1590	1625	261.6	64.9	225.0
1.50	5510.8	1447	1585	1624	261.2	65.3	224.7
1.75	5855.2	1442	1584	1621	260.2	65.1	223.8
2.00	6199.7	1441	1578	1619	260.2	65.1	223.8
2.25	6199.7	1443	1581	1618	260.7	65.2	224.3
2.50	5855.2	1443	1581	1618	261.7	65.5	225.1
2.75	6199.7	1442	1578	1618	261.8	65.4	225.2
3.00	5855.2	1446	1586	1622	265.5	66.3	228.2
3.25	5855.2	1450	1596	1629	266.5	66.6	229.2
3.50	5855.2	1455	1598	1632	263.9	66.1	227.0
3.75	5855.2	1450	1589	1624	259.7	65.0	223.3
4.00	5855.2	1446	1585	1621	258.1	64.5	222.0
4.25	5855.2	1445	1587	1621	256.6	64.1	220.6
4.50	6199.7	1442	1584	1618	255.4	63.9	219.6
4.75	5510.8	1442	1581	1617	255.3	63.9	219.6

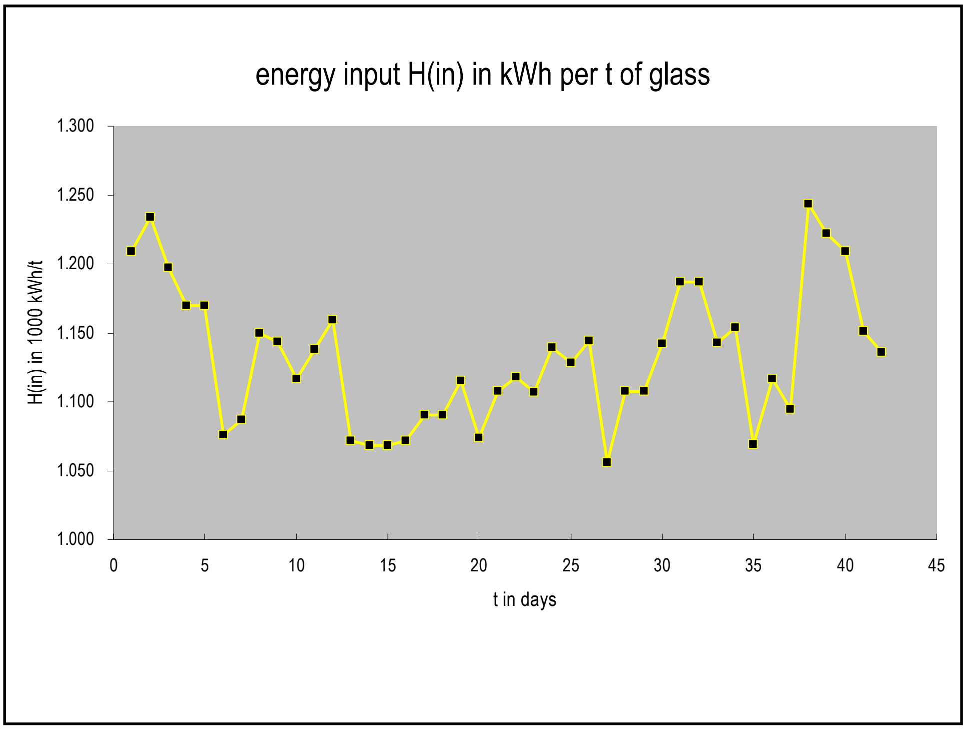


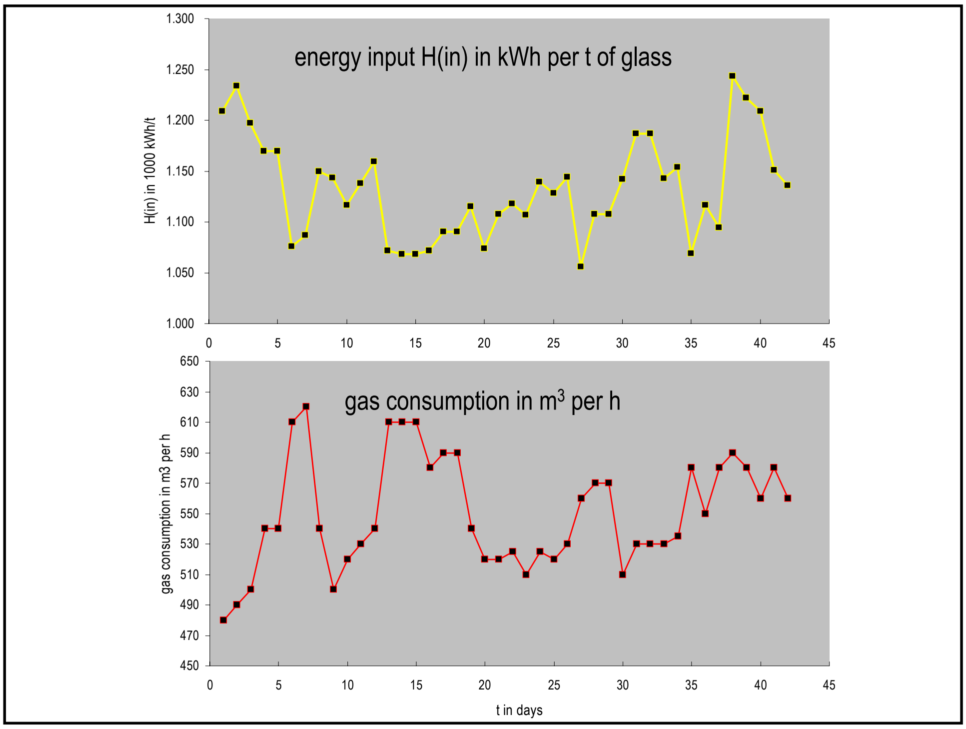
Furnace data, collected over 6 weeks; melting area = 40 m²

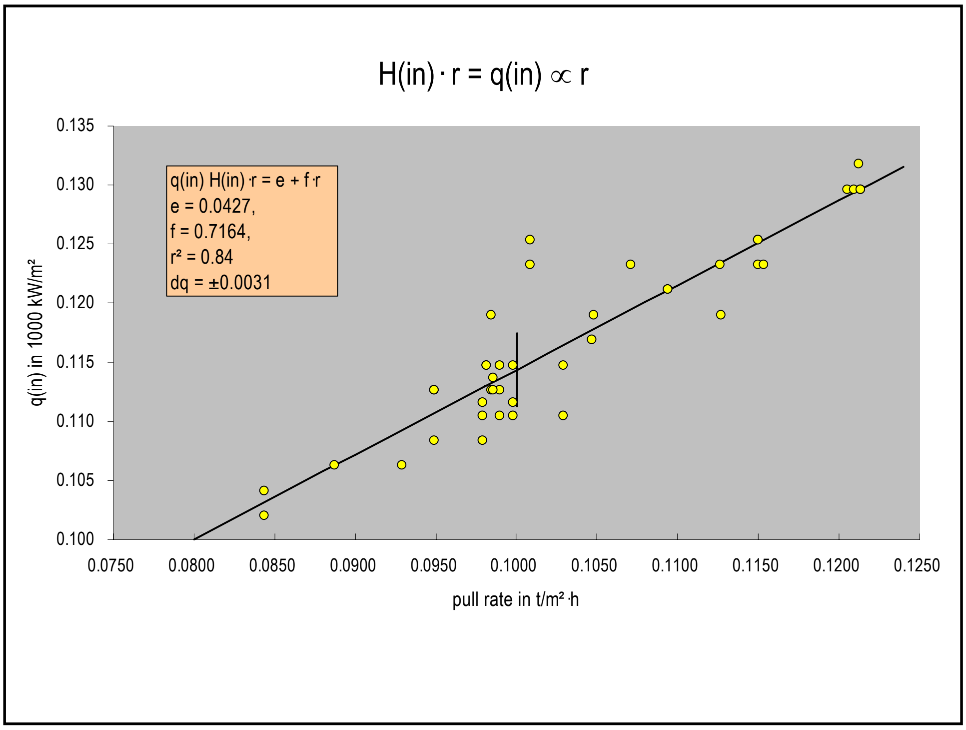
no.	date	p	r	r	gas	gas	Hin	1/r	qin	Tex	Toff	Tre	Tstack
		t/d	t/m²·d	t/m²·h	Nm3/h	Nm3/d	kwh/kg	m²·h/t	kW/m2				
1	1	81.0	2.03	0.0844	480	11520	1.209	11.85	0.102				
2	2	81.0	2.03	0.0844	490	11760	1.234	11.85	0.104				
3	3	85.2	2.13	0.0888	500	12000	1.197	11.27	0.106				
4	4	94.2	2.36	0.0981	540	12960	1.169	10.19	0.115				
5	5	94.2	2.36	0.0981	540	12960	1.169	10.19	0.115				
6	6	115.7	2.89	0.1205	610	14640	1.076	8.30	0.130				
7	7	116.4	2.91	0.1213	620	14880	1.087	8.25	0.132				
8	8	95.8	2.40	0.0998	540	12960	1.150	10.02	0.115				
9	9	89.2	2.23	0.0929	500	12000	1.143	10.76	0.106				
10	10	95.0	2.38	0.0990	520	12480	1.117	10.11	0.111				
11	11	95.0	2.38	0.0990	530	12720	1.138	10.11	0.113				
12	12	95.0	2.38	0.0990	540	12960	1.160	10.11	0.115				
13	13	116.1	2.90	0.1209	610	14640	1.072	8.27	0.130				
14	14	116.5	2.91	0.1214	610	14640	1.068	8.24	0.130				
15	15	116.5	2.91	0.1214	610	14640	1.068	8.24	0.130				
16	16	110.4	2.76	0.1150	580	13920	1.072	8.70	0.123				
17	17	110.4	2.76	0.1150	590	14160	1.090	8.70	0.125				
18	18	110.4	2.76	0.1150	590	14160	1.090	8.70	0.125				
19	19	98.8	2.47	0.1029	540	12960	1.115	9.72	0.115				
20	20	98.8	2.47	0.1029	520	12480	1.074	9.72	0.111				
21	21	95.8	2.40	0.0998	520	12480	1.107	10.02	0.111				
22	22	95.8	2.40	0.0998	525	12600	1.118	10.02	0.112				
23	23	94.0	2.35	0.0979	510	12240	1.107	10.21	0.108				
24	24	94.0	2.35	0.0979	525	12600	1.139	10.21	0.112				
25	25	94.0	2.35	0.0979	520	12480	1.129	10.21	0.111				

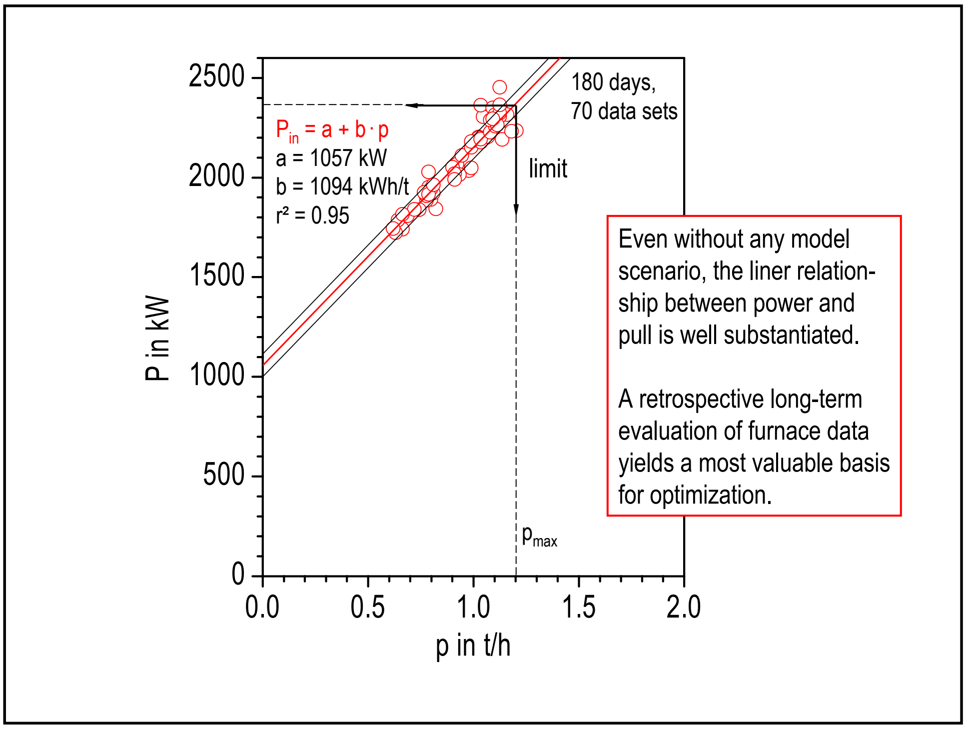



gas consumption in m3 per h
650
630
610
590
570
550
530
510
490
470
450
gas consumption in m3 per h
0
5
10
15
20
25
30
35
40
45
t in days


energy input H(in) in kWh per t of glass
1.300
1.250
1.200
1.150
1.100
1.050
1.000
H(in) in 1000 kWh/t
0
5
10
15
20
25
30
35
40
45
t in days

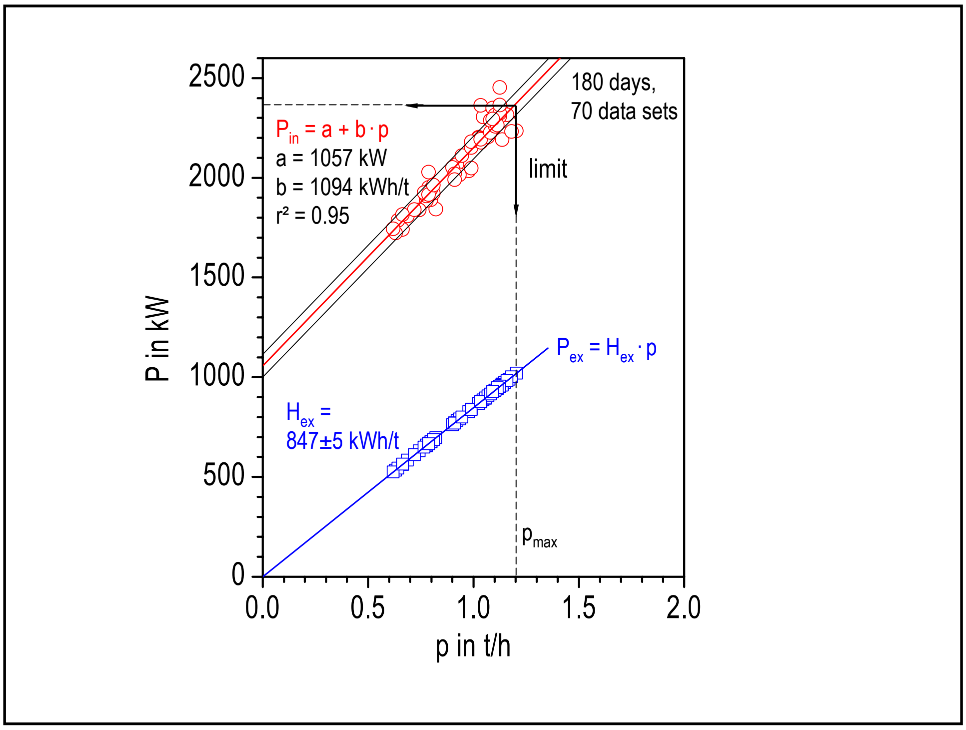

energy input H(in) in kWh per t of glass
H(in) in 1000 kWh/t
1.300
1.250
1.200
1.150
1.100
1.050
1.000
0
5
10
15
20
25
30
35
40
45
gas consumption in m3 per h
gas consumption in m3 per h
650
630
610
590
570
550
530
510
490
470
450
0
5
10
15
20
25
30
35
40
45
t in days

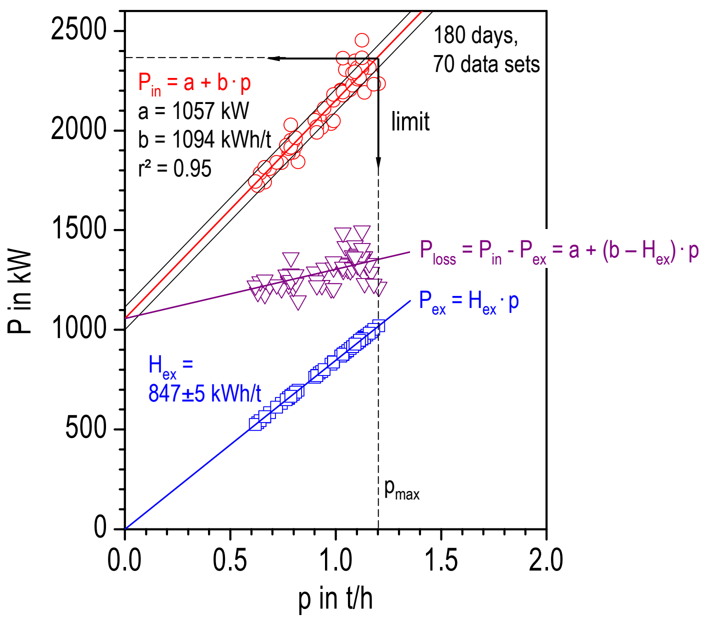

H(in) · r = q(in) ∝ r
q(in) H(in) ·r = e + f ·r
e = 0.0427,
f = 0.7164,
r² = 0.84
dq = ±0.0031
q(in) in 1000 kW/m²
0.135
0.130
0.125
0.120
0.115
0.110
0.105
0.100
0.0750
0.0800
0.0850
0.0900
0.0950
0.1000
0.1050
0.1100
0.1150
0.1200
0.1250
pull rate in t/m² ·h

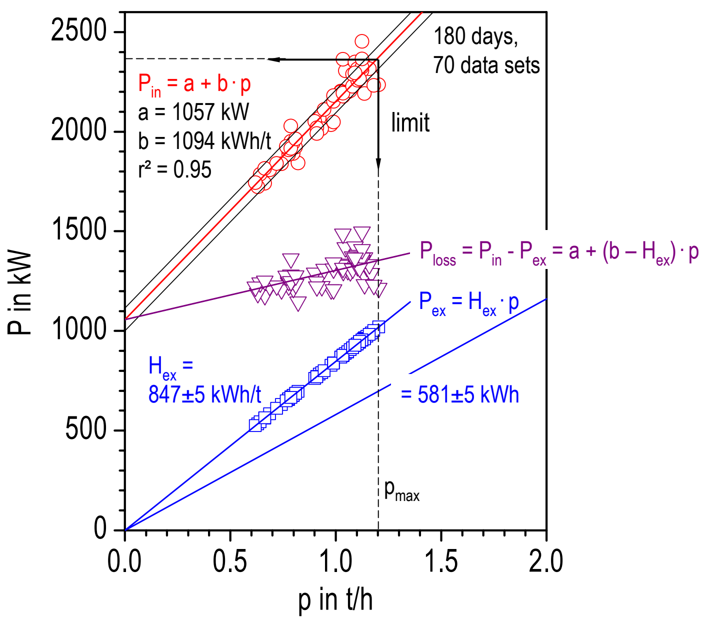


Even without any model scenario, the liner relationship between power and pull is well substantiated.

A retrospective long-term evaluation of furnace data yields a most valuable basis for optimization.




180 days,
70 data sets
$P_{in} = a + b \cdot p$
a = 1057 kW
b = 1094 kWh/t
r² = 0.95
limit
$P_{loss} = P_{in} - P_{ex} = a + (b - H_{ex}) \cdot p$
$P_{ex} = H_{ex} \cdot p$
H_{ex} =
847±5 kWh/t
p_{max}
P in kW
2500
2000
1500
1000
500
0
0.0
0.5
1.0
1.5
2.0
p in t/h


180 days,
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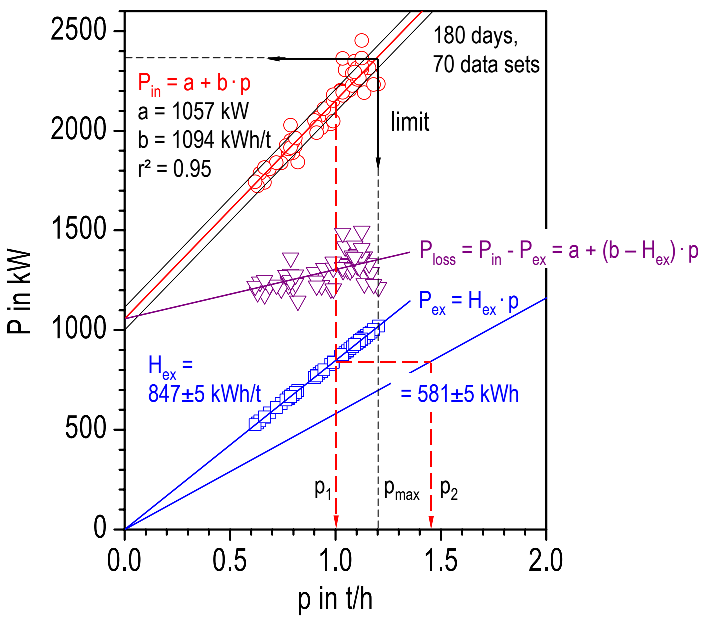
limit
$P_{loss} = P_{in} - P_{ex} = a + (b - H_{ex}) \cdot p$
$P_{ex} = H_{ex} \cdot p$
H_{ex} =
847±5 kWh/t
= 581±5 kWh
p_{max}
P in kW
2500
2000
1500
1000
500
0
0.0
0.5
1.0
1.5
2.0
p in t/h



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:

$$P_{ex} = H_{ex} \cdot p; \qquad H_{ex} = (1 - y_C) \cdot \Delta H^0_{chem} + c_{P,melt} \cdot \Delta T_{ex}$$

By difference, the cumulative loss is obtained:

$$P_{loss} = P_{in} - P_{ex} = a + (b - H_{ex}) \cdot p > 0$$

$$= \underbrace{P_{wu} + P_{wo} + P_{wx}}_{\textit{independent of } p} + P_{stack}$$

has the same slope as P_{loss}: slope = (b - H_{ex})

Evaluating P_{in} according to the heat balance yields:

$$P_{in} = \underbrace{P_{ex} + P_{wu}}_{P_{ht}} + \underbrace{P_{wo} + P_{wx} + P_{stack}}_{P_{loss\text{-}fire}} \Rightarrow P_{in} - P_{ht} = P_{loss-fire}$$

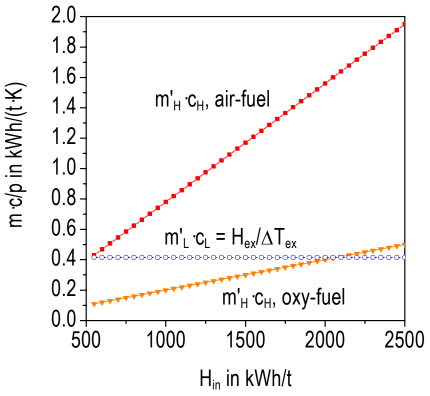
same slope as P_{loss}

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 = off, oxy-off, and air



j =	c_j in $\frac{\text{Wh}}{\text{m}^3\cdot\text{K}}$	V_j/V_{fuel} in $\frac{\text{m}^3}{\text{m}^3}$	z_j in $\frac{1}{10^3\,\text{K}}$
off	0.49	10.6	0.52
off-oxy	0.65	9.6	0.20
air	0.43	3.1	0.41

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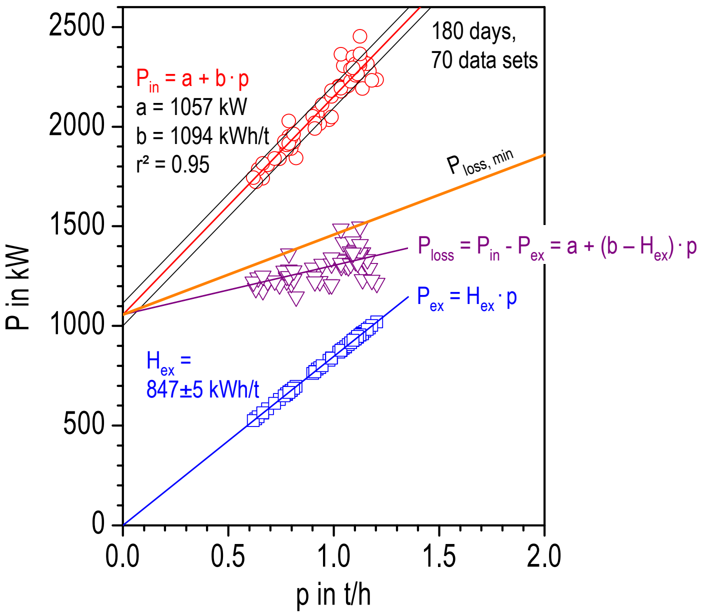
According to the theory of heat exchangers (co-current mode), the maximum transferred power at infinitely high α_{ht} is given by

$$P_{ht-MAX} = \underbrace{\frac{1}{1+f_{HL}}}_{\le ½} \cdot \underbrace{z_{off} \cdot \Delta T_{ad}}_{\approx 1} \cdot P_{in} \propto x \cdot b \cdot p \qquad \Rightarrow \text{factor } x \le ½$$

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

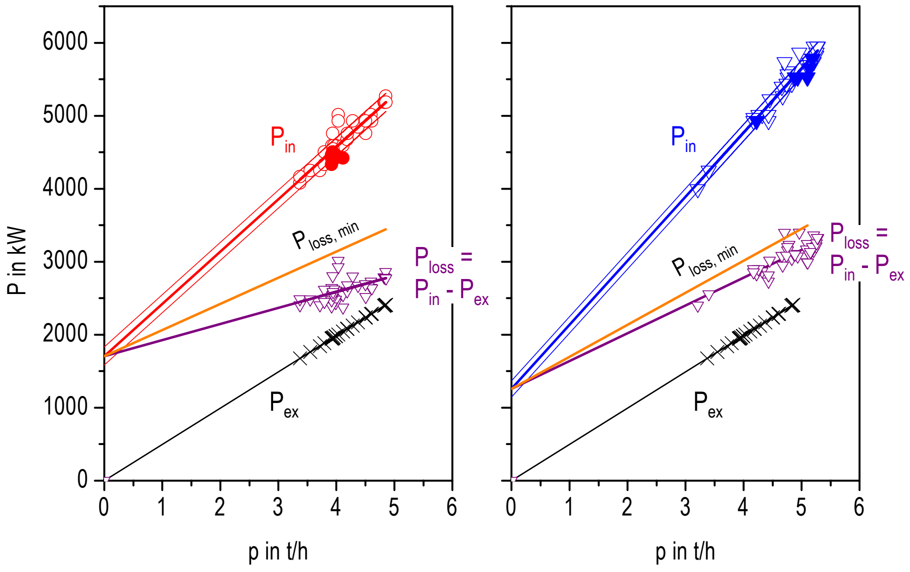
As long as $0 < (b - H_{ex}) < b_{imb}$, the only constraint is due to the imbalance of cold and hot stream heat capacity flows.

case	threshold of slope $\partial P_{loss}/\partial p$	principal constraint involved
A	$b - H_{ex} = 0$	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; chemical constraint
B	$0 < b - H_{ex} \leq b_{imb}$	P_{stack} increases with P_{in}; an increasing portion of P_{in} cannot be transferred to the tank due to flow imbalance only; α_{ht} not constrained; at prevailing flow imbalance: chemical constraint
C	$b - H_{ex} > b_{imb}$	P_{stack} increases with P_{in}; an increasing portion of P_{in} cannot be transferred to the tank due to a constrained α_{ht}: thermal constraint



two “practically identical” horseshoe flame container glassfurnaces

40 m^2, large regenerator 40.5 m^2, medium size regenerator



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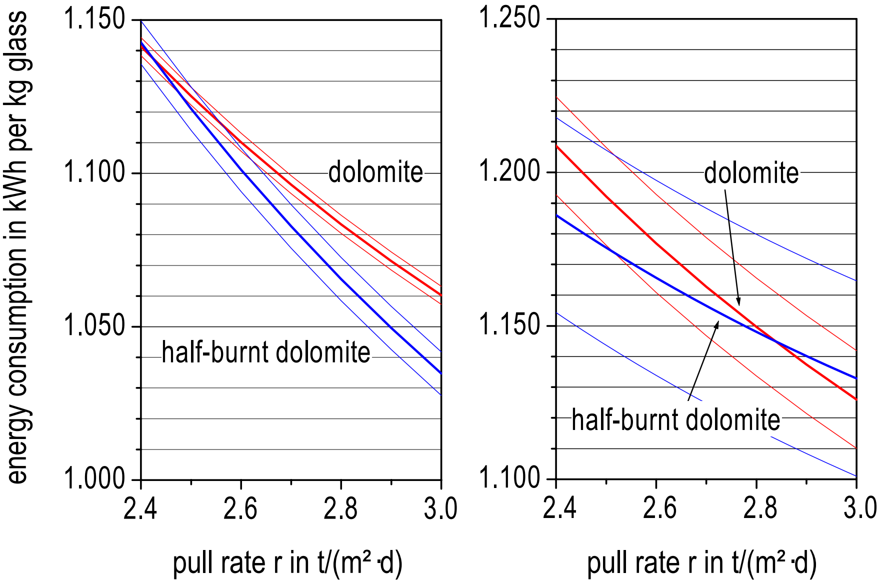
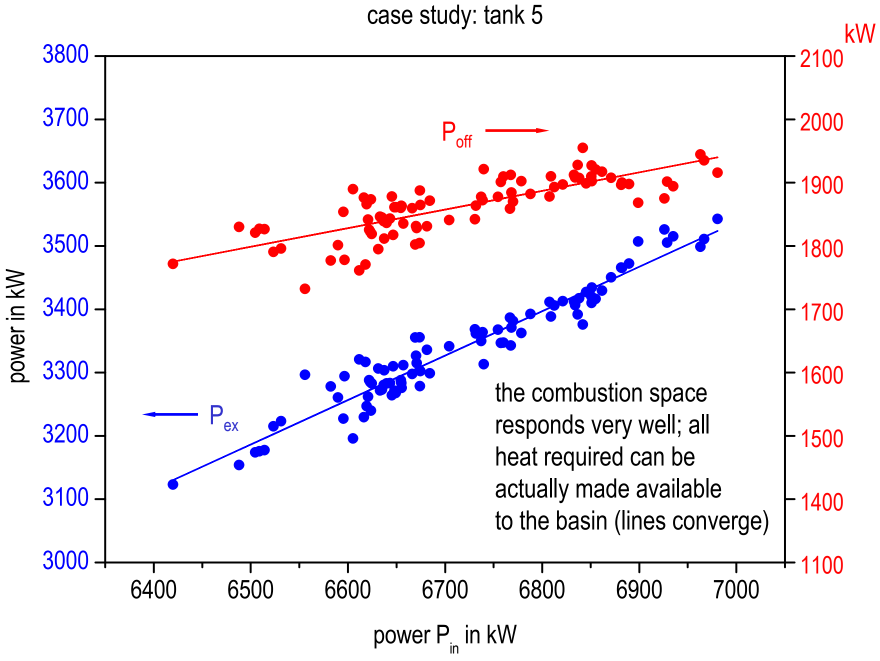
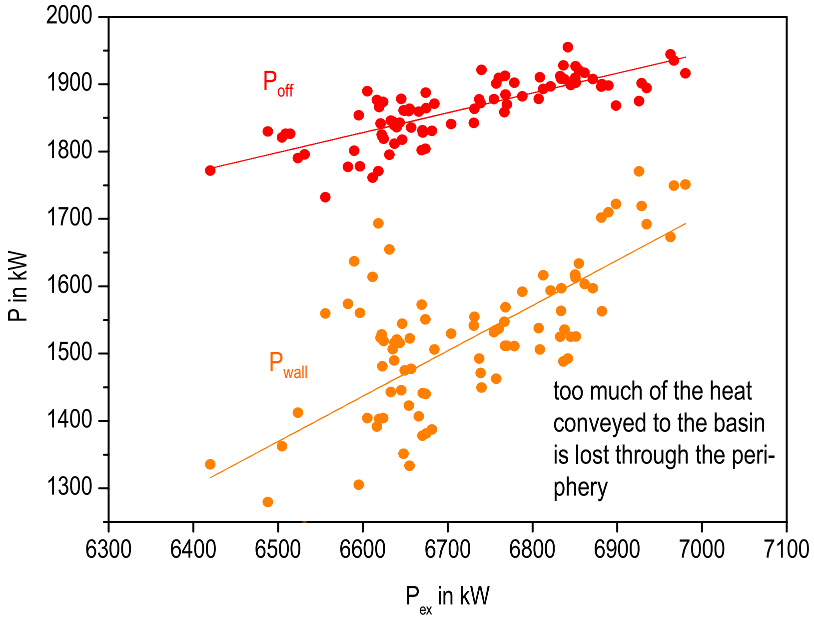


case study: tank 5

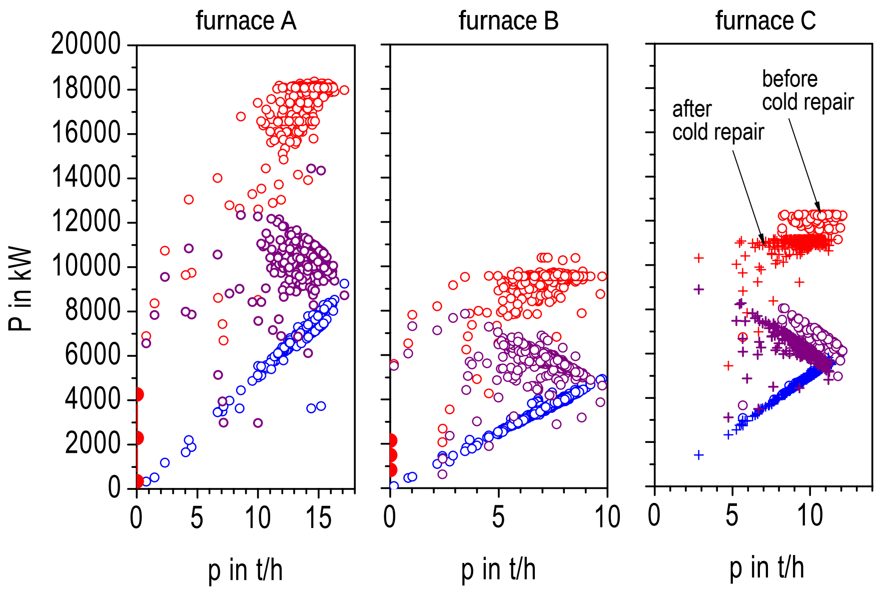


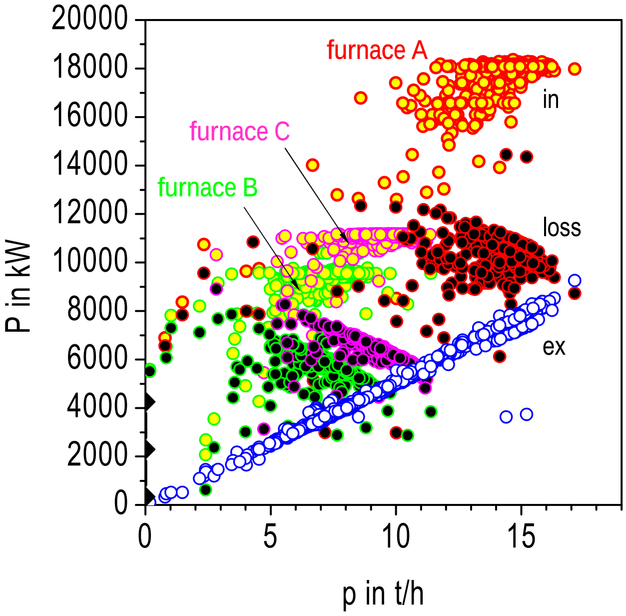
the combustion space responds very well; all heat required can be actually made available to the basin (lines converge)

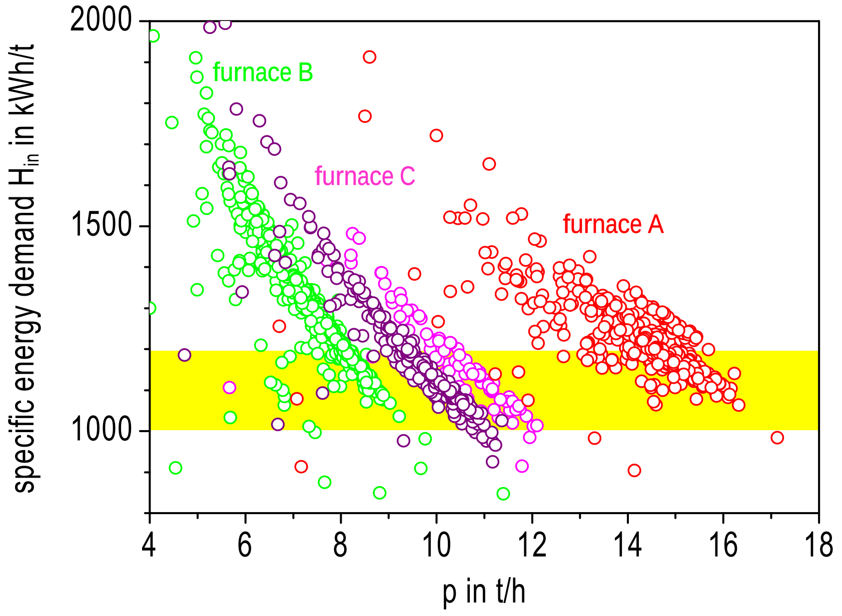
case study: tank 5



too much of the heat conveyed to the basin is lost through the periphery

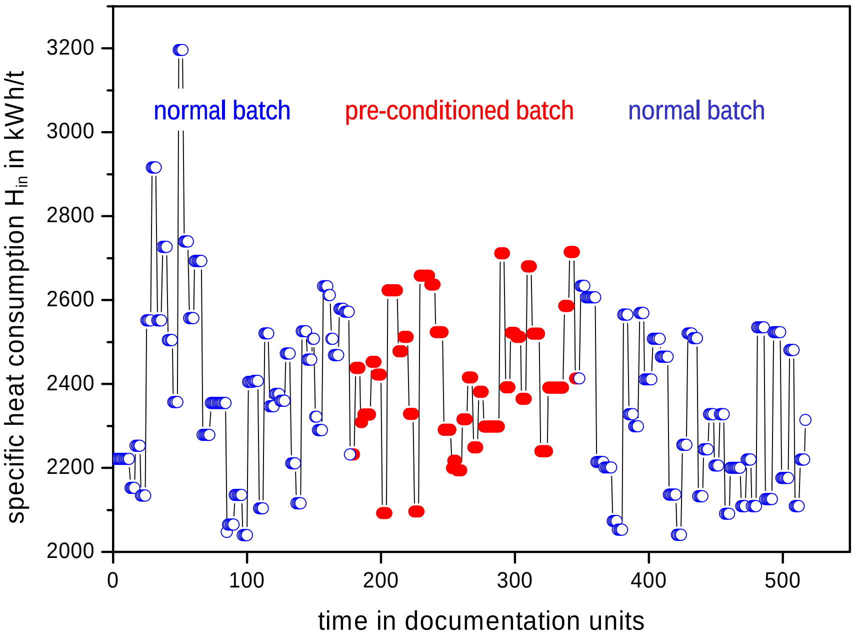

furnace A
furnace B
furnace C
P in kW
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
5
10
15
p in t/h
0
5
10
p in t/h
0
5
10
p in t/h
after
cold repair
before
cold repair


20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
P in kW
furnace A
furnace C
furnace B
in
loss
ex
0
5
10
15
p in t/h

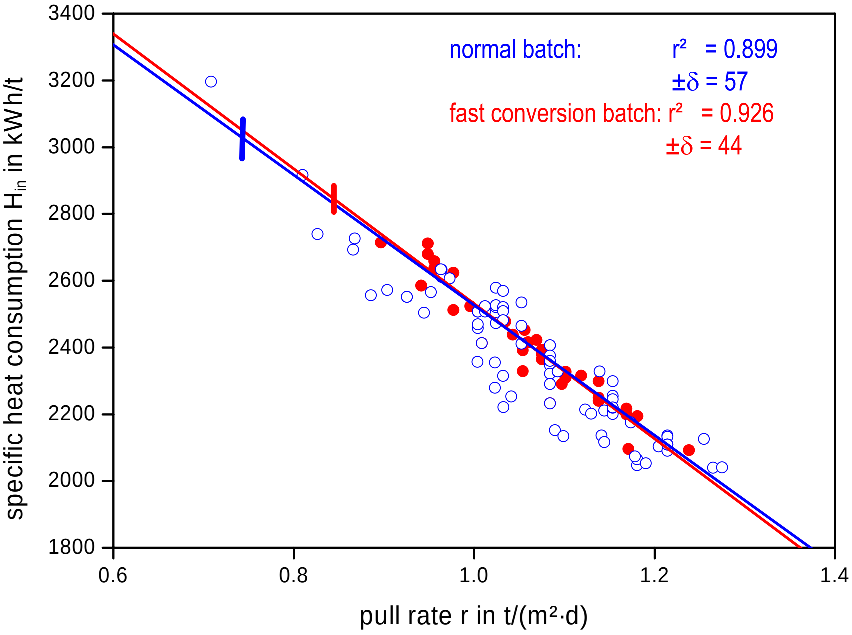


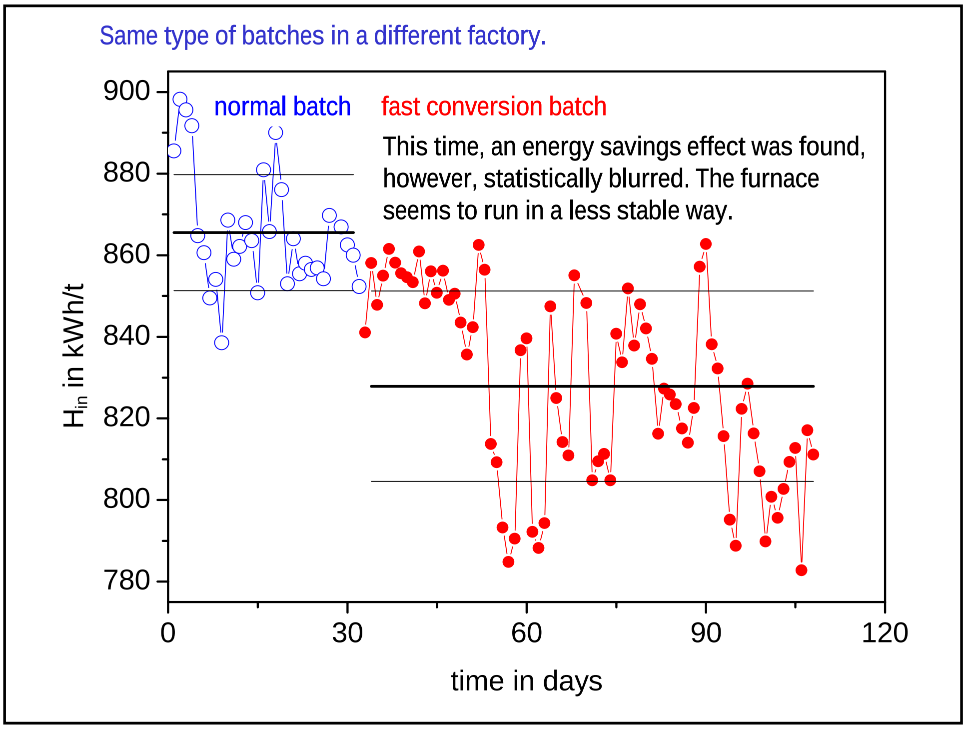
- Introduction & motivation
- Discussion of constraints as seen in a zero-dimensional model
- How to practically distinguish between a thermal and a chemical constraint? (Zero-dimensional analysis of real furnaces)
- Industrial experience with a fast conversion batch
- An extended conclusion: *Quo vadis* glass melting process?

Due to the manager‘s impatience, no significant difference was found ...



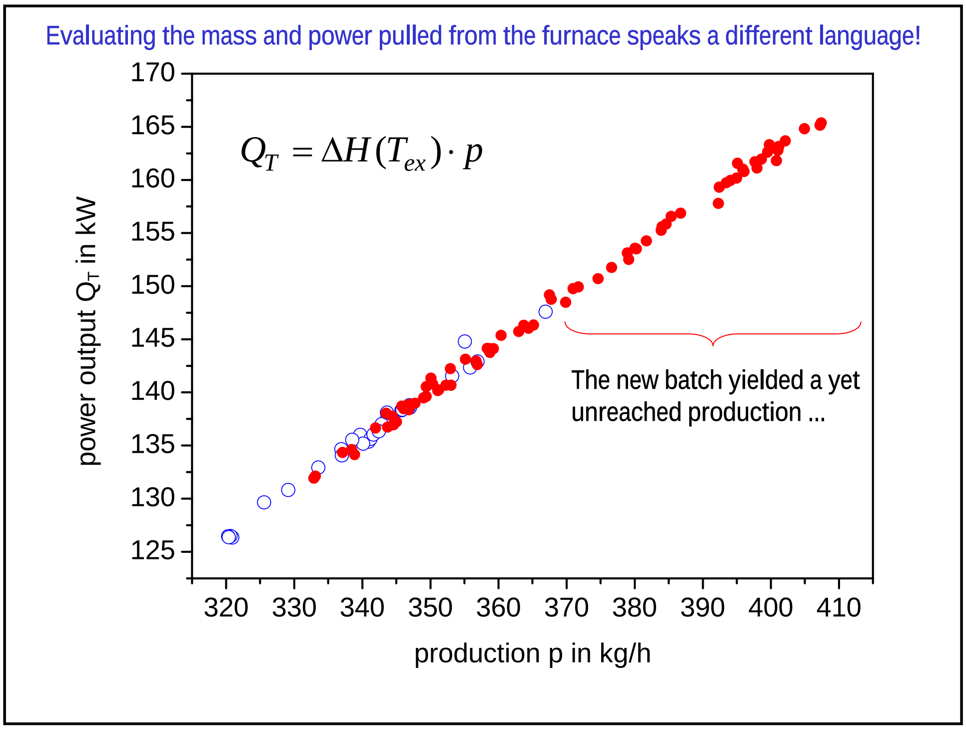
... although the new batch quickly makes the furnace more stable.





Same type of batches in a different factory.

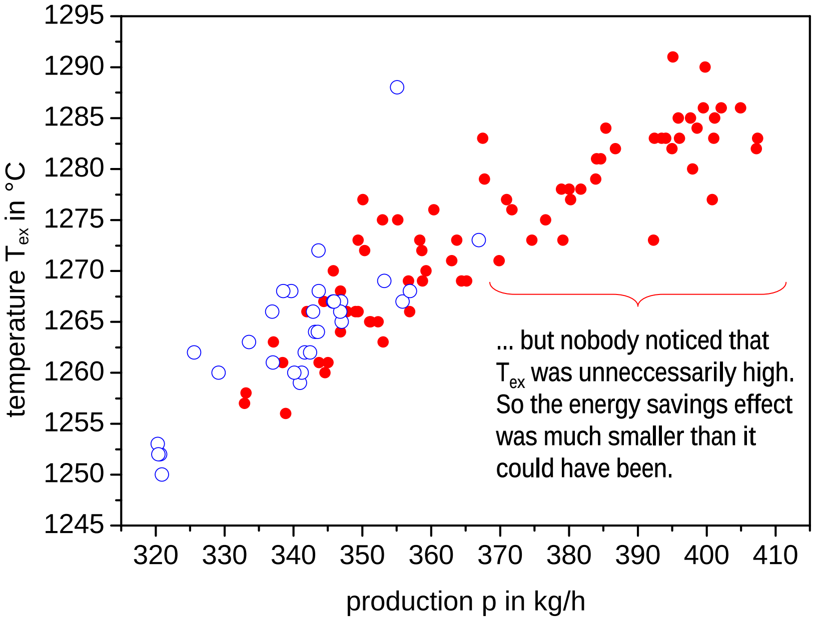
This time, an energy savings effect was found, however, statistically blurred. The furnace seems to run in a less stable way.



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

$$Q_T = \Delta H(T_{ex}) \cdot p$$

The new batch yielded a yet unreached production ...



... but nobody noticed that T_{ex} was unneccessarily 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
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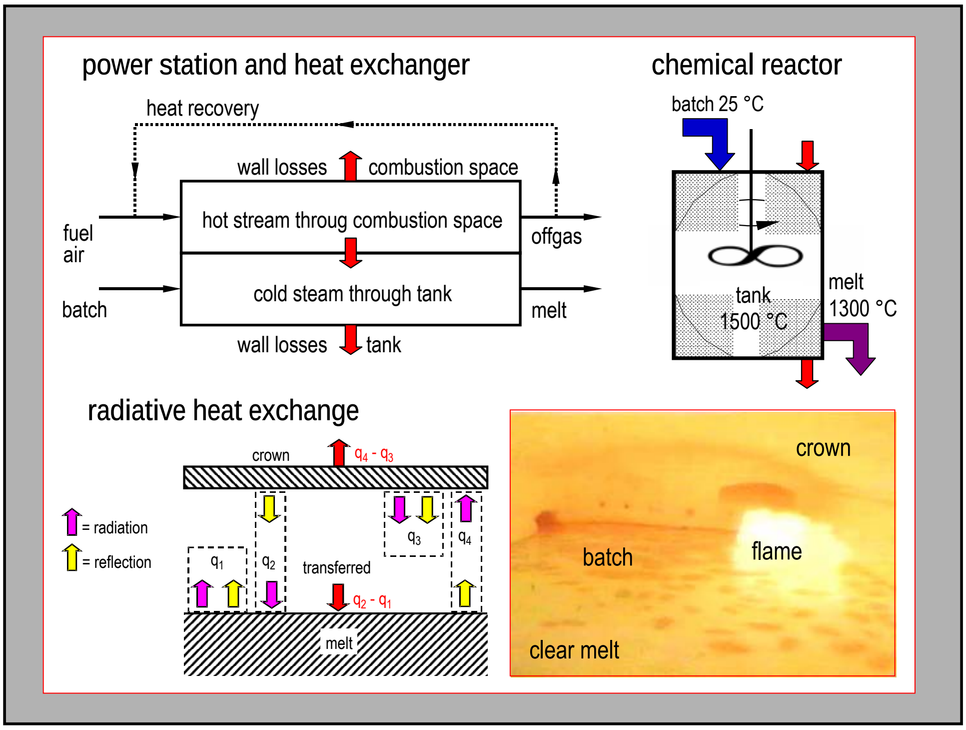
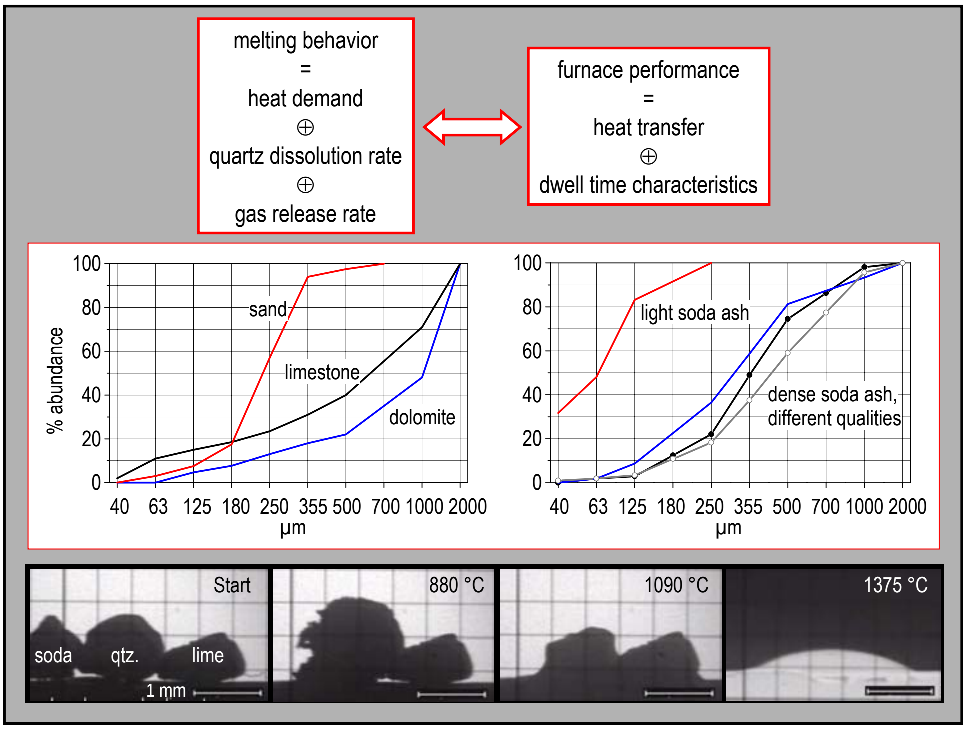
- An extended conclusion: *Quo vadis* glass melting process?



power station and heat exchanger

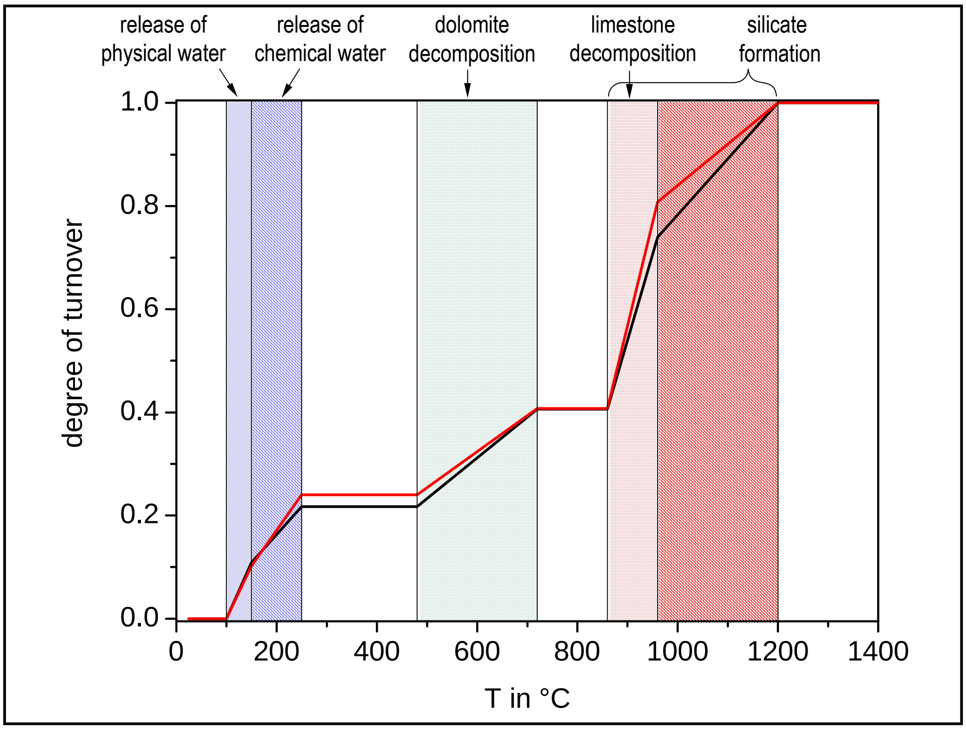
chemical reactor

radiative heat exchange



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

furnace performance
=
heat transfer
⊕
dwell time characteristics



$Na_2CO_3 + SiO_2 \rightarrow Na_2SiO_3 + CO_2$

T_{eq} = 287 °C; ΔH_{chem} = 185 kWh/t

$Na_2CO_3 + 2SiO_2 \rightarrow Na_2Si_2O_5 + CO_2$

T_{eq} = 256 °C, ΔH_{chem} = 127 kWh/t

$2Na_2CO_3 + CaCO_3 + 3SiO_2 \rightarrow N_2CS_3 + 3CO_2$

T_{eq} = 281 °C, ΔH_{chem} = 191 kWh/t

$Na_2CO_3 + 3CaCO_3 + 6SiO_2 \rightarrow NC_3S_6 + 4CO_2$

T_{eq} = 152 °C, ΔH_{chem} = 128 kWh/t

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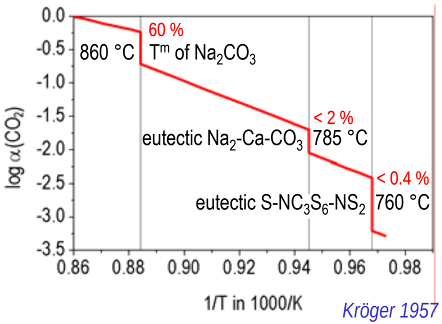
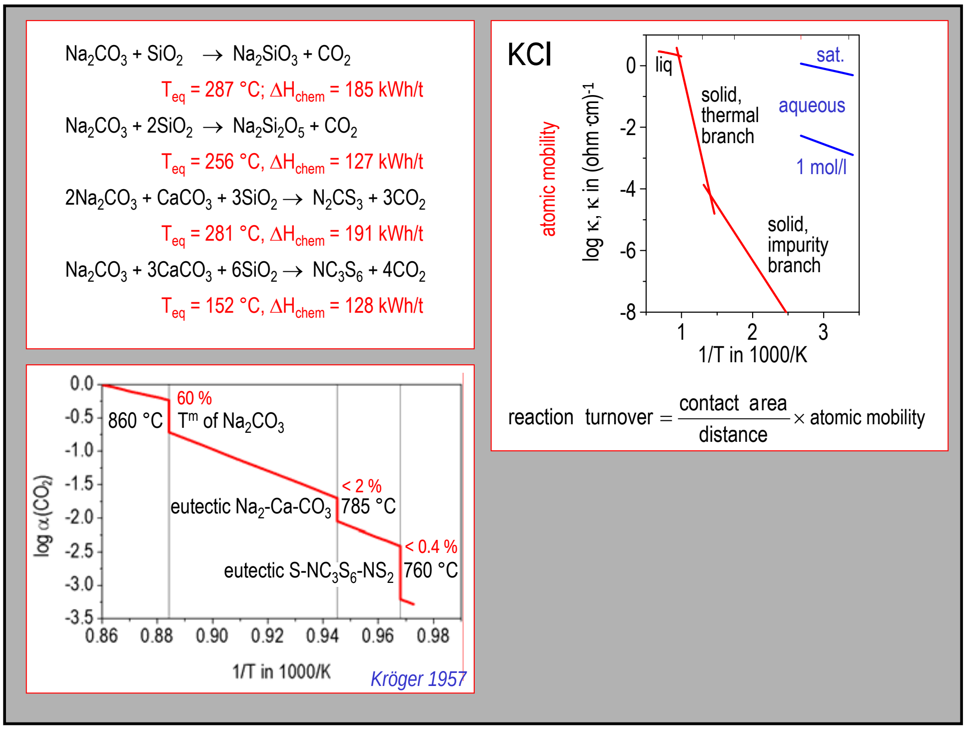


Kröger 1957



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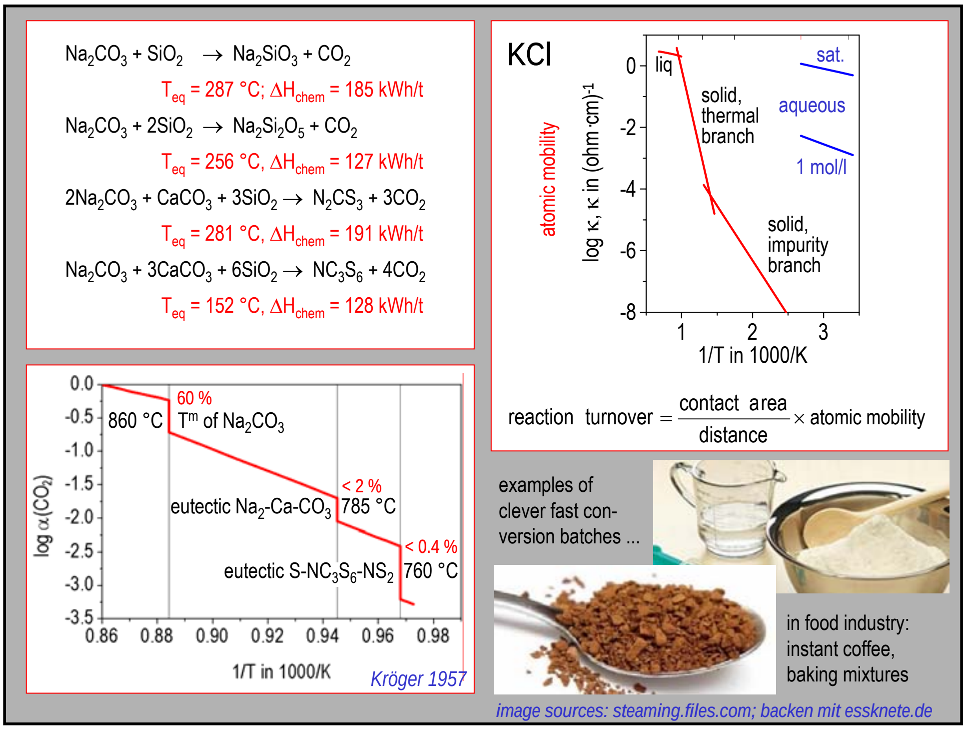
Kröger 1957

KCl

$$\text{reaction turnover} = \frac{\text{contact area}}{\text{distance}} \times \text{atomic mobility}$$



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Kröger 1957

KCl

$$\text{reaction turnover} = \frac{\text{contact area}}{\text{distance}} \times \text{atomic mobility}$$

examples of clever fast conversion batches ...

in food industry: instant coffee, baking mixtures

image sources: steaming.files.com; backen mit essknete.de

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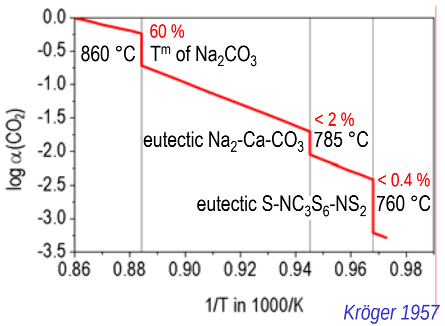
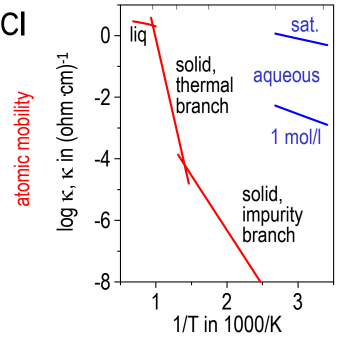


Kröger 1957

KCl



$$\text{reaction turnover} = \frac{\text{contact area}}{\text{distance}} \times \text{atomic mobility}$$

- the optimization potential of the steps taking place prior to the high-T melting process is widely unexploited
- 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

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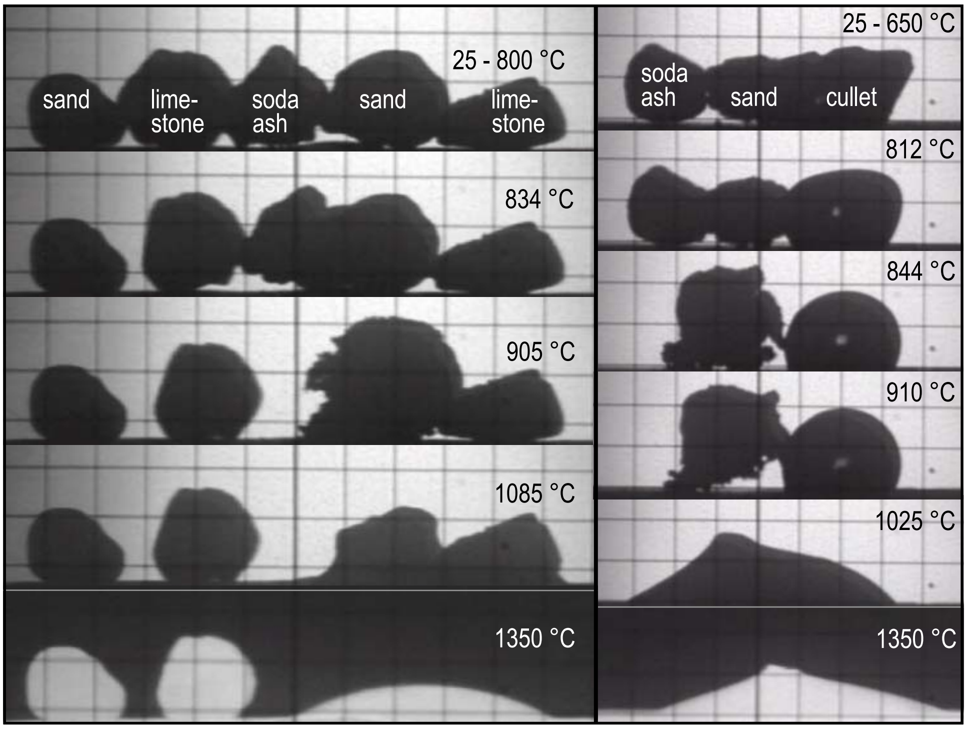
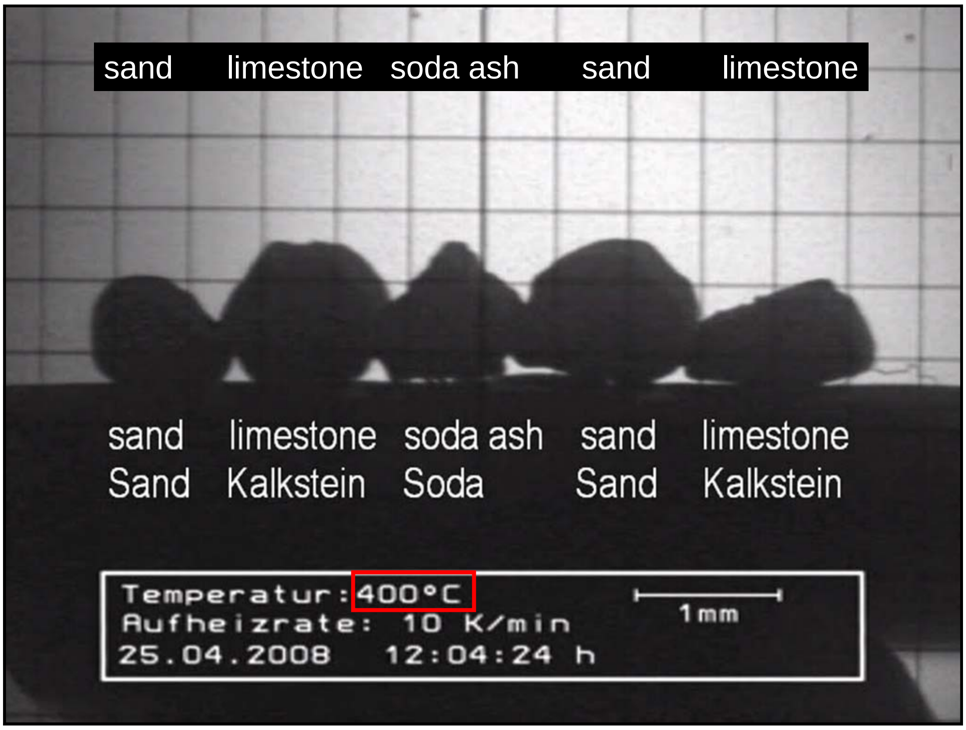
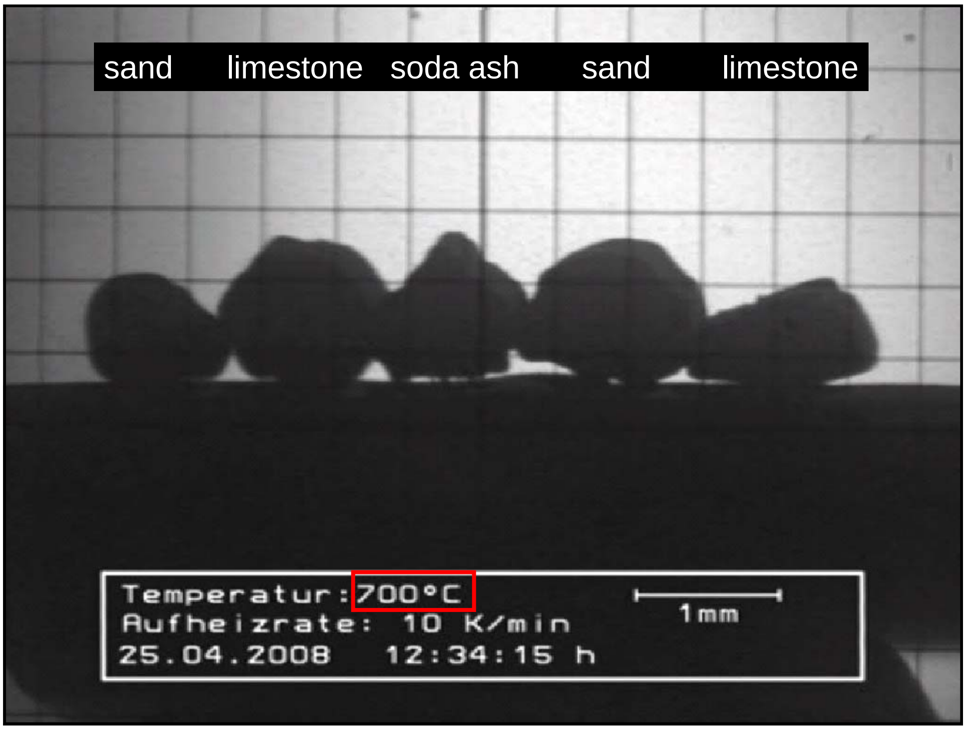
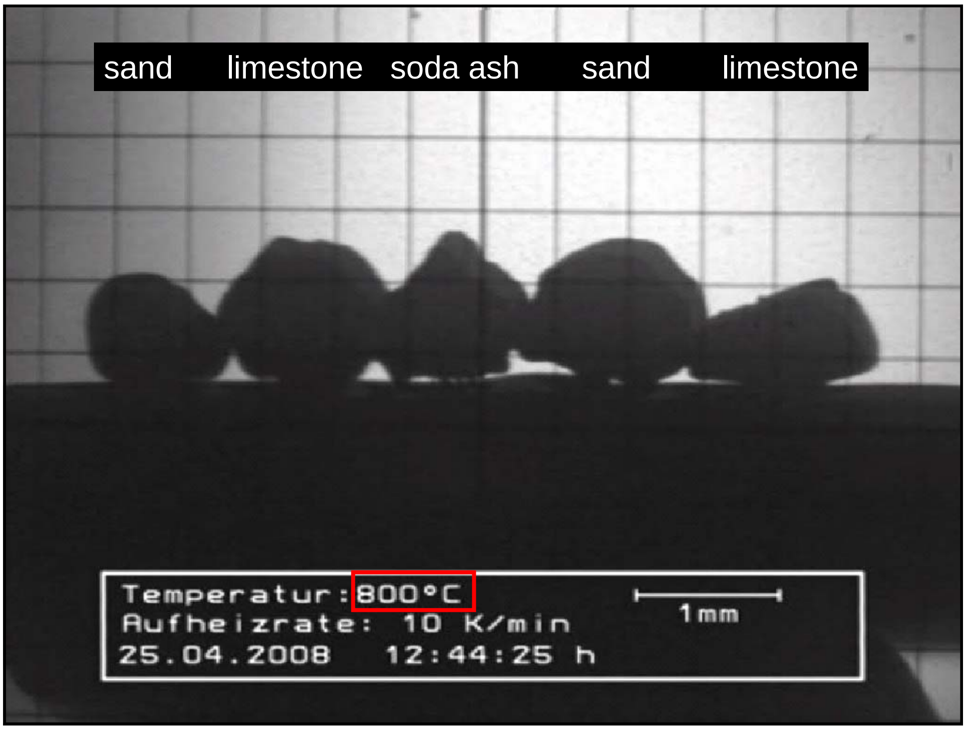
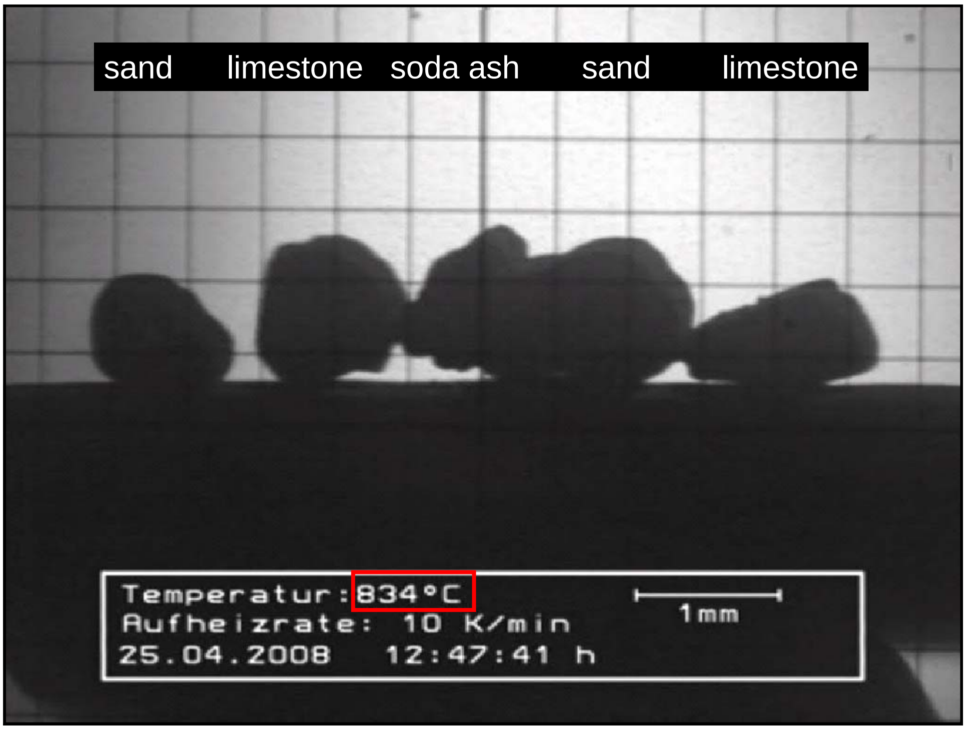
thumb movie:
limestone + soda ash + sand
(not activated)

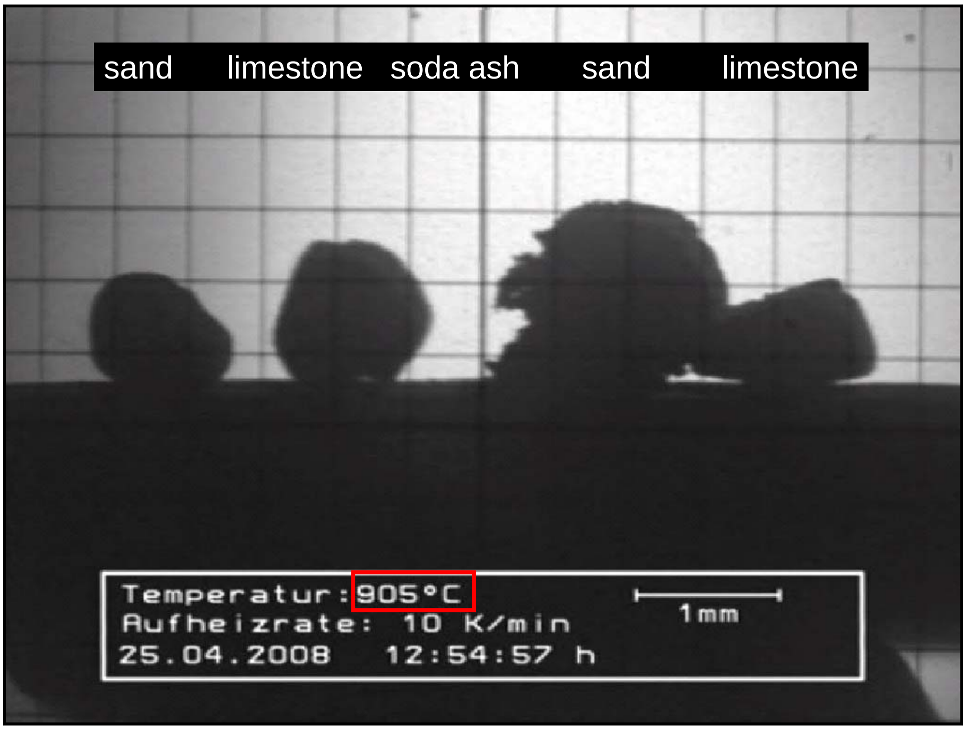

25 - 800 °C
sand
lime-
stone
soda
ash
sand
lime-
stone
834 °C
905 °C
1085 °C
1350 °C
25 - 650 °C
soda
ash
sand
cullet
812 °C
844 °C
910 °C
1025 °C
1350 °C

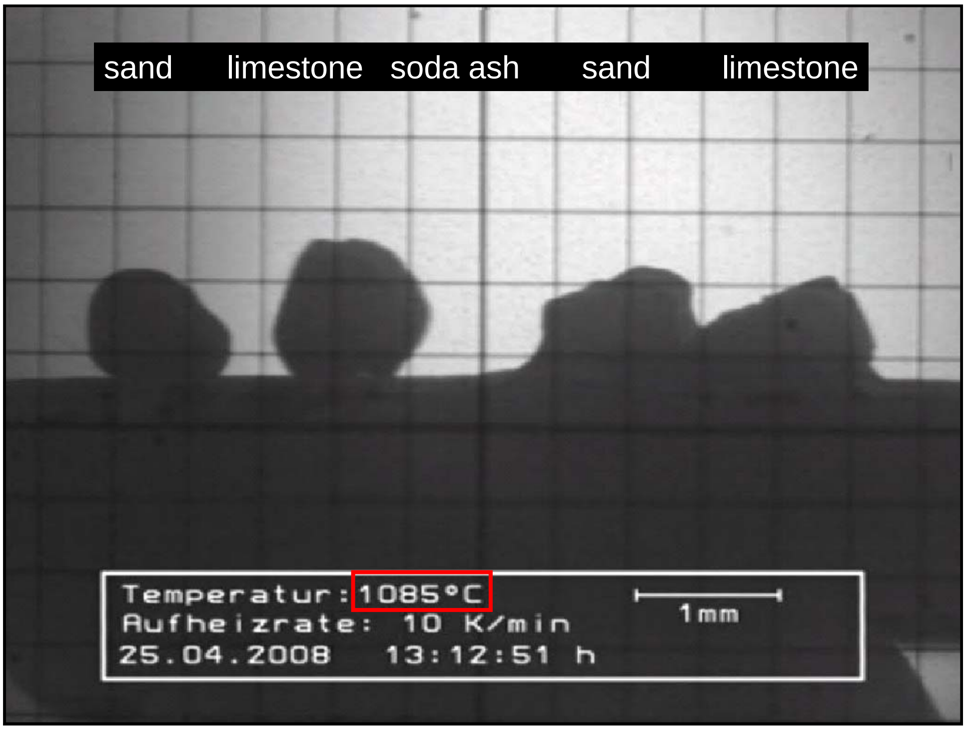

sand
limestone
soda ash
sand
limestone
sand
Sand
limestone
Kalkstein
soda ash
Soda
sand
Sand
limestone
Kalkstein
Temperatur: 400°C
Aufheizrate: 10 K/min
25.04.2008 12:04:24 h
1 mm

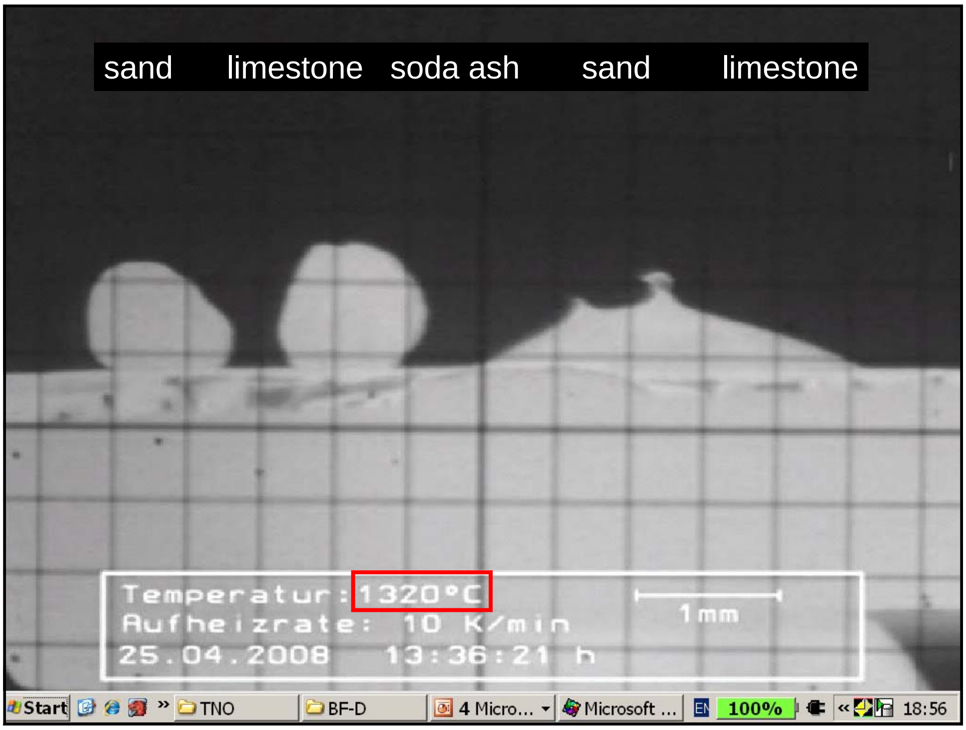

sand
limestone
soda ash
sand
limestone
Temperatur: 700°C
Aufheizrate: 10 K/min
25.04.2008 12:34:15 h
1mm


sand
limestone
soda ash
sand
limestone
Temperatur: 800°C
Aufheizrate: 10 K/min
25.04.2008 12:44:25 h
1mm

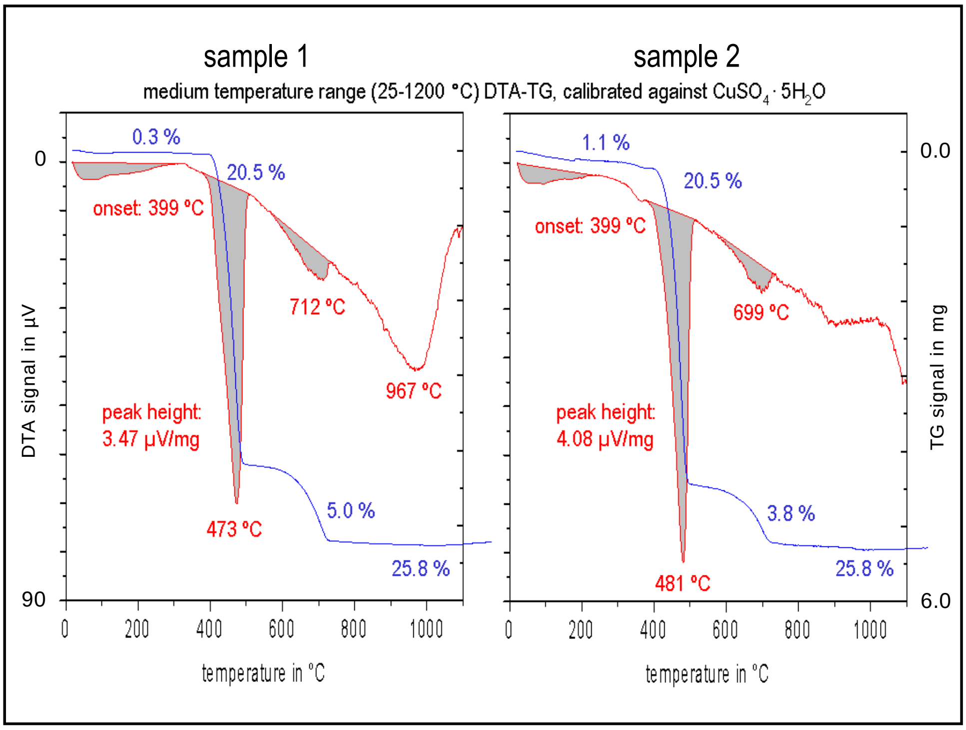

sand
limestone
soda ash
sand
limestone
Temperatur: 834°C
Aufheizrate: 10 K/min
25.04.2008 12:47:41 h
1mm


sand
limestone
soda ash
sand
limestone
Temperatur: 905°C
Aufheizrate: 10 K/min
25.04.2008 12:54:57 h
1mm

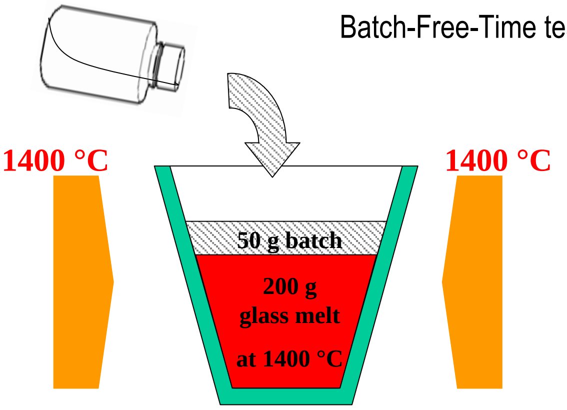

sand
limestone
soda ash
sand
limestone
Temperatur:1085°C
Aufheizrate: 10 K/min
25.04.2008 13:12:51 h
1 mm

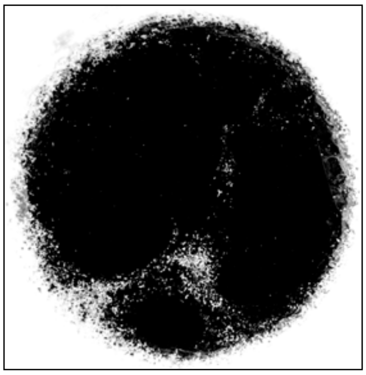

sand
limestone
soda ash
sand
limestone
Temperatur:1320°C
Aufheizrate: 10 K/min
25.04.2008 13:36:21 h
1 mm
Start
TNO
BF-D
4 Micro...
Microsoft ...
EN
100%
18:56


sand
limestone
soda ash
sand
limestone
Temperatur: 1350 °C
Aufheizrate: 10 K/min
25.04.2008 13:39:20 h
1 mm


sample 1
sample 2
medium temperature range (25-1200 °C) DTA-TG, calibrated against CuSO4 · 5H2O
0.3 %
20.5 %
onset: 399 °C
712 °C
967 °C
peak height: 3.47 µV/mg
473 °C
5.0 %
25.8 %
1.1 %
20.5 %
onset: 399 °C
699 °C
peak height: 4.08 µV/mg
481 °C
3.8 %
25.8 %
DTA signal in µV
0
90
TG signal in mg
0.0
6.0
0
200
400
600
800
1000
temperature in °C
temperature in °C

modified Batch-Free-Time test





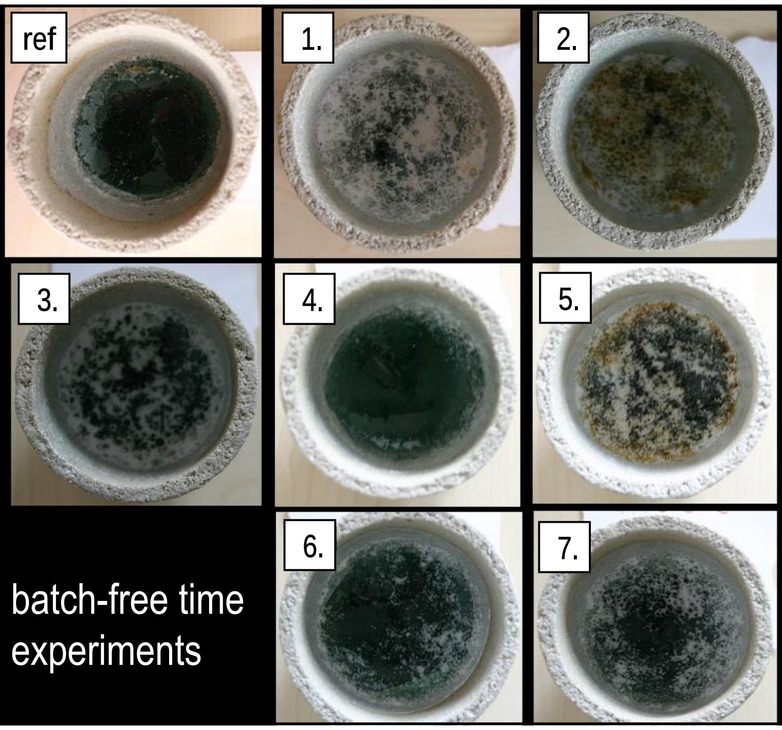
experimental parameters:

T_{melt} = 1400 °C

t_{hold} = 10 und 15 min

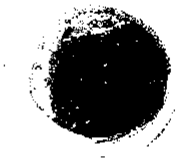
T_{anneal} = 550 °C

q_{cool} = -2 K/min



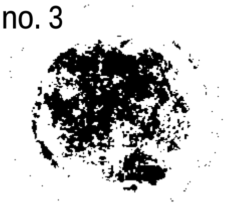
batch-free time experiments

no. 1

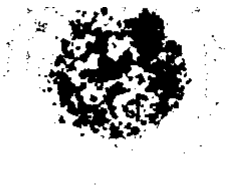


no. 2

no. 3

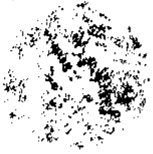


no. 4

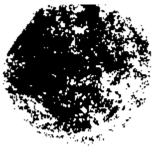


no. 5

no. 6



no. 7

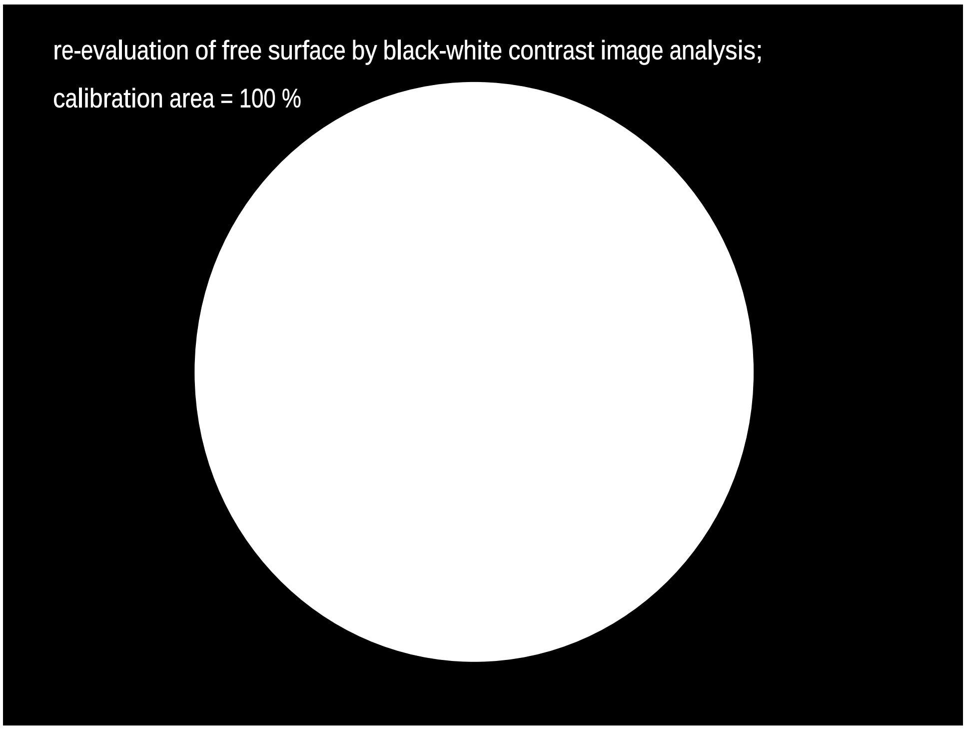


no. 8

batch-free time tests

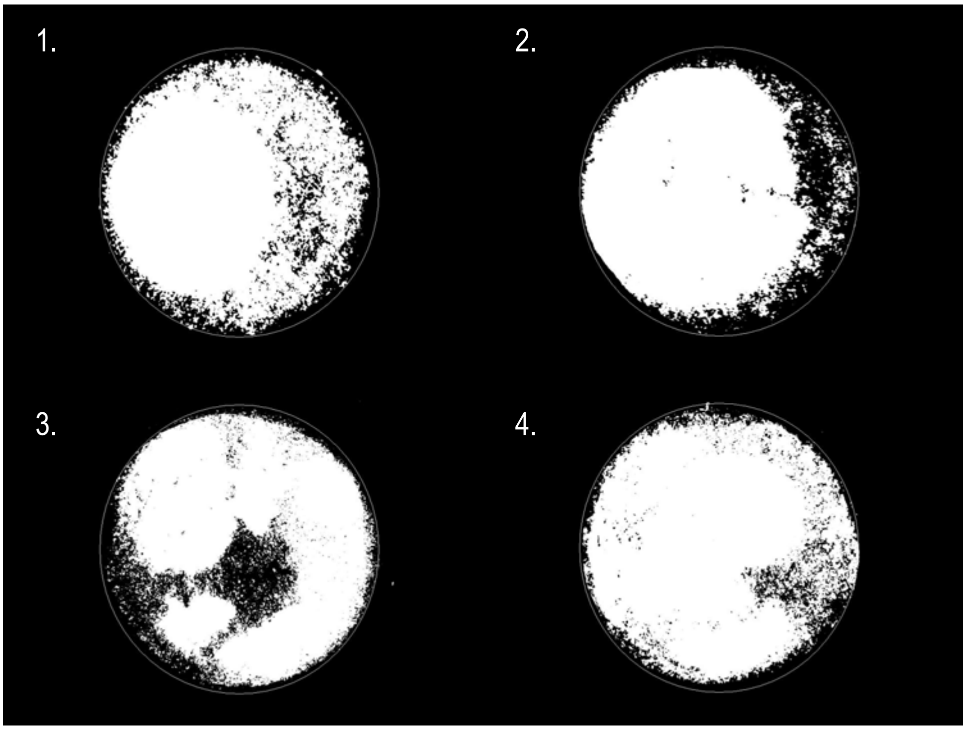
black-white contrast;

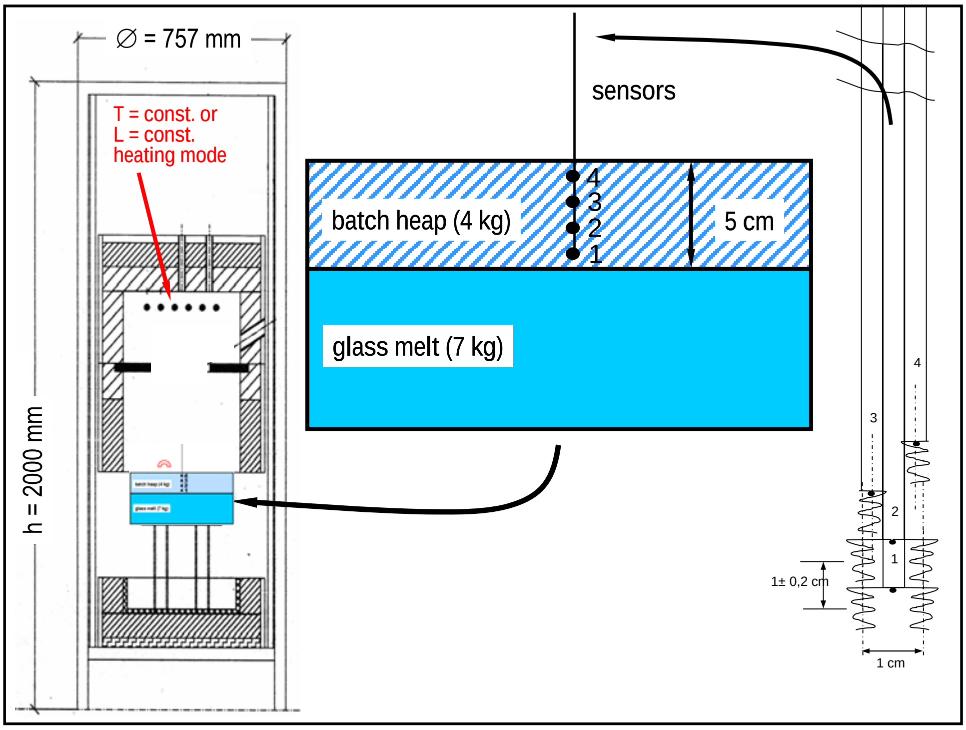
black = clear melt

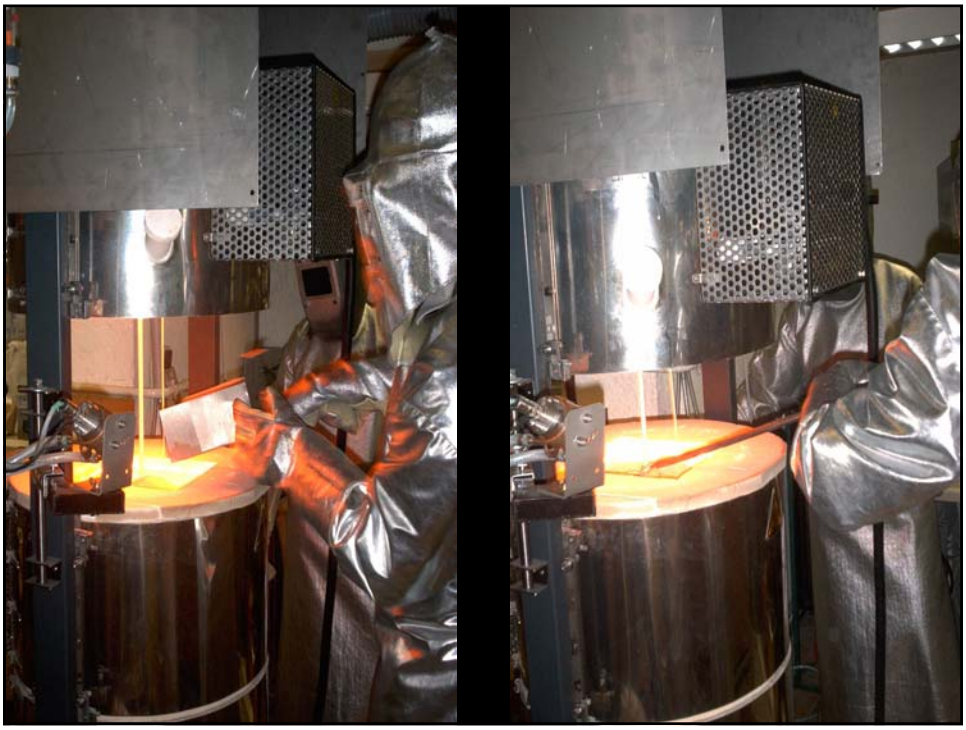


re-evaluation of free surface by black-white contrast image analysis;

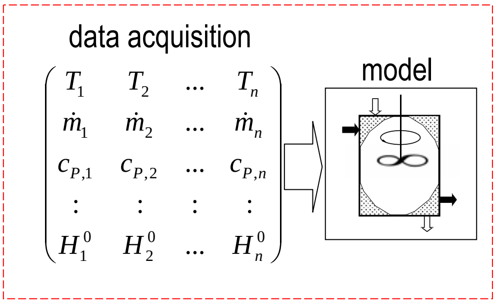
calibration area = 100 %


1.
2.
3.
4.


∅ = 757 mm
h = 2000 mm
T = const. or
L = const.
heating mode
sensors
batch heap (4 kg)
glass melt (7 kg)
5 cm
4
3
2
1
1± 0,2 cm
1 cm



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

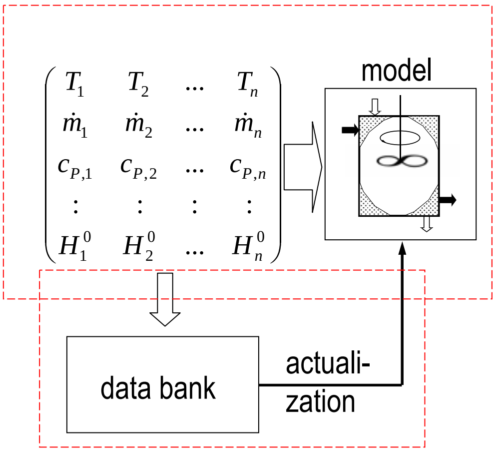


data acquisition

$$\begin{pmatrix} T_1 & T_2 & \dots & T_n \\ \dot{m}_1 & \dot{m}_2 & \dots & \dot{m}_n \\ c_{P,1} & c_{P,2} & \dots & c_{P,n} \\ : & : & : & : \\ H_1^0 & H_2^0 & \dots & H_n^0 \end{pmatrix}$$

model

step 2: retrospective analysis: reactor (dwell time) behavior; on-line actualization of model



$$\begin{pmatrix} T_1 & T_2 & \cdots & T_n \\ \dot{m}_1 & \dot{m}_2 & \cdots & \dot{m}_n \\ c_{P,1} & c_{P,2} & \cdots & c_{P,n} \\ : & : & : & : \\ H_1^0 & H_2^0 & \cdots & H_n^0 \end{pmatrix}$$

model

data bank

actuali-zation

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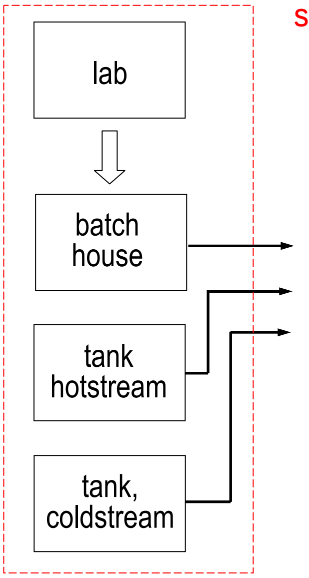
step 3: in-factory analysis of heat and mass flows; data acquisition and formatting



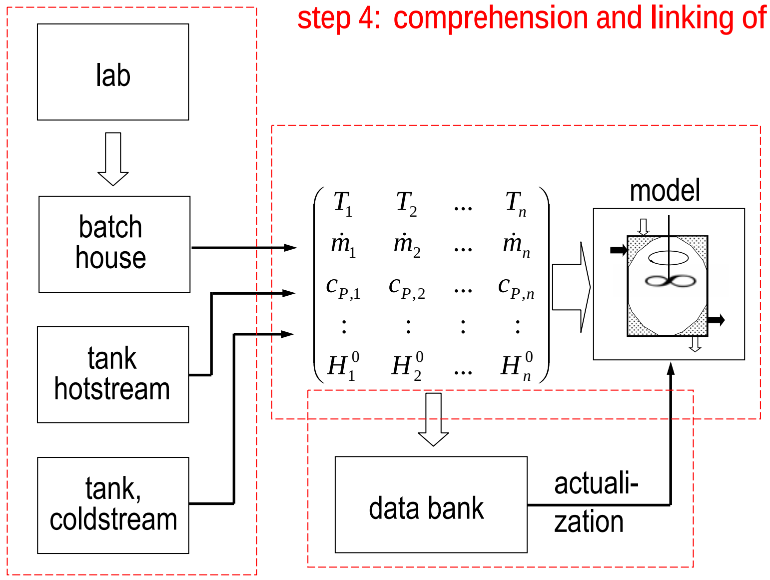
lab

batch house

tank hotstream

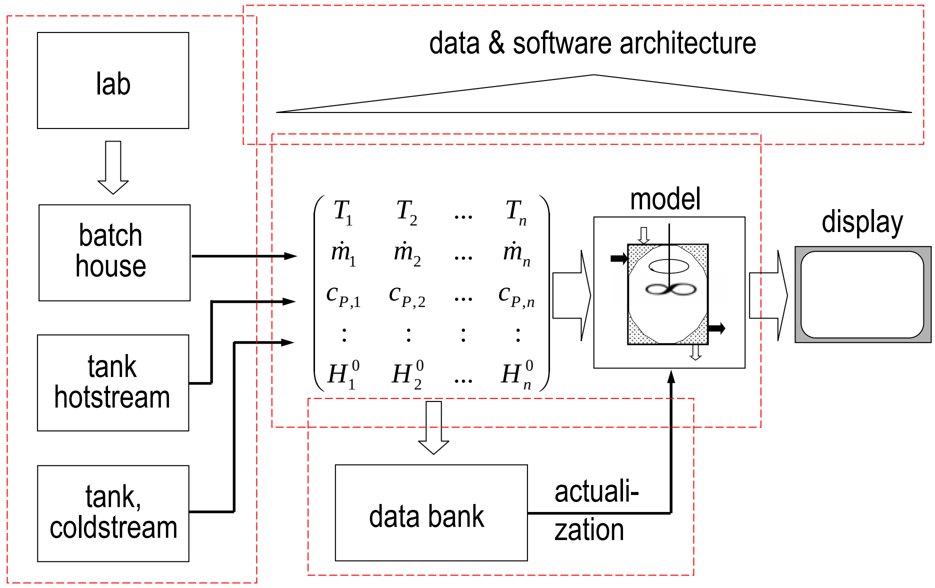
tank, coldstream

step 4: comprehension and linking of data



$$\begin{pmatrix} T_1 & T_2 & \dots & T_n \\ \dot{m}_1 & \dot{m}_2 & \dots & \dot{m}_n \\ c_{P,1} & c_{P,2} & \dots & c_{P,n} \\ : & : & : & : \\ H_1^0 & H_2^0 & \dots & H_n^0 \end{pmatrix}$$

step 5: realization: structuring of the processes



$$\begin{pmatrix} T_1 & T_2 & \dots & T_n \\ \dot{m}_1 & \dot{m}_2 & \dots & \dot{m}_n \\ c_{P,1} & c_{P,2} & \dots & c_{P,n} \\ : & : & : & : \\ H_1^0 & H_2^0 & \dots & H_n^0 \end{pmatrix}$$

step 6: factory test and evaluation

Thank you
for your kind attention!