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Analysis of the Physical Constraints of Performance of Fossile Fuel Fired Glass Furnaces

R. Conradt

14th International Seminar on Furnace Design, Operation & Process Simulation
Velké Karlovice, Czech Republic, June 21-22, 2017

Wed. June 21, 09:45-10:15 h
conradt@ghi.rwth-aachen.de

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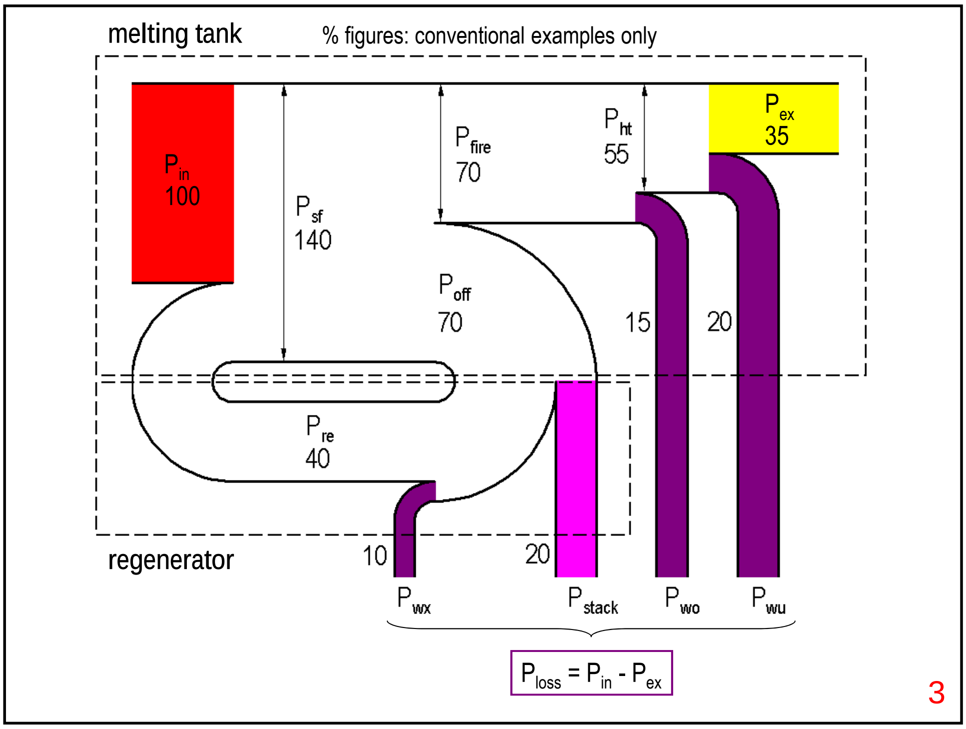
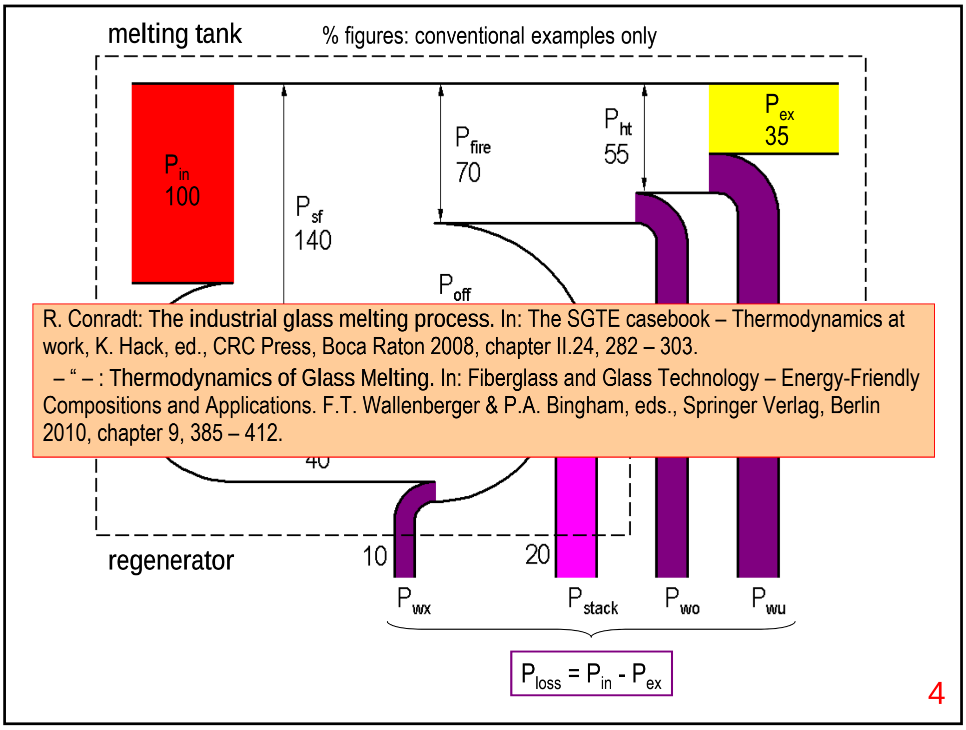
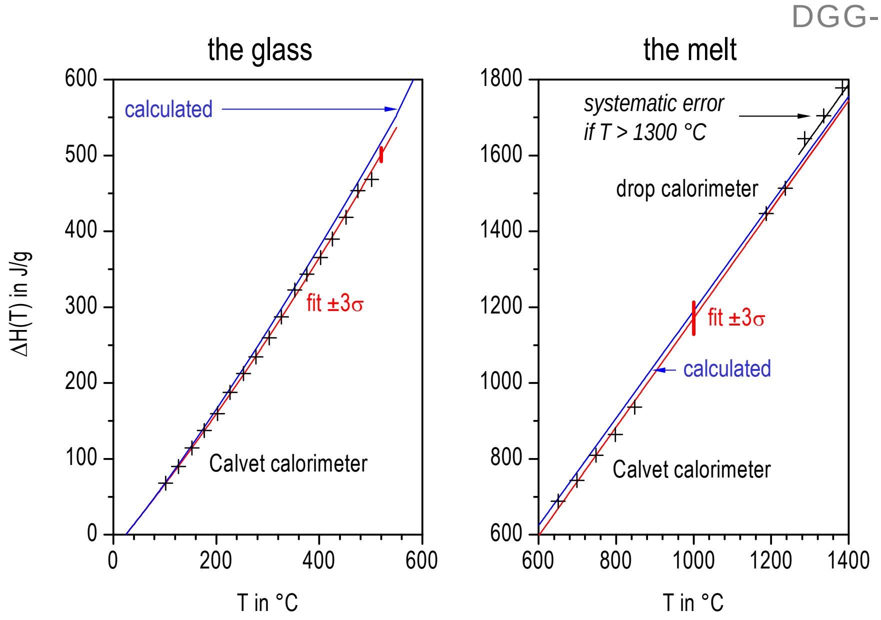
energetics

2


melting tank
% figures: conventional examples only
P in 100
P sf 140
P fire 70
P ht 55
P ex 35
P off 70
15
20
P re 40
regenerator
10
20
P wx
P stack
P wo
P wu
P loss = P in - P ex
3


melting tank
% figures: conventional examples only
P in 100
P sf 140
P fire 70
P ht 55
P ex 35
P off
R. Conradt: The industrial glass melting process. In: The SGTE casebook – Thermodynamics at work, K. Hack, ed., CRC Press, Boca Raton 2008, chapter II.24, 282 – 303.
– " – : Thermodynamics of Glass Melting. In: Fiberglass and Glass Technology – Energy-Friendly Compositions and Applications. F.T. Wallenberger & P.A. Bingham, eds., Springer Verlag, Berlin 2010, chapter 9, 385 – 412.
regenerator
10
20
P wx
P stack
P wo
P wu
P loss = P in - P ex
4

DGG-1



thesis: Simon Bartolomey, Lina Heuser

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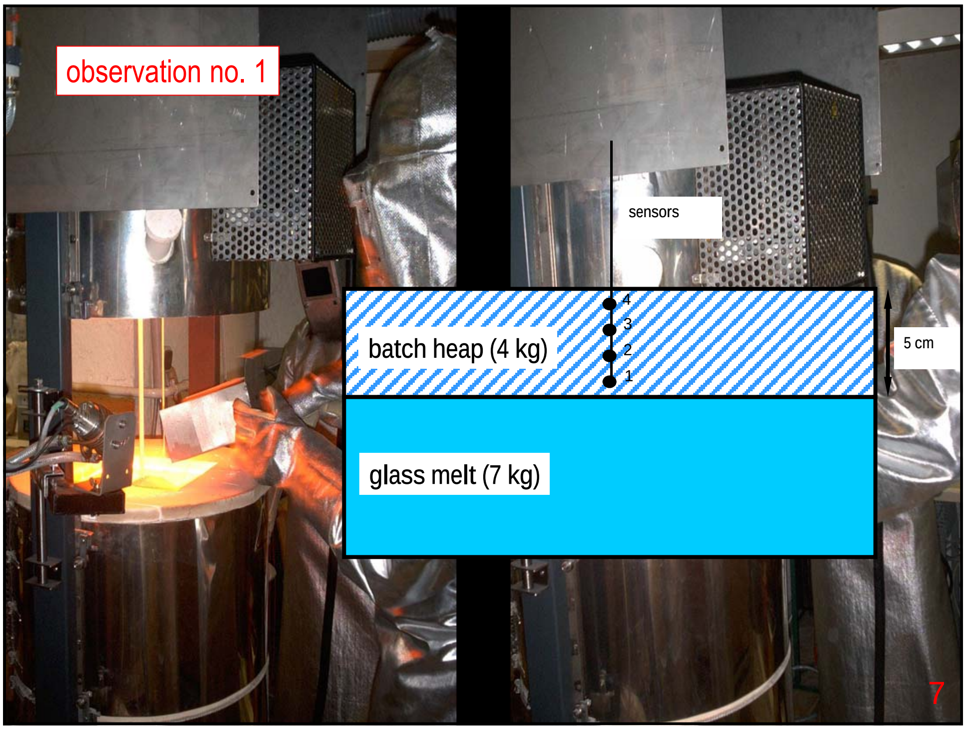
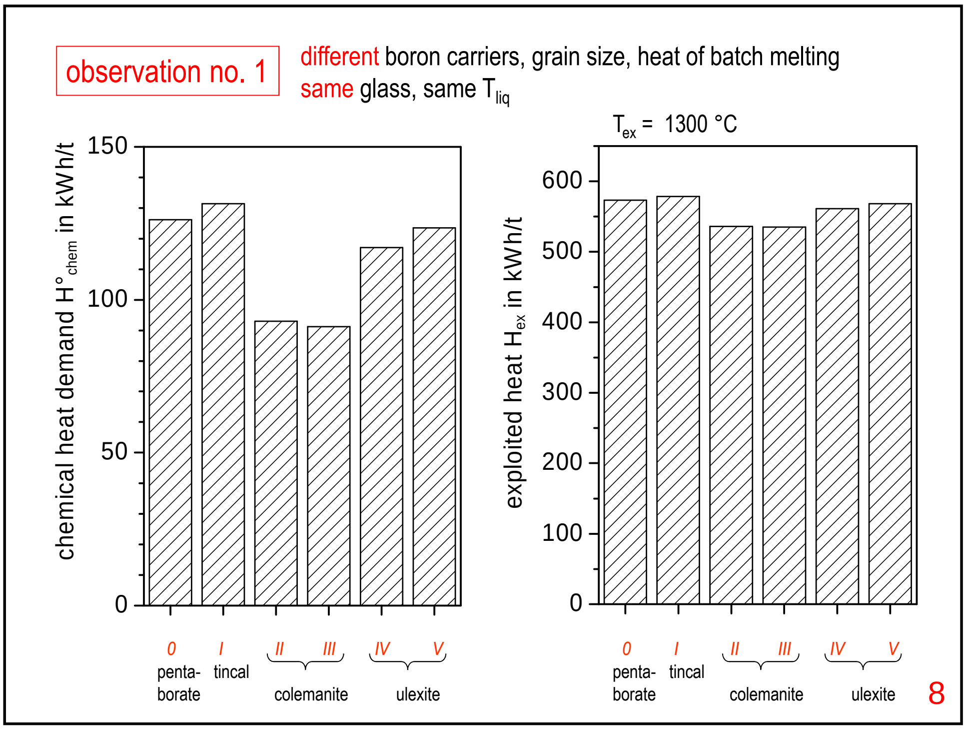
energy vs. conversion rate

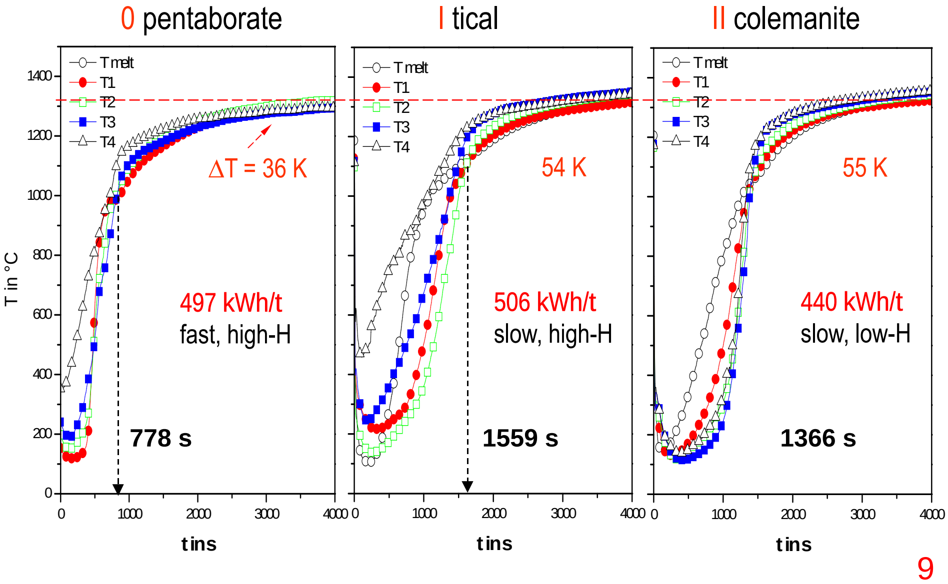
6


observation no. 1
sensors
4
3
2
1
batch heap (4 kg)
5 cm
glass melt (7 kg)
7


observation no. 1
different boron carriers, grain size, heat of batch melting
same glass, same T_{liq}
T_{ex} = 1300 °C
chemical heat demand $H°_{chem}$ in kWh/t
150
100
50
0
exploited heat H_{ex} in kWh/t
600
500
400
300
200
100
0
0
I
II
III
IV
V
penta-borate
tincal
colemanite
ulexite
8

observation no. 1

batch melting rate does not clearly correlate with heat demand of batch melting



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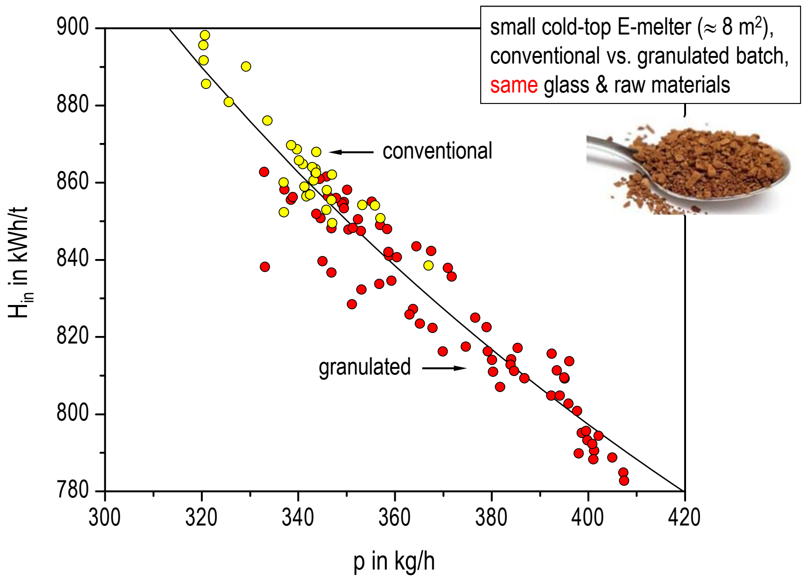
observation no. 2

reaction rate has key impact on specific heat demand



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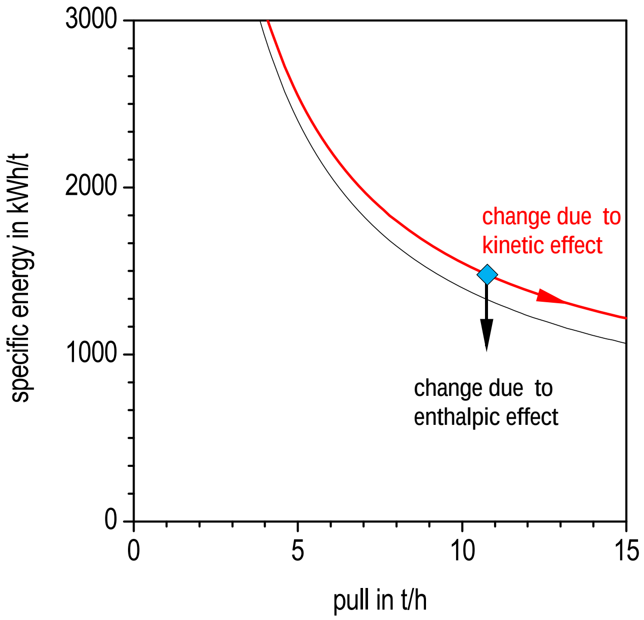

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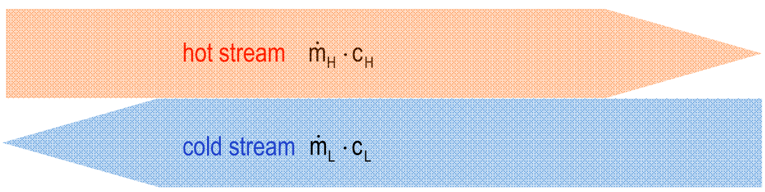
observation no. 3

furnace design and operation play a key role

heat capacity match

$$z_{HL} = \frac{\text{available power in combustion space}}{\text{power uptake capacity of melt}}$$



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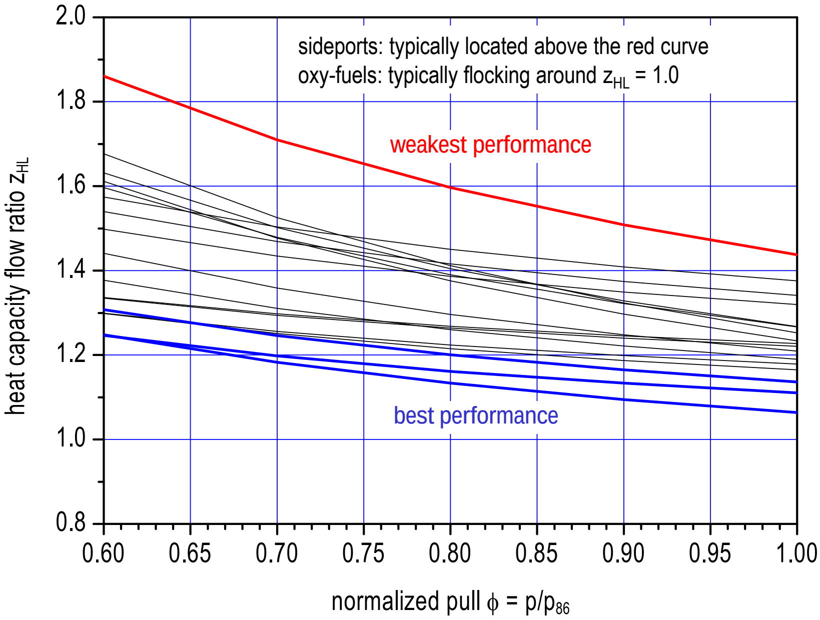
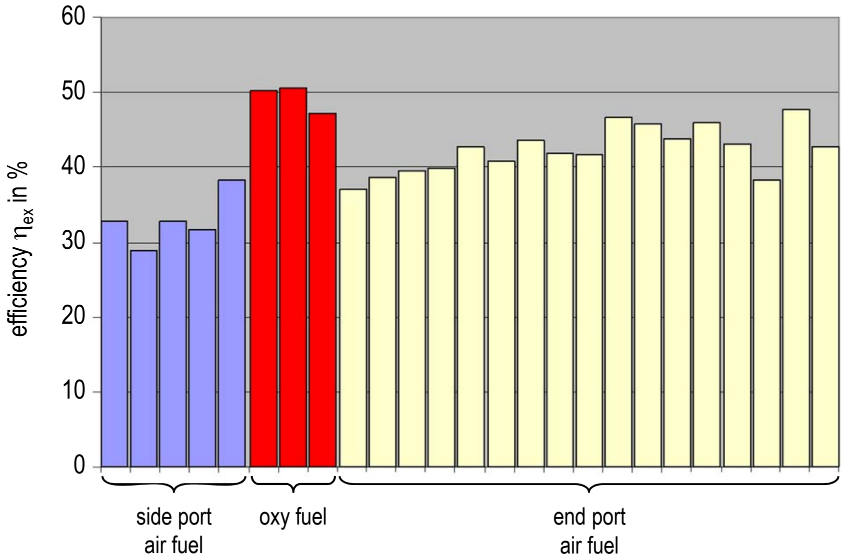
graphs: end port furnaces



survey: 25 container glass furnaces;
efficiency primarily correlated to z_{HL}



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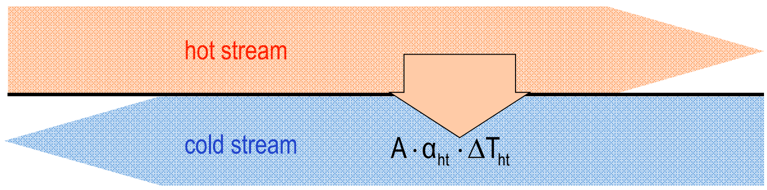
What is the role of heat transfer?

$$NTU = \frac{\text{power transfer through hearth area A}}{\text{available power in combustionspace}}$$



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heat flux to the batch

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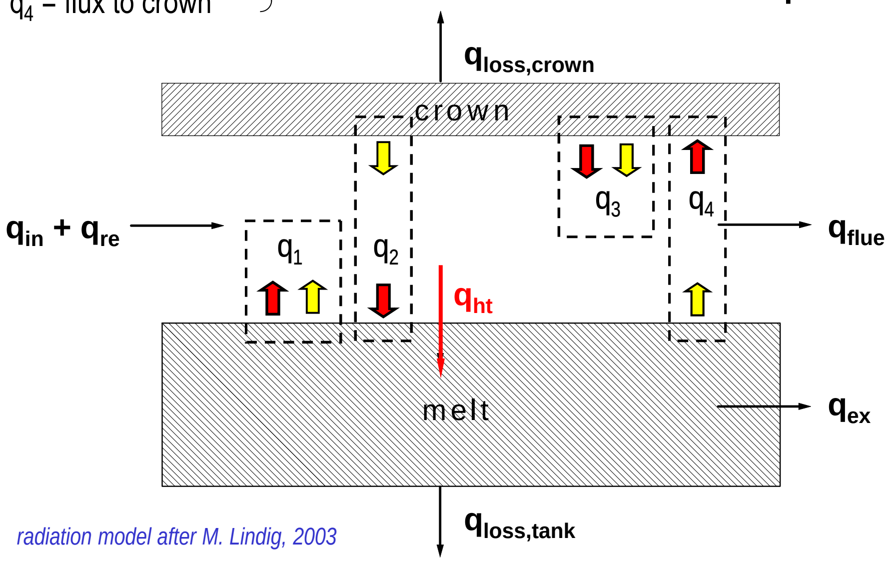
q_1 = flux from melt
q_2 = flux to melt
q_3 = flux from crown
q_4 = flux to crown

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

= radiation;
= reflection
q in kW/m²



radiation model after M. Lindig, 2003

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

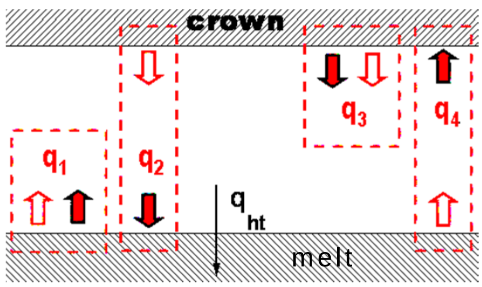
$\Rightarrow q_2 - q_1 = q_{ht}$ = flux transferred

$$q_1 = C_S \cdot \varepsilon_{melt} \cdot T_{melt}^4 + (1 - \varepsilon_{melt}) q_2 \text{ *)}$$

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

$$q_3 = C_S \cdot \varepsilon_{crown} \cdot T_{crown}^4 + (1 - \varepsilon_{crown}) q_4$$

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



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

eq. system solved for q_1 to $q_4 \Rightarrow q_{ht}$

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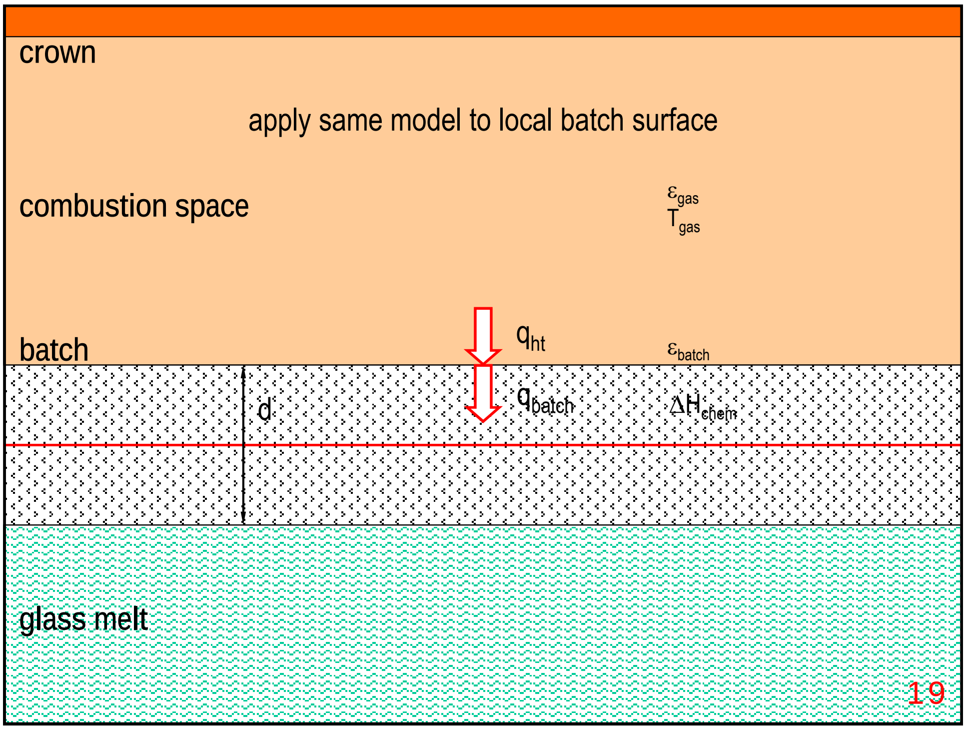
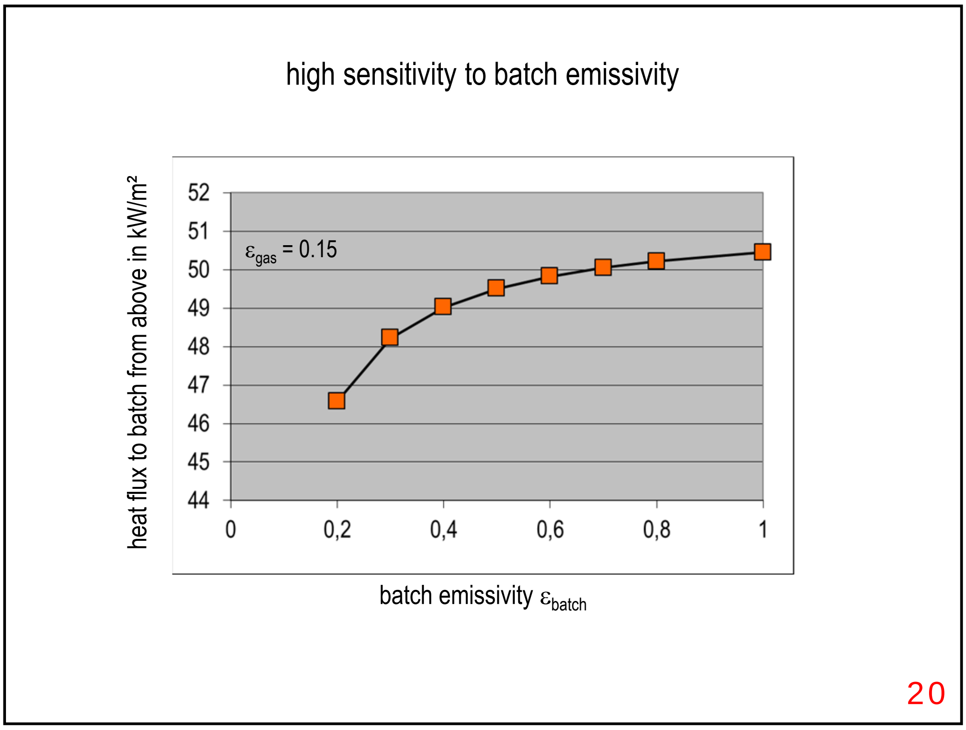
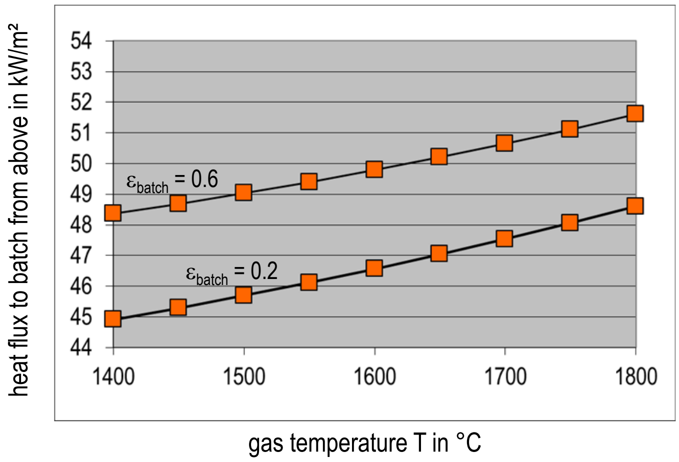

crown
apply same model to local batch surface
combustion space
ε_{gas}
T_{gas}
batch
q_{ht}
ε_{batch}
d
q_{batch}
ΔH_{chem}
glass melt
19


high sensitivity to batch emissivity
heat flux to batch from above in kW/m²
ε_{gas} = 0.15
52
51
50
49
48
47
46
45
44
0
0,2
0,4
0,6
0,8
1
batch emissivity ε_{batch}
20

moderately high sensitivity to gas temperature



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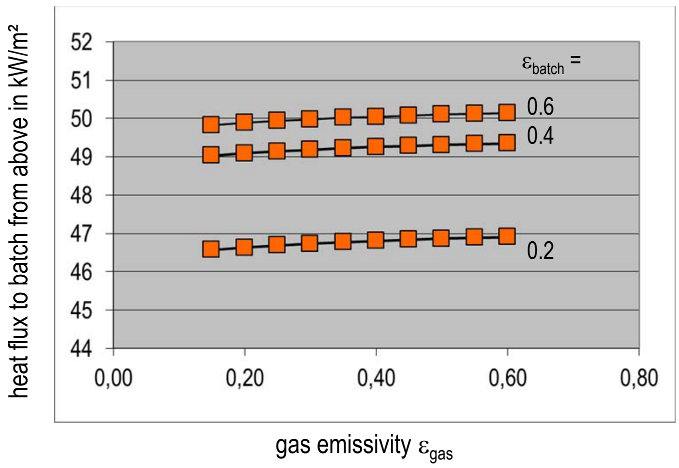
no sensitivity to gas emissivity during batch melting



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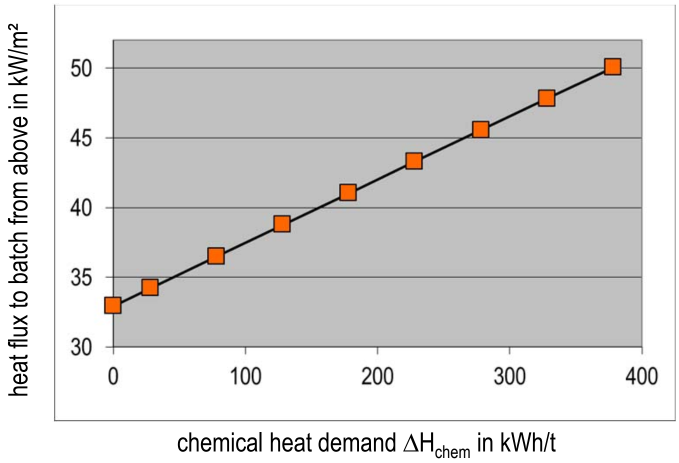
high sensitivity to chemical heat demand



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experimental check

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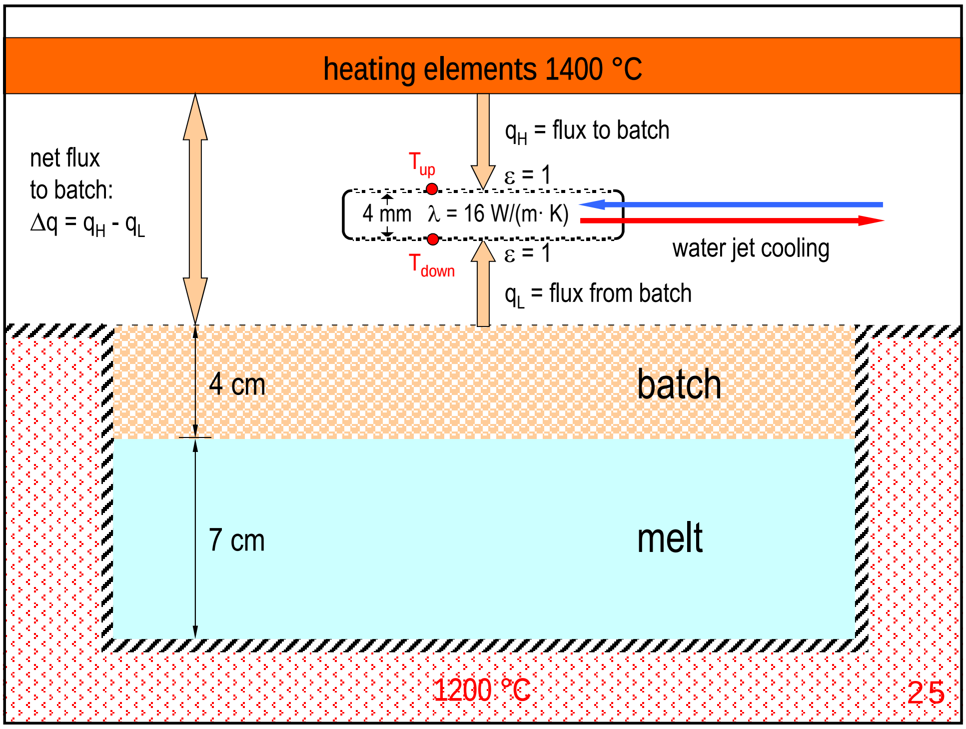
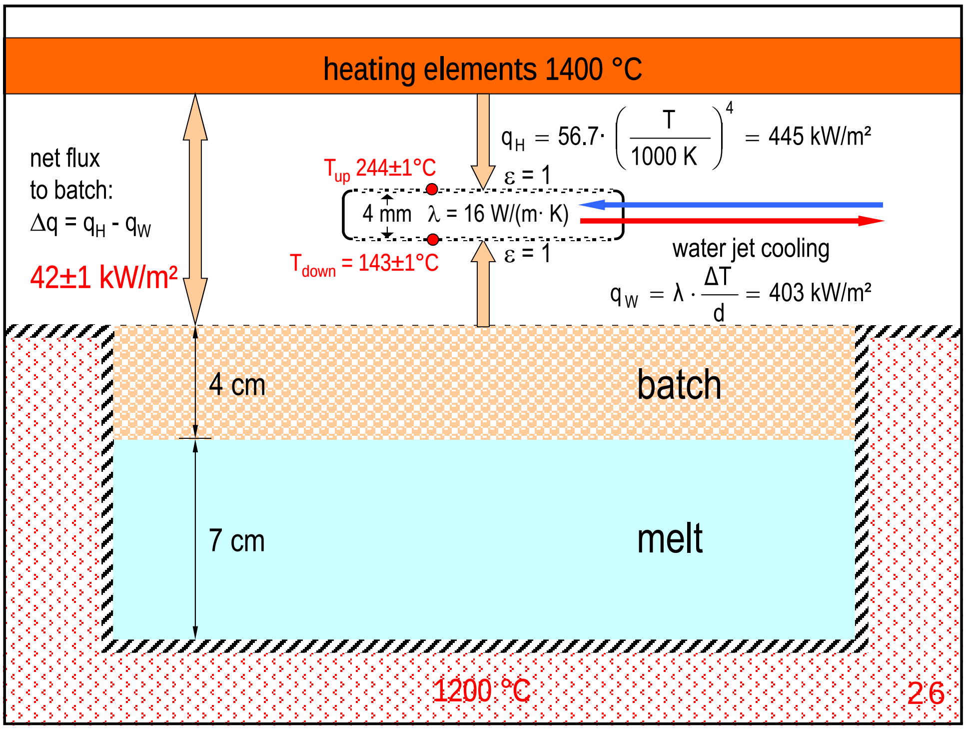
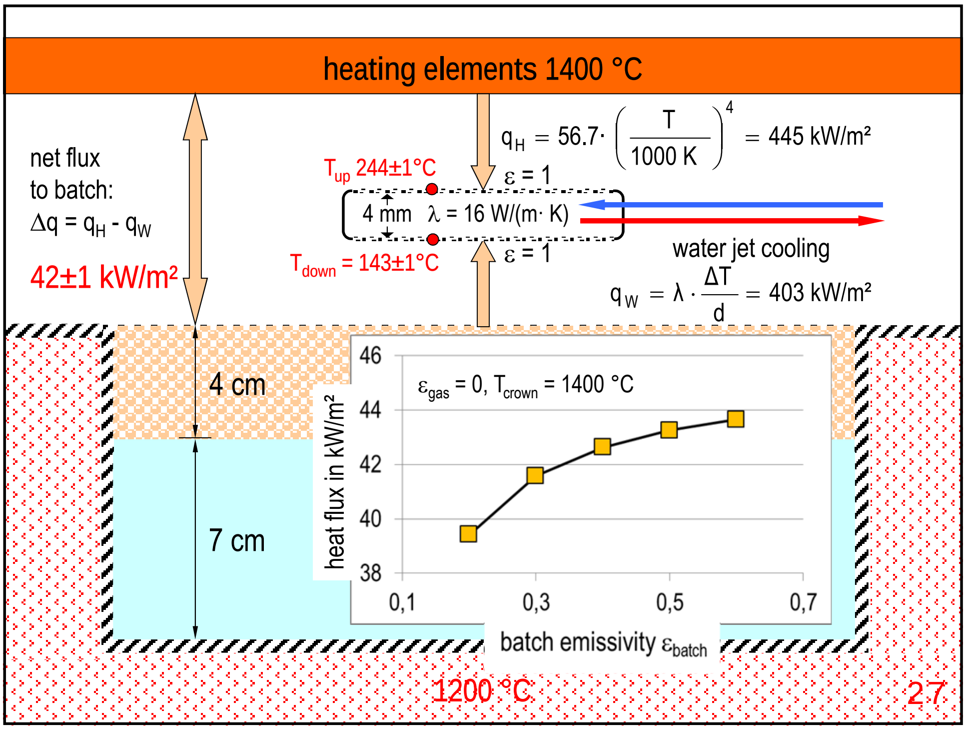
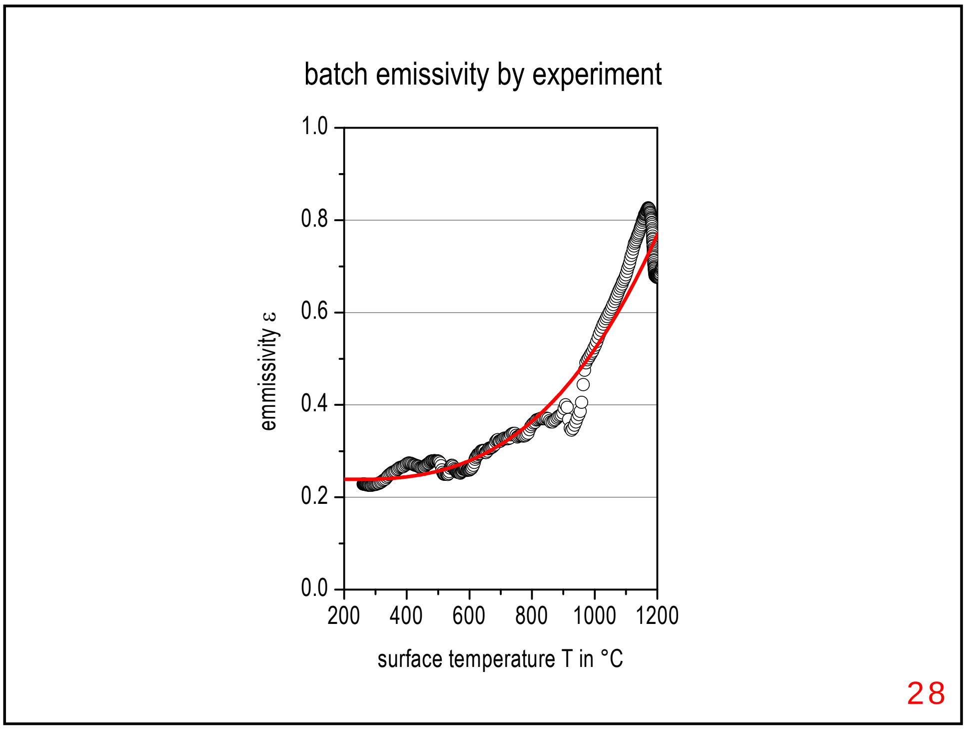

heating elements 1400 °C
net flux
to batch:
Δq = qH - qL
qH = flux to batch
Tup
ε = 1
4 mm λ = 16 W/(m· K)
ε = 1
Tdown
water jet cooling
qL = flux from batch
4 cm
batch
7 cm
melt
1200 °C
25


heating elements 1400 °C
net flux
to batch:
Δq = qH - qW
42±1 kW/m²
qH = 56.7· (T / 1000 K)^4 = 445 kW/m²
Tup 244±1°C
ε = 1
4 mm λ = 16 W/(m· K)
Tdown = 143±1°C
ε = 1
water jet cooling
qW = λ · ΔT / d = 403 kW/m²
4 cm
batch
7 cm
melt
1200 °C
26


heating elements 1400 °C
net flux
to batch:
Δq = qH - qW
42±1 kW/m²
Tup 244±1°C
Tdown = 143±1°C
4 mm λ = 16 W/(m· K)
qH = 56.7· (T / 1000 K)^4 = 445 kW/m²
ε = 1
ε = 1
water jet cooling
qW = λ · ΔT / d = 403 kW/m²
4 cm
7 cm
heat flux in kW/m²
εgas = 0, Tcrown = 1400 °C
46
44
42
40
38
0,1
0,3
0,5
0,7
batch emissivity εbatch
1200 °C
27


batch emissivity by experiment
emissivity ε
1.0
0.8
0.6
0.4
0.2
0.0
200
400
600
800
1000
1200
surface temperature T in °C
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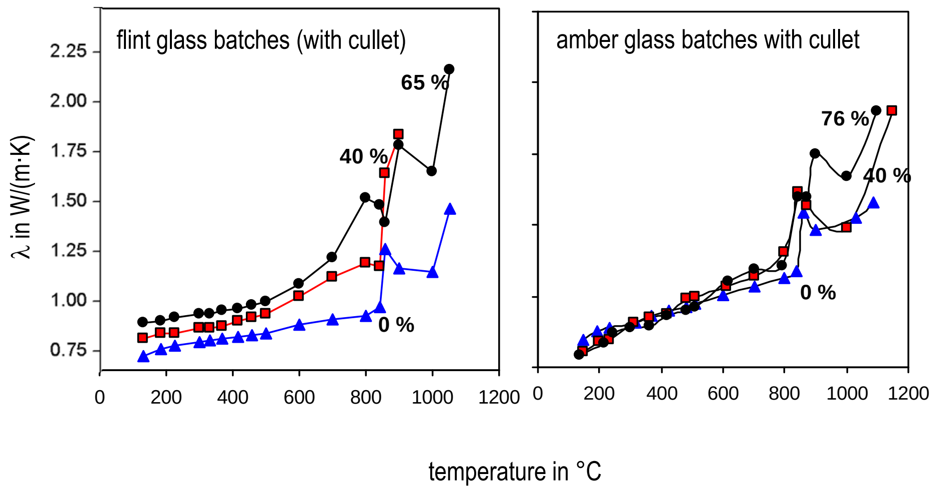
effective heat conductivity of container glass batch

local determination via heat pulse run time in 200 g batches



own work, GTB 2004; Ceram. Trans. 2012

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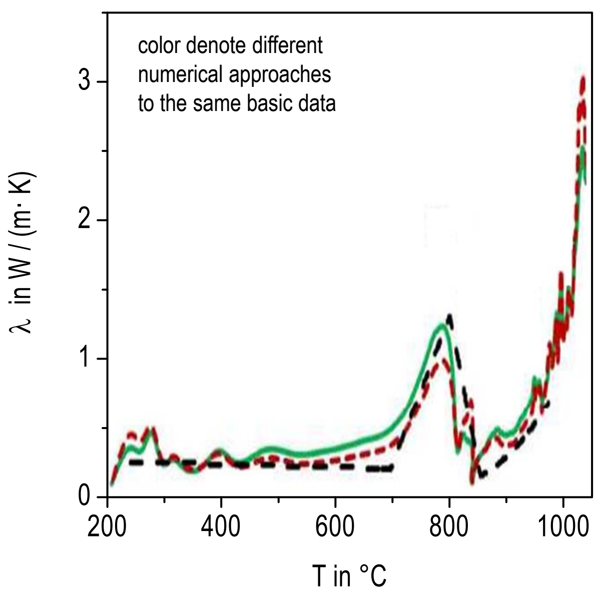
effective heat conductivity of rad. waste glass batch



data by P. Hrma

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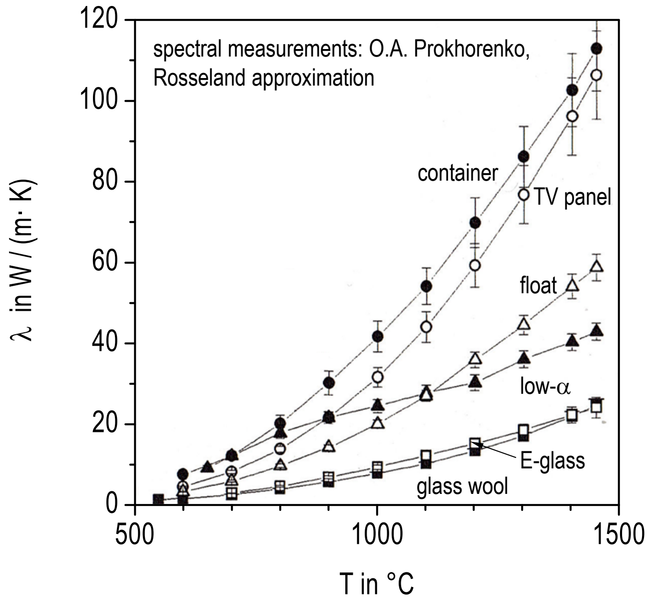

T.P Seward III & T. Vascott (eds.): High-T glass melt property database for process modeling, 2005

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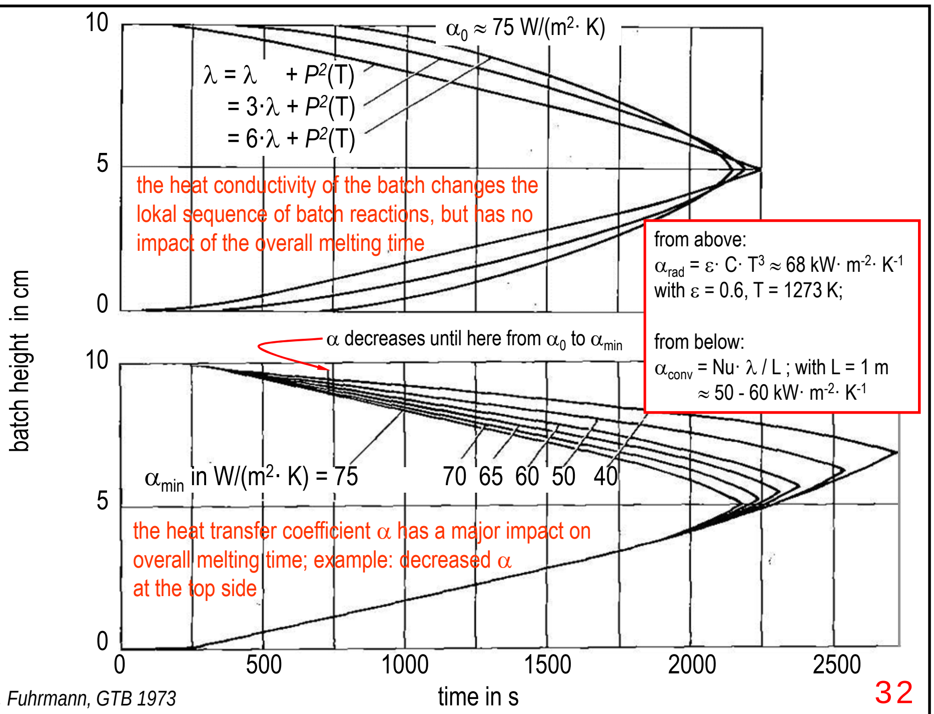

H. Fuhrmann, GTB 1973

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the rate determining step

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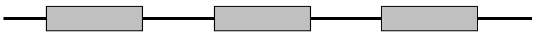
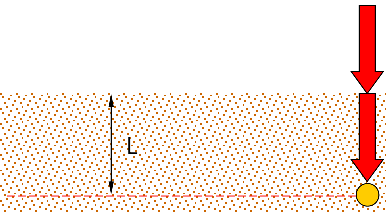


$$\frac{1}{\alpha_{rad}} \qquad L\cdot\frac{1}{\lambda_{eff}} \qquad \frac{1}{d\cdot c_P\cdot\rho}\cdot\frac{1}{\omega}$$

$$\alpha_{eff}=\frac{1}{\frac{1}{\alpha_{rad}}+L\cdot\frac{1}{\lambda_{eff}}+\frac{1}{d\cdot c_P\cdot\rho}\cdot\frac{1}{\omega}}$$



heat transfer: α_{rad} in W / (m^2· K)

heat conduction: λ_{eff} in W / (m· K)

local reaction rate: ω in s^{-1}

thus, we have to compare:

$$\alpha_{rad},\ \frac{\lambda_{eff}}{L},\ d\cdot c_P\cdot\rho\cdot\omega$$

the smallest one it rate controlling

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$$c_P \cdot \rho \approx 1.9 \frac{MJ}{m^3 \cdot K}; \quad \omega \approx \frac{1}{t_{BFT}} \approx \frac{1}{40\,\text{min}} = 4.2 \cdot 10^{-4} s \Rightarrow \boxed{d \cdot c_P \cdot \rho \cdot \omega \approx 80 \frac{W}{m^2 \cdot K}}$$

critical at later stage; design fast conversion batches

$$\lambda_{eff} \approx 0.5 \ldots 2 \frac{W}{m \cdot K} \Rightarrow \boxed{\frac{\lambda_{eff}}{L} \approx 20 \frac{W}{m^2 \cdot K} \to d \cdot c_P \cdot \rho \cdot \omega}$$

critical at early stage; shorten early stage by batch preheating; pellets; transparent cullet; low-H batches

$$\text{from previous analysis} \Rightarrow \boxed{\alpha_{rad} \approx 60 \ldots 200 \frac{kW}{m^2}}$$

critical at too low T_{gas} only; gas emissivity has no impact during the stage of batch melting

interim conclusion

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the rate determining step: how to check it in a real industrial situation ?

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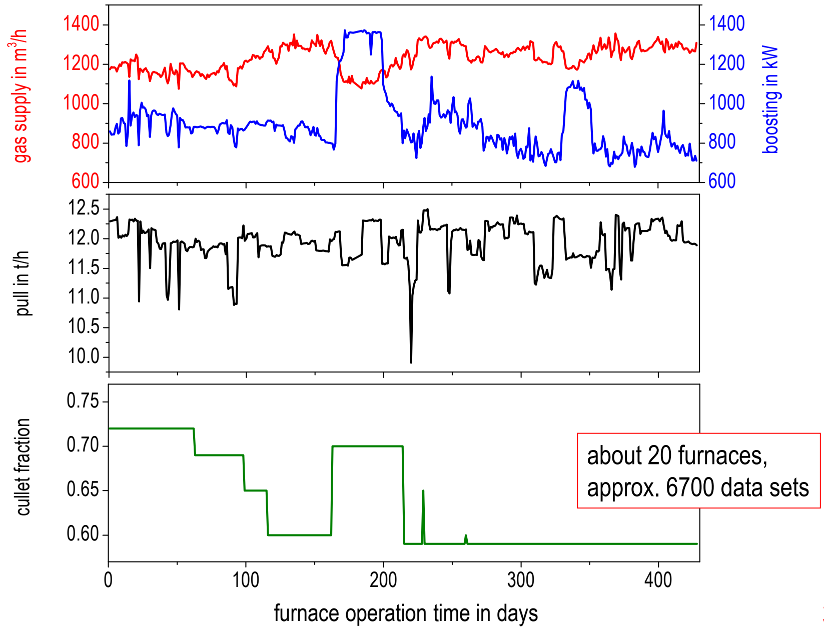
Example: 97 m^2 end port fired furnace, air-gas, green:
fuel input, fuel composition; *boost*; *pull; pull temperature*; *batch composition & cullet fraction*



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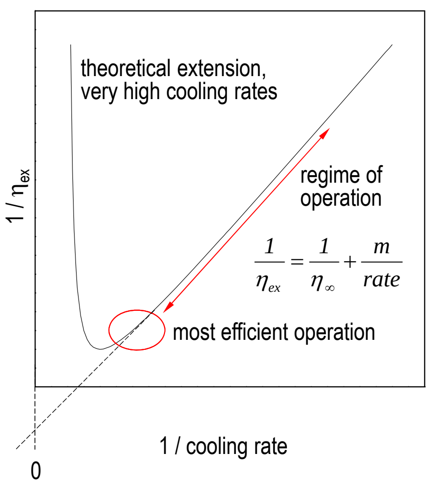
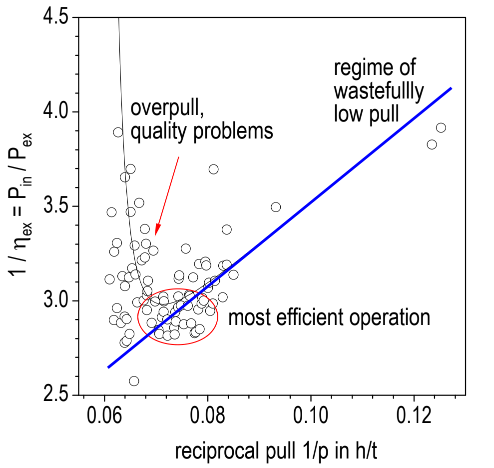
thermodynamic modeling of chillers
Gordon & Ng, J. Appl. Phys 1994
η_{ex} = coefficient of performance



glass furnace

Cr green conrainer, < 13.5 t/h, 94 m^2, 5 years



Three constants only:
intercept $1/\eta_\infty$, slope m, ΔH^{vap}

$$P_{in} = m \cdot H_{ex} + \frac{H_{ex}}{\eta_\infty} \cdot p = a + b \cdot p$$

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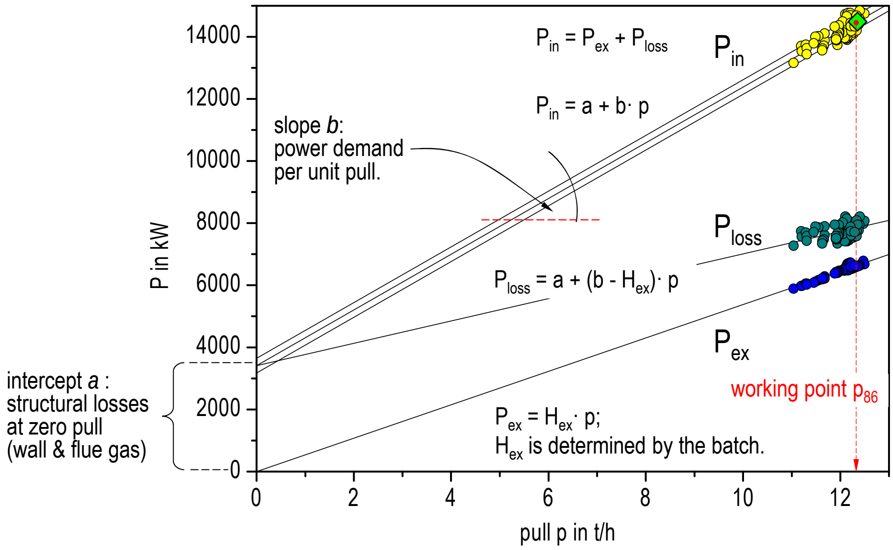
97 m^2 end port fired furnace, air-gas, green, 70±2 % cullet



three key parameters: a, b, H_{ex};

b – H_{ex} represents the heat transfer constraint: $b - H_{ex} = H_{ex} \cdot \left(\frac{1}{\eta_\infty} - 1 \right) \cdot p$

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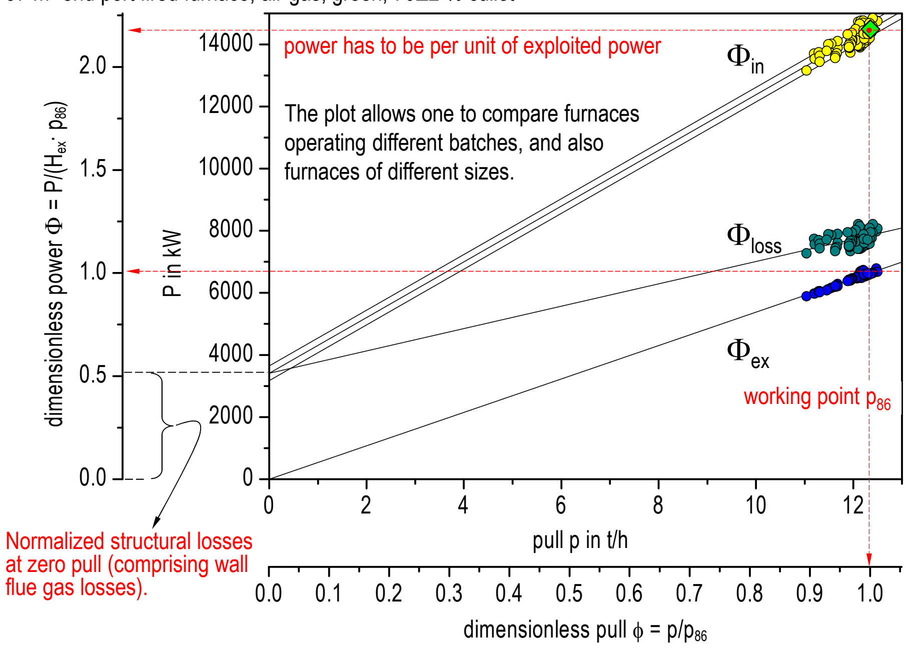
97 m^2 end port fired furnace, air-gas, green, 70±2 % cullet



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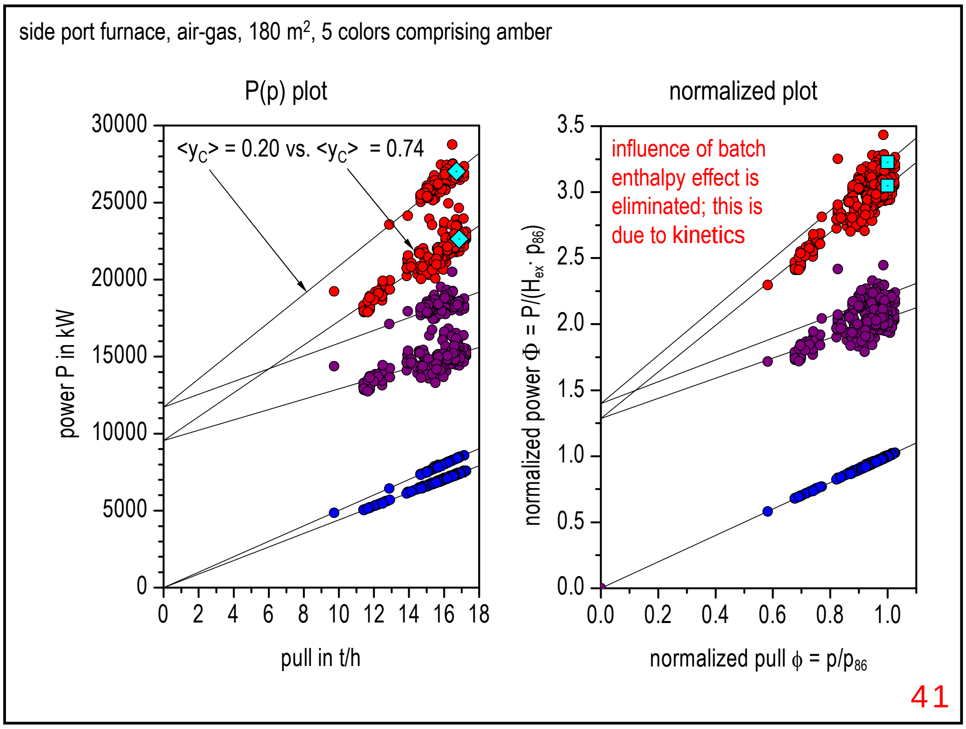
side port furnace, air-gas, 180 m², 5 colors comprising amber
P(p) plot
normalized plot
<y_C> = 0.20 vs. <y_C> = 0.74
power P in kW
pull in t/h
influence of batch enthalpy effect is eliminated; this is due to kinetics
normalized power Φ = P/(H_ex · p_86)
normalized pull ϕ = p/p_86
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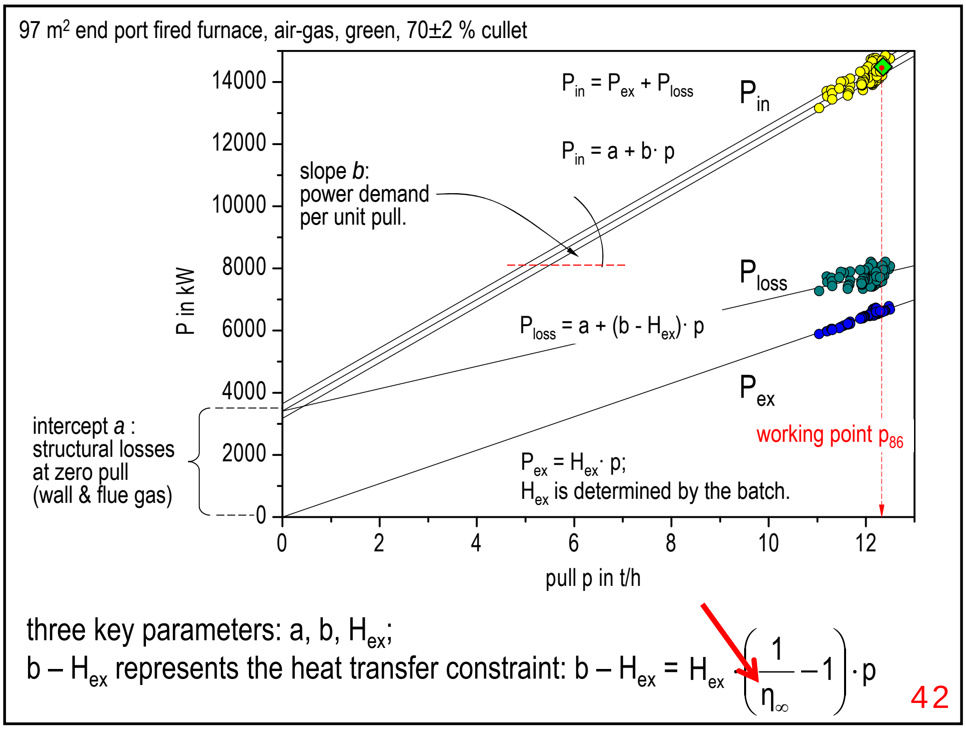
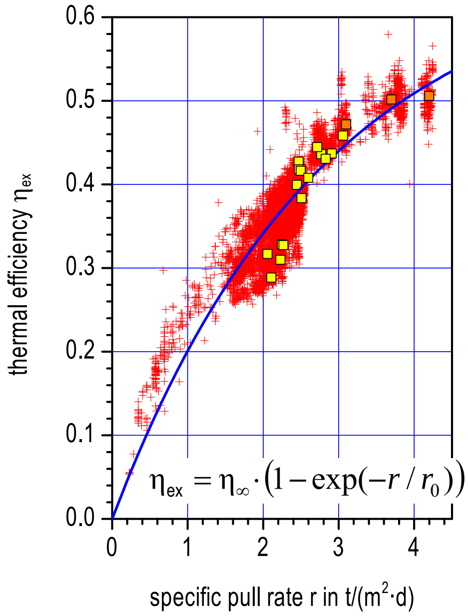

97 m² end port fired furnace, air-gas, green, 70±2 % cullet
P_in = P_ex + P_loss
P_in
P_in = a + b· p
slope b: power demand per unit pull.
P_loss
P_loss = a + (b - H_ex)· p
P_ex
working point p_86
P_ex = H_ex· p; H_ex is determined by the batch.
intercept a : structural losses at zero pull (wall & flue gas)
P in kW
pull p in t/h
three key parameters: a, b, H_ex;
b – H_ex represents the heat transfer constraint: b – H_ex = H_ex (1/η_∞ – 1) · p
42

evaluation of 6700 data sets, 20 container glass furnaces, over 2 - 4 years, 10 – 90 % cullet



two main constraints:

heat transfer

η_{∞} = 0.68±0.01 *)

z_{HL} overrules α_{ht}

chemical turnover rate

r_0 = 2.83±0.05 t / ($m^2 \cdot$ d)

*) It is the upper limit of efficiency ot heat exploitation in any thinkable process using fossile fuel as only energy source:

$$\eta_{\infty} \approx 1 - \sqrt{\frac{T_0}{T_{ad}}} = \eta_{C.A.}$$

η_{∞} = 0.67 for air-fuel, and 0.69 for oxy-fuel.

Only electrical heating, due to high Fermi Temperature of electrodes

$$\eta_{\infty} \approx 1 - \sqrt{\frac{T_0}{T_{FERMI}}} \to 1$$

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Thank you
for your kind attention!

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