CelSian

The contribution of thermodynamics in determining the parameters of elaboration and energy efficiency

C. Claireaux, CelSian

ICG
International Commission on Glass

Glass for a sustainable future

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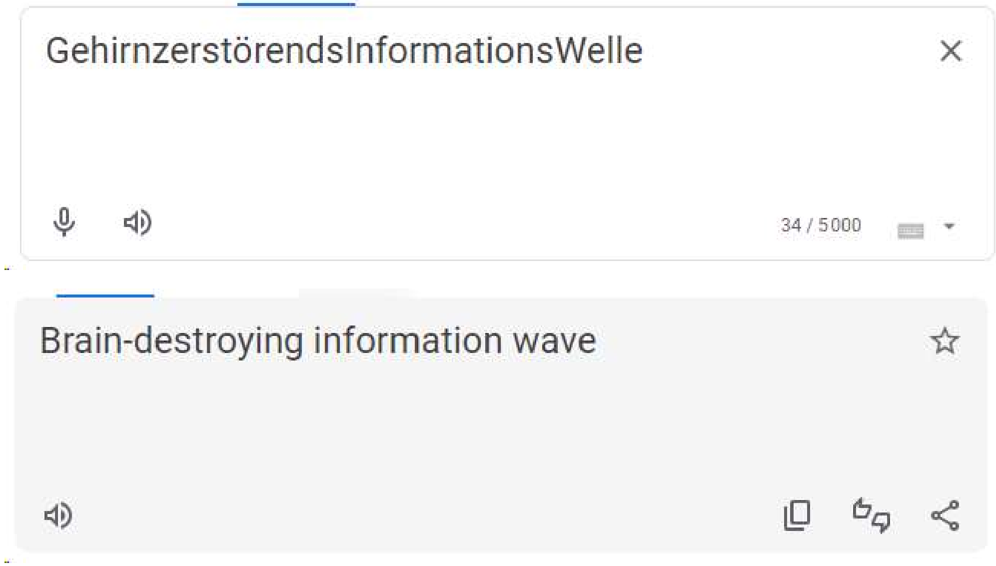
UNION
POUR LA SCIENCE
ET LA TECHNOLOGIE
VERRIÈRES

We are not getting any younger - 2012

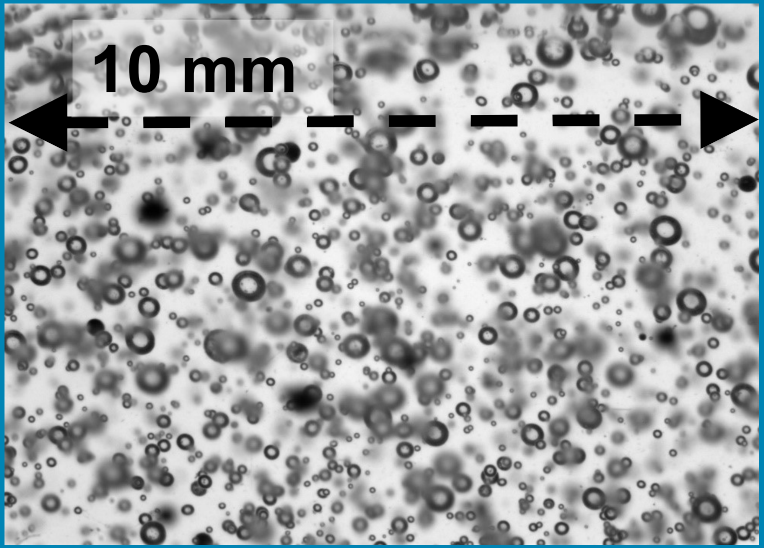


GehirnzerstörendsInformationsWelle

Brain-destroying information wave

R Conradt, 2019. Prospects and physical limits of processes and technologies in glass melting. Journal of Asian Ceramic Societies 7 (4) 377-396

Real case scenario



A furnace producing amber colored bottles doesn’t reach the desired pull at a satisfactory level of quality [bubbles!]

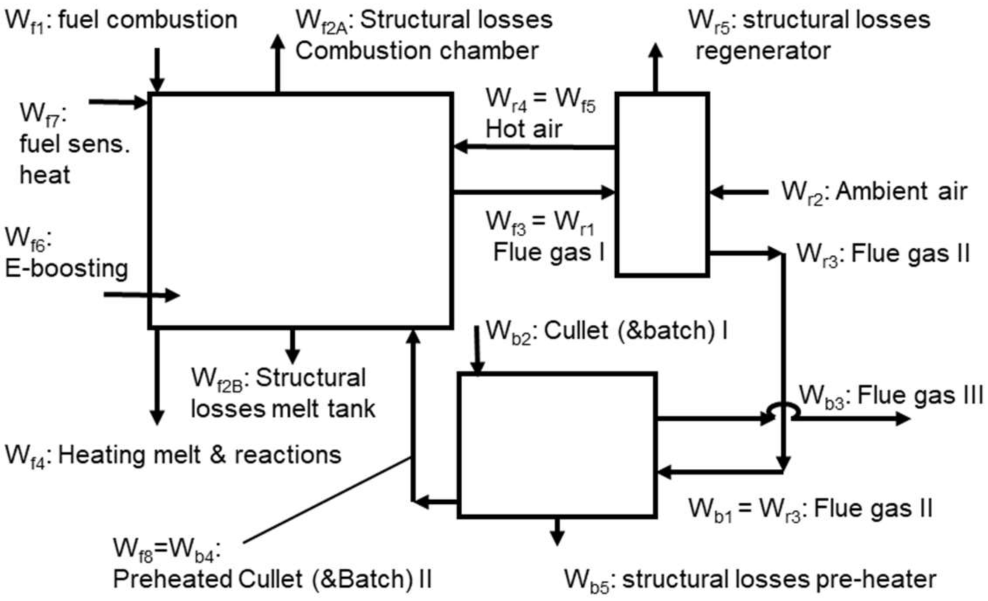
Energy can neither be created nor destroyed, only altered in form.

Energy balance

WHAT COMES IN

P_{in}

- Combustion
- Boosting



Refence state: 273.15 K / 0°C
f = furnace balance
r = recuperator / regenerator balance
b = batch preheat balance

WHAT COMES OUT

P_{ex}

- Hot glass melt

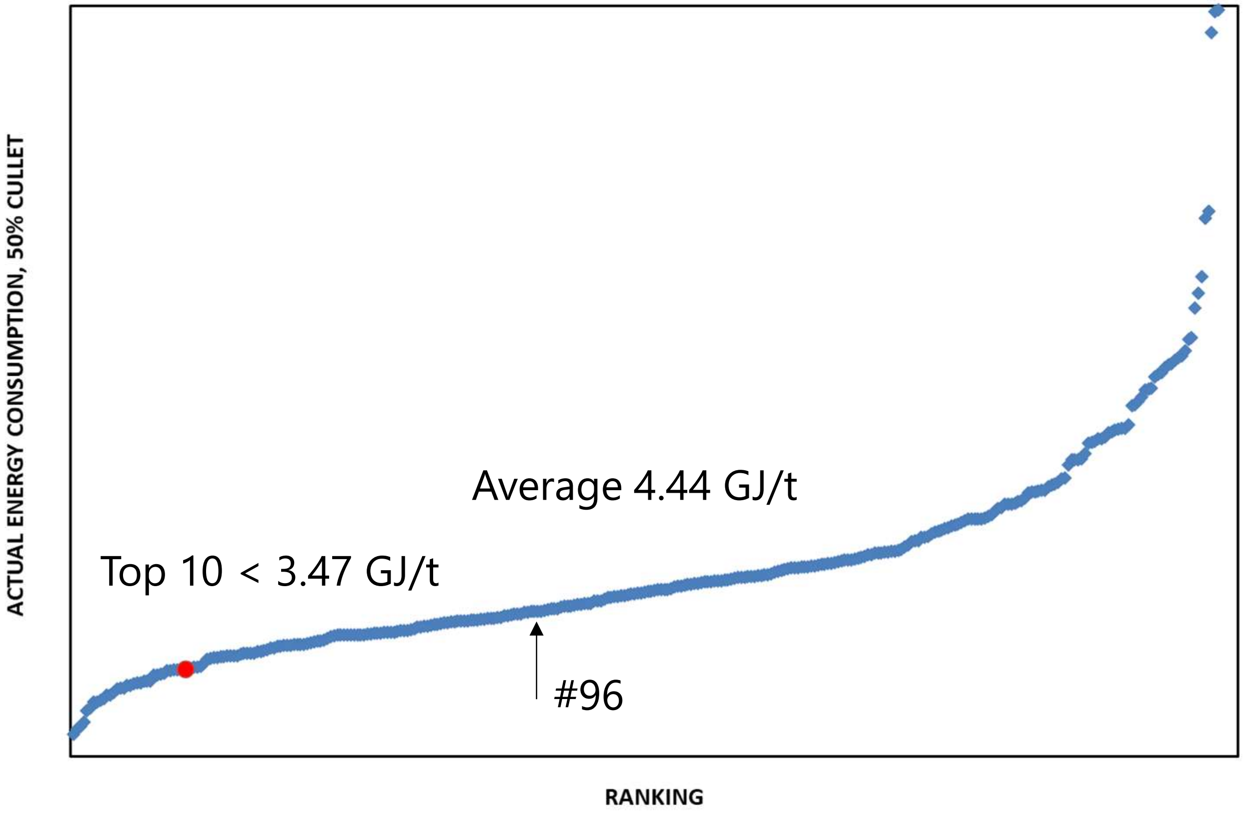
P_{loss}

- Hot flue gases
- Structural losses

A furnace consumes energy

Power supplied to the electrical boosting [kW]	P_{boost}
Flow of gas supplied to the burners and the composition and/or caloric value of the gas	$P_{comb} = H_{comb} V'_{fuel}$
→ Pin, the power input	$P_{in} = P_{comb} + P_{boost}$

Benchmark, for container furnaces



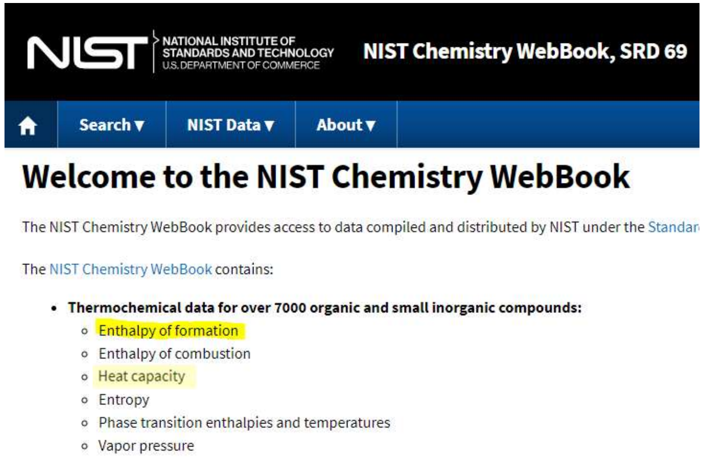
A furnace is a chemical reactor

Pull rate [tons glass per day]	p	
Cullet fraction entering the furnace	y_{cullet}	Energy demand setup
Temperature at which the glass exits	T_{ex}	
Energy required to convert the raw materials into glass	ΔH°_{chem}	
Energy required to heat the glass to T_{ex}	ΔH	

→ Pex, the exploited power

$$P_{ex} = p((1-y_{cullet})\Delta H^{\circ}_{chem} + \Delta H(T_{ex}))$$

Wait, what? – ΔH and ΔH°_{chem}

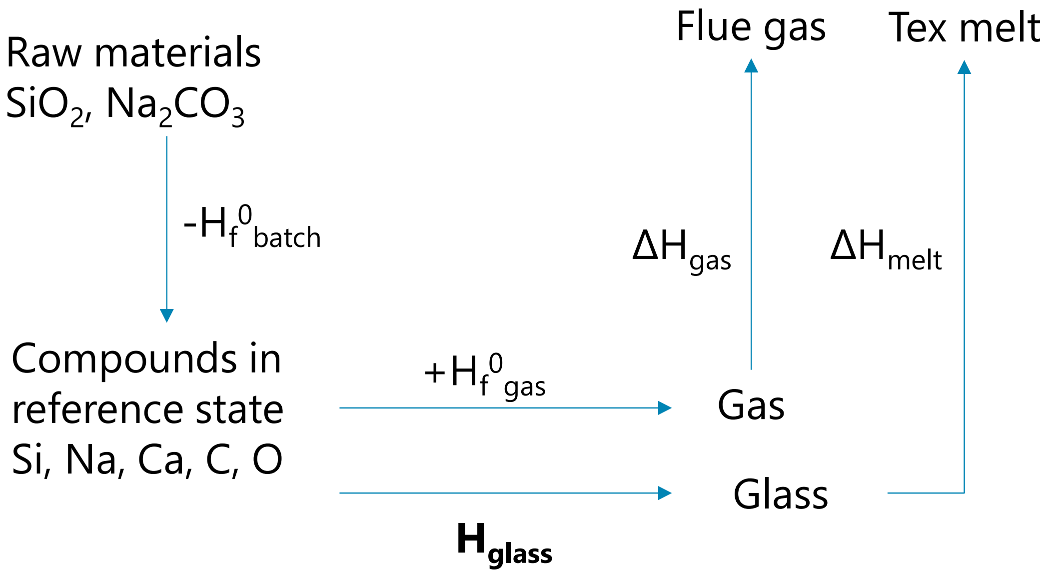


Welcome to the NIST Chemistry WebBook

The NIST Chemistry WebBook provides access to data compiled and distributed by NIST under the Standar

The NIST Chemistry WebBook contains:

- **Thermochemical data for over 7000 organic and small inorganic compounds:**
  - Enthalpy of formation
  - Enthalpy of combustion
  - Heat capacity
  - Entropy
  - Phase transition enthalpies and temperatures
  - Vapor pressure



Raw materials
SiO_2, Na_2CO_3

$-H_f^0{}_{batch}$

Compounds in reference state
Si, Na, Ca, C, O

$+H_f^0{}_{gas}$

Gas

ΔH_{gas}

Flue gas

Glass

ΔH_{melt}

Tex melt

H_{glass}

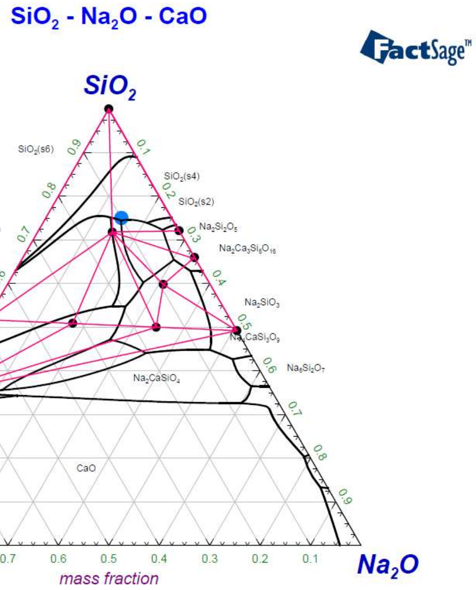
$$H_{glass} = H_{vit} + H_{MIX}$$

R. Conradt, P. Pimkhaokham, 1990

Heat of formation of the glass

75%	SiO_2
10%	CaO
15%	Na_2O

35.1%	$Na_2O\ .\ 3CaO\ .\ 6SiO_2$
33.3%	$Na_2O\ .\ 2SiO_2$
31.6%	SiO_2



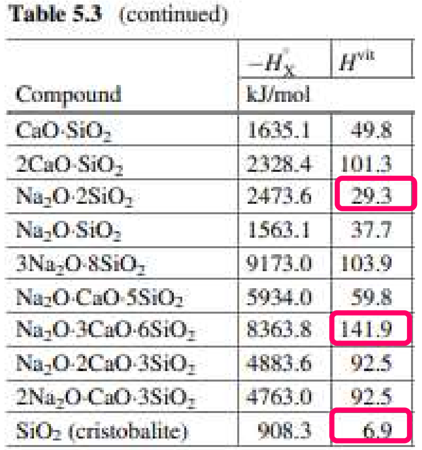


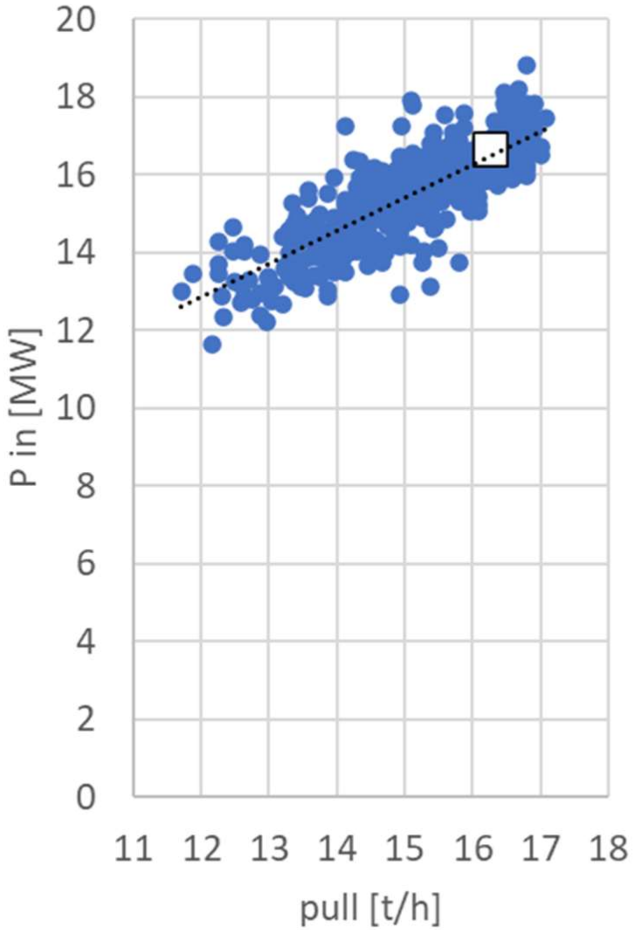
Table 5.3 (continued)

	$-H_X^{\circ}$	H^{vit}
Compound	kJ/mol	
$CaO{\cdot}SiO_2$	1635.1	49.8
$2CaO{\cdot}SiO_2$	2328.4	101.3
$Na_2O{\cdot}2SiO_2$	2473.6	29.3
$Na_2O{\cdot}SiO_2$	1563.1	37.7
$3Na_2O{\cdot}8SiO_2$	9173.0	103.9
$Na_2O{\cdot}CaO{\cdot}5SiO_2$	5934.0	59.8
$Na_2O{\cdot}3CaO{\cdot}6SiO_2$	8363.8	141.9
$Na_2O{\cdot}2CaO{\cdot}3SiO_2$	4883.6	92.5
$2Na_2O{\cdot}CaO{\cdot}3SiO_2$	4763.0	92.5
SiO_2 (cristobalite)	908.3	6.9

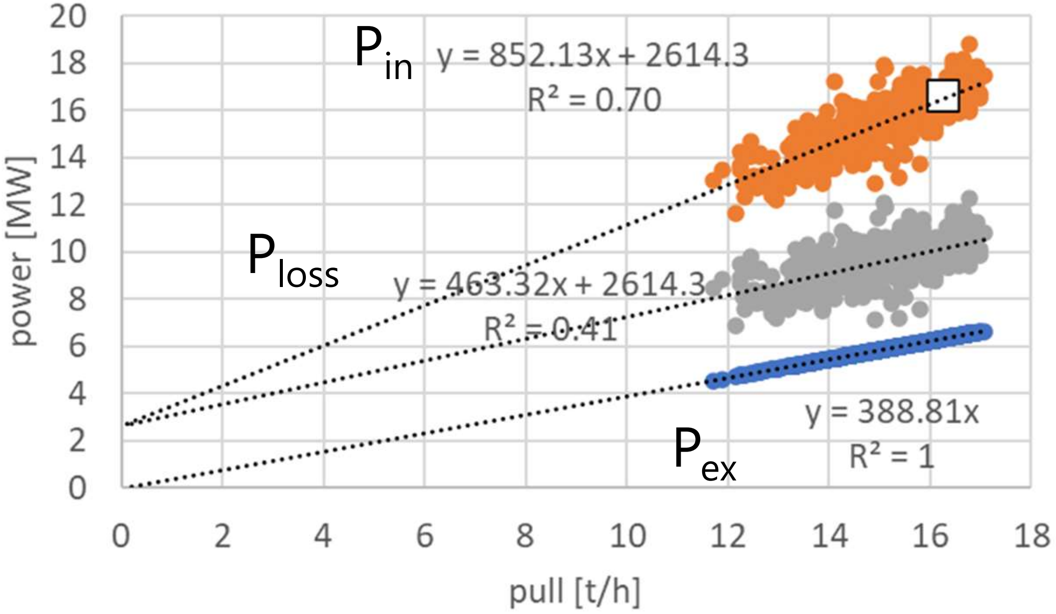
Conradt, R. (2021). Fiberglass Batch-to-Melt Process. In: Li, H. (eds) Fiberglass Science and Technology. Springer, Cham.

- Heat of vitrification of definite compounds
- Mixing energy neglectable
- Same approach for ΔH_{melt}

Power plot



$$\eta = \frac{P_{ex}}{P_{in}} = 38\%$$



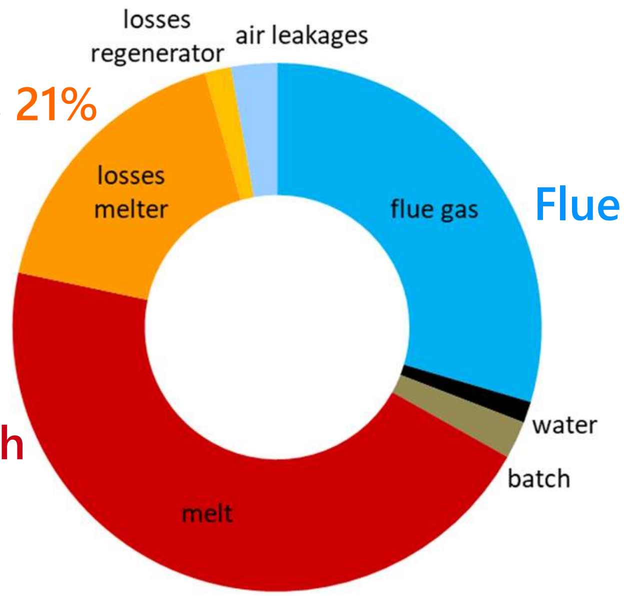
P_{loss} at 0 pull	2614 kWh
Power demand per pull unit	852 kWh/t
Exploited heat	389 kWh/t

How is the energy spent overall? Energy balance (container/float)

Wall losses 21%

Flue gas 30%

Glass & batch
49%

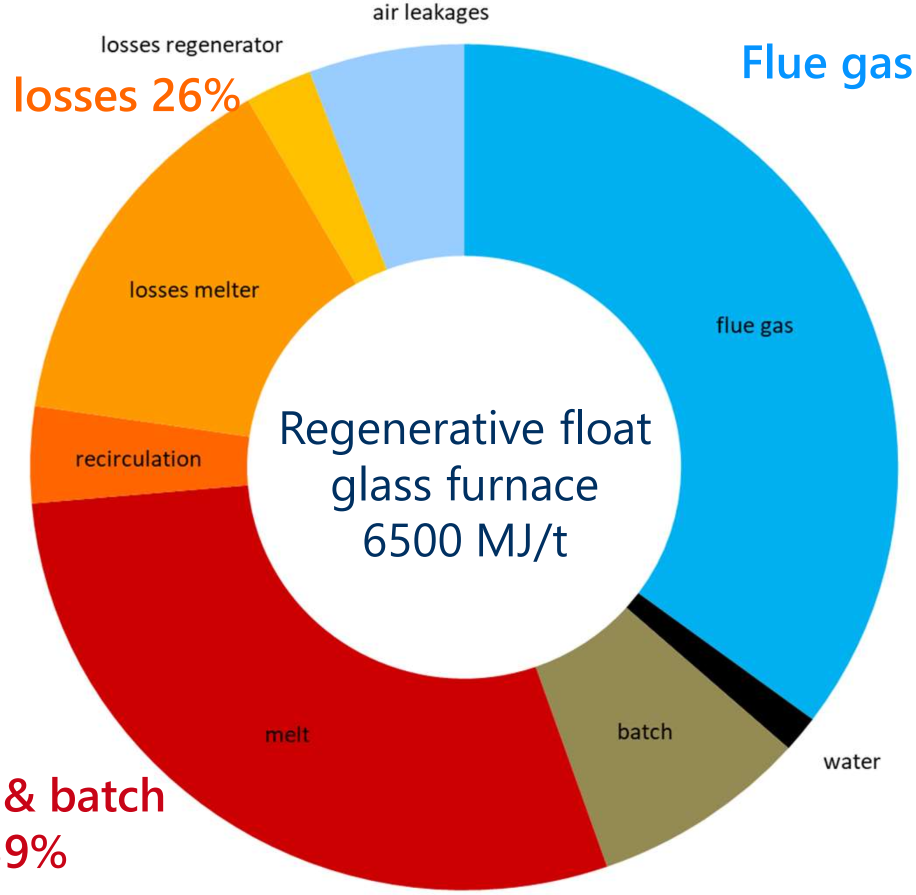


End port regenerative
container glass furnace
4500 MJ/t

Wall losses 26%

Flue gas 35%

Glass & batch
39%



Regenerative float
glass furnace
6500 MJ/t

What can we do so far?

Boosting, combustion, pull, cullet ratio, batch composition → Energy balance and efficiency

A system at equilibrium tends to maximize its entropy.

A fine balance

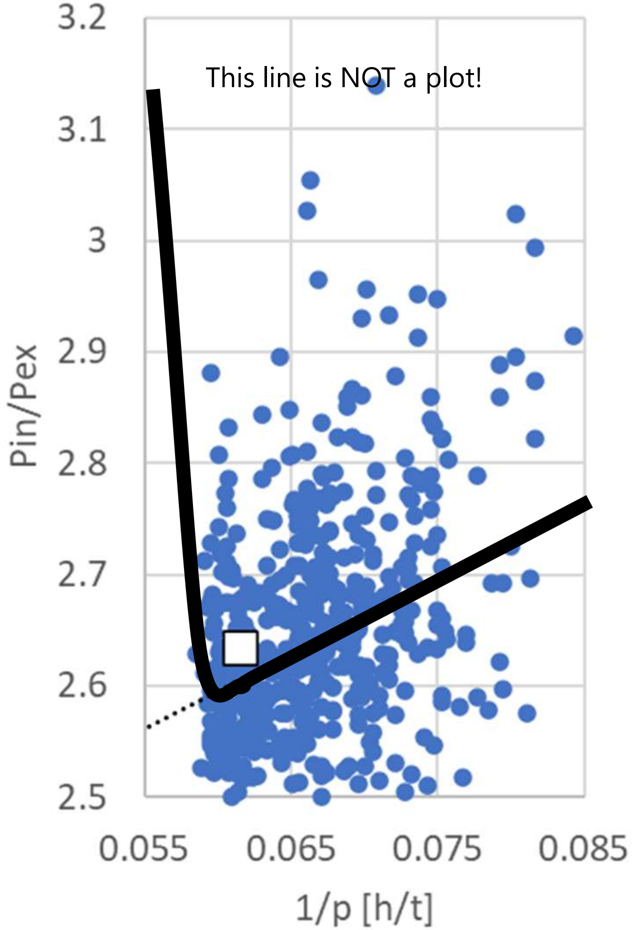
Heat flows from a hot body to a cooler one…

While increasing entropy

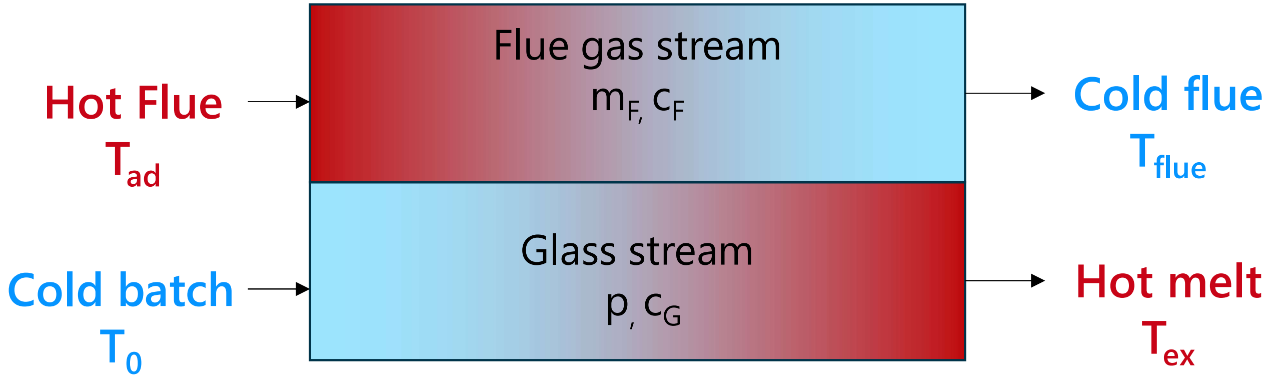
High temperature difference

- High heat transfer rate – short residence time
- High energy degradation

Chiller plot



Temperature efficiency



Hot Flue

T_{ad}

Flue gas stream

$m_{F,}\ c_F$

Cold flue

T_{flue}

Cold batch

T_0

Glass stream

$p_,\ c_G$

Hot melt

T_{ex}

$m_{F,}$ p mass flow [t/h]

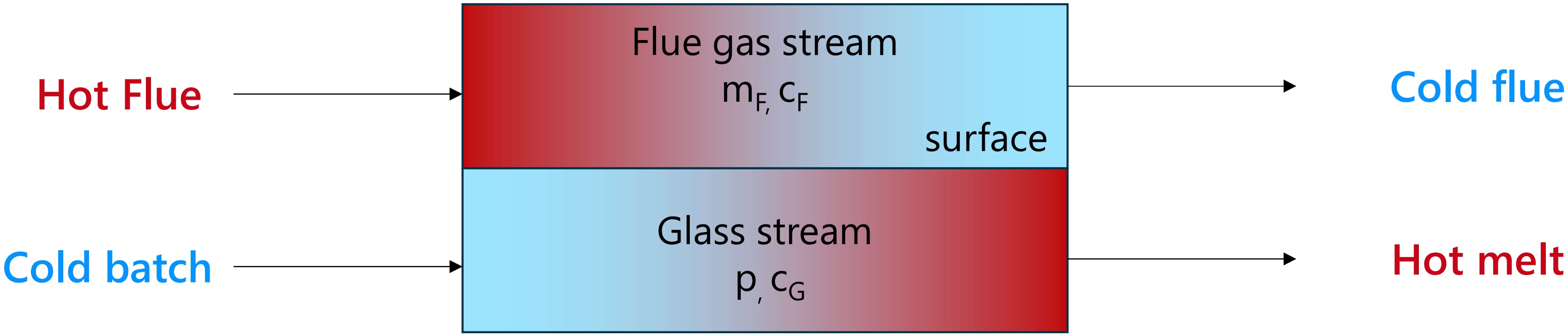
c heat capacity per ton[kWh/(tK)]

$$\zeta = \frac{T_{ex} - T_0}{T_{ad} - T_0}$$

	°C	ζ
T_0	20	
T_{ex}	1300	
T_{ad} air gas	2442	**0.53**
T_{ad} air oil	2520	**0.51**
T_{ad} oxy fuel	2780	**0.46**
T_{ad} oxy H_2	3200	**0.40**

Glass melter = heat exchanger

Matching the power delivered to the power exploited



Hot Flue

Flue gas stream

$m_{F,}$ c_F

surface

Cold flue

Cold batch

Glass stream

$p_{,}$ c_G

Hot melt

$m_{F,}$ p mass flow [t/h]
c heat capacity per ton[kWh/(tK)]

$$z_{FG} = \frac{\dot{m}_F c_F}{p c_G}$$

Heat capacity flow ratio → 1

Heat capacity flow ratio

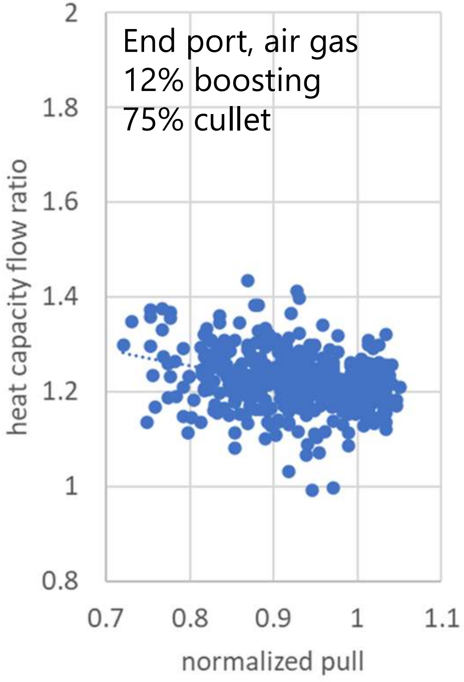
$$z_{FG} = \zeta \frac{P_{in}}{P_{ex}} \left(1 - \frac{P_{boost}}{P_{in}}\right)$$

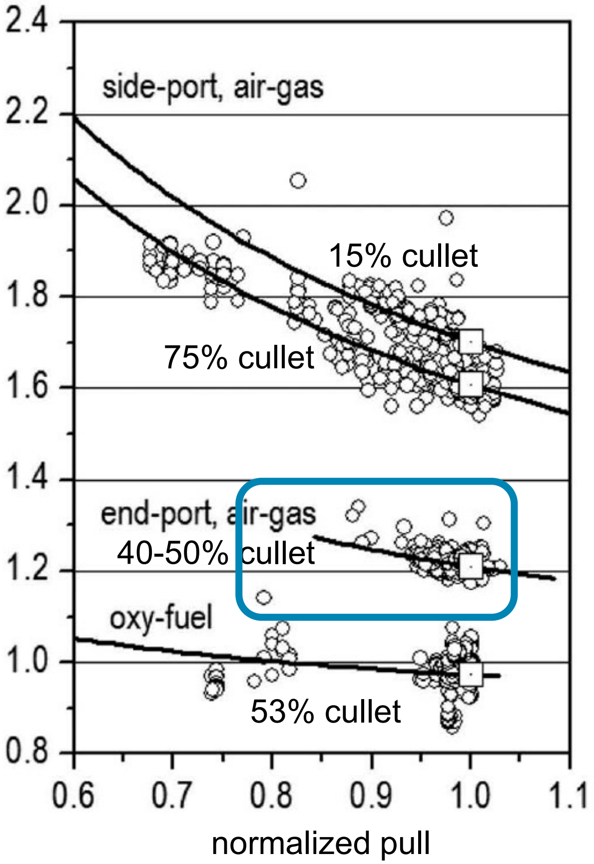
Normalized pull

$$p_{86} = \langle p \rangle + \sigma_p$$

<p> average pull rate

σ_p standard deviation





Radiative heat transfer from the combustion space is key

95% heat flux combustion → glass

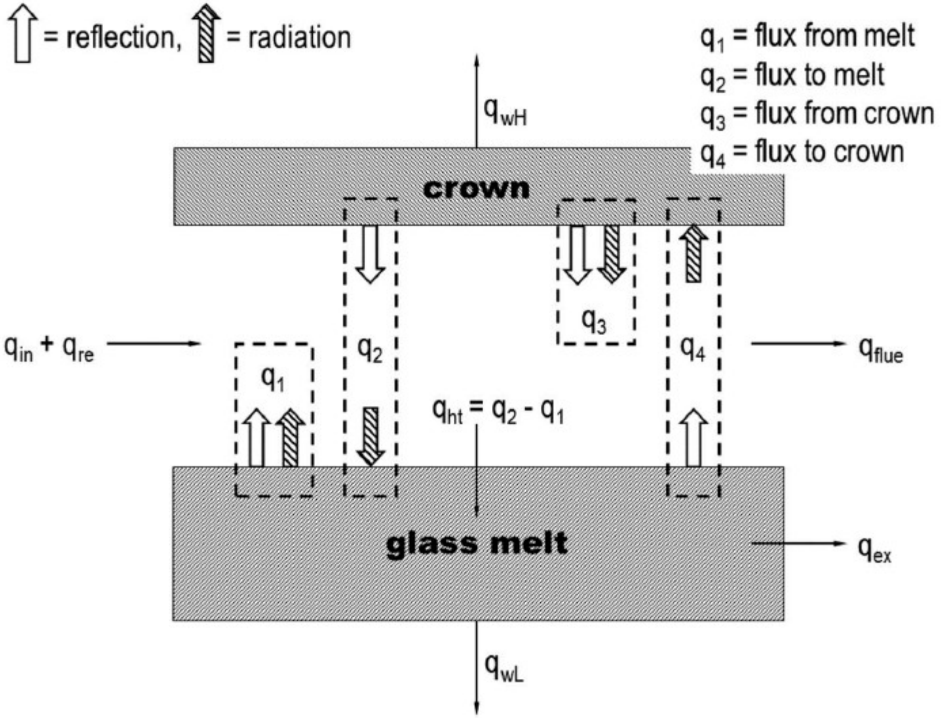
Grey radiation model

Emissions = $\varepsilon\sigma T^4$ [kW/m^2]

Balance of heat fluxes q [kW/m^2]

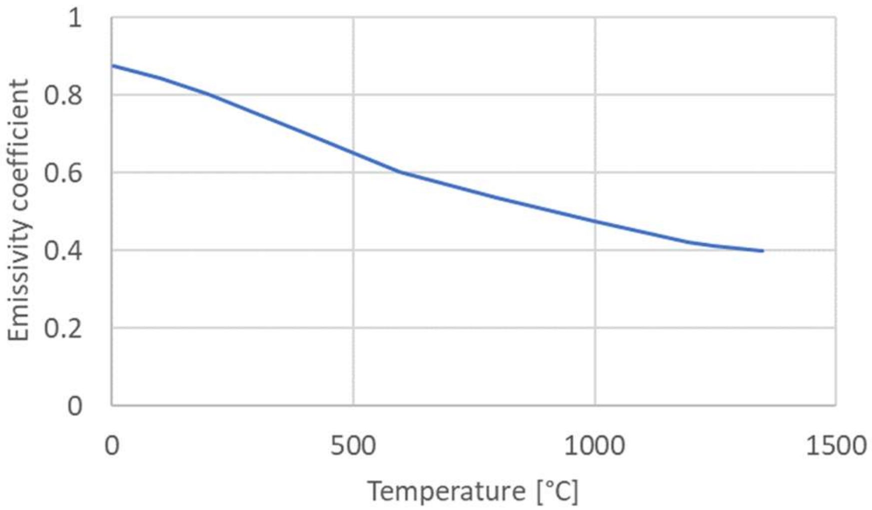
a, b, c functions of ε gas, melt, crown

$$T_{crown} = \left[\frac{c}{b}\left(q_{loss} + rH_{ex}\right) - \frac{a}{b}T_{gas}^4 + \left(1 + \frac{a}{b}\right)T_{melt}^4\right]^{\frac{1}{4}}$$



Emissivity of the crown

For most oxide-based materials ε ≈ 0.4



Emisshield®

Unless coated with high emissivity paints

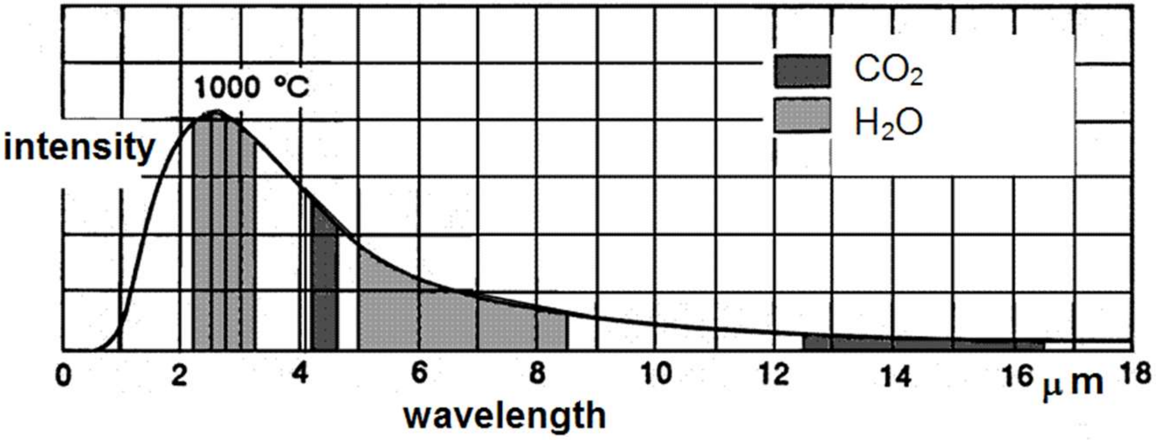
Emissivity of the combustion space

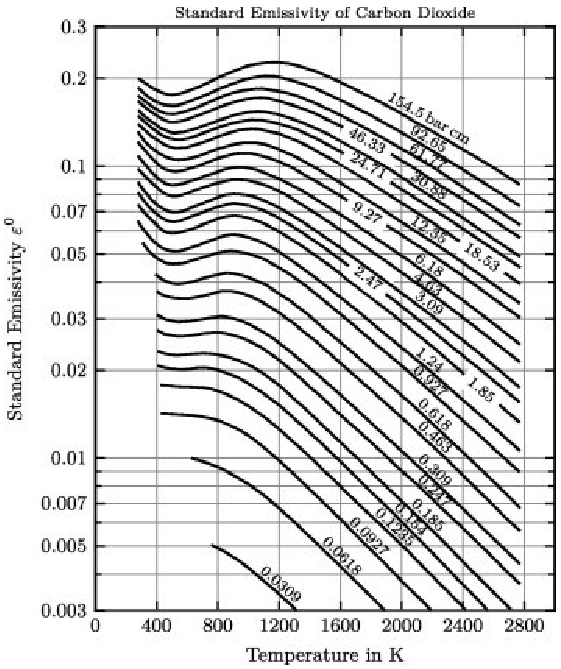
Flame emission coefficient = f(T, [CO_2], [H_2O], flame thickness, [soot])

Luminous, sooty flames ε = 0.25

Non sooty flames

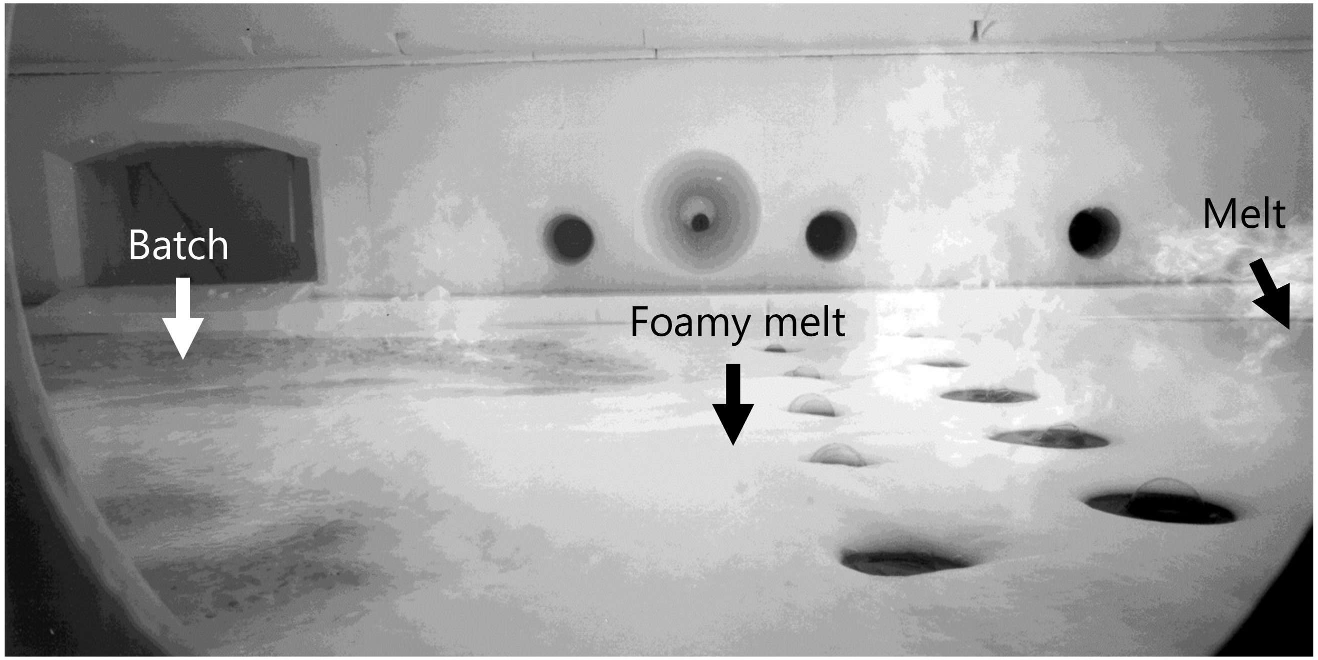
Air gas ε = 0.12 / Oxy-fuel ε = 0.4

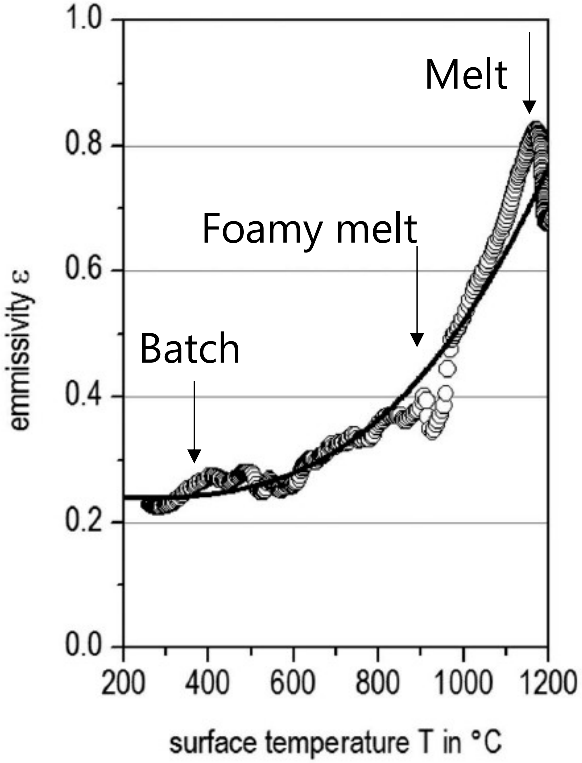




Hottel’s charts

Emissivity of the glass





And in reality?

ε melt (clear)	0.6
ε crown	0.4
ε gas (luminous air gas)	0.25
T melt	1350°C
T gas	1573°C
T crown	1570°C
q boosting	8 kW/m²
q losses	78 kW/m²
H ex	389 kW/m²

$$P_{ex} = p((1-y_{cullet})\Delta H^\circ_{chem} + \Delta H(T_{ex})$$

Theoretical specific pull rate

3.12 t/m²/day

Actual specific pull rate

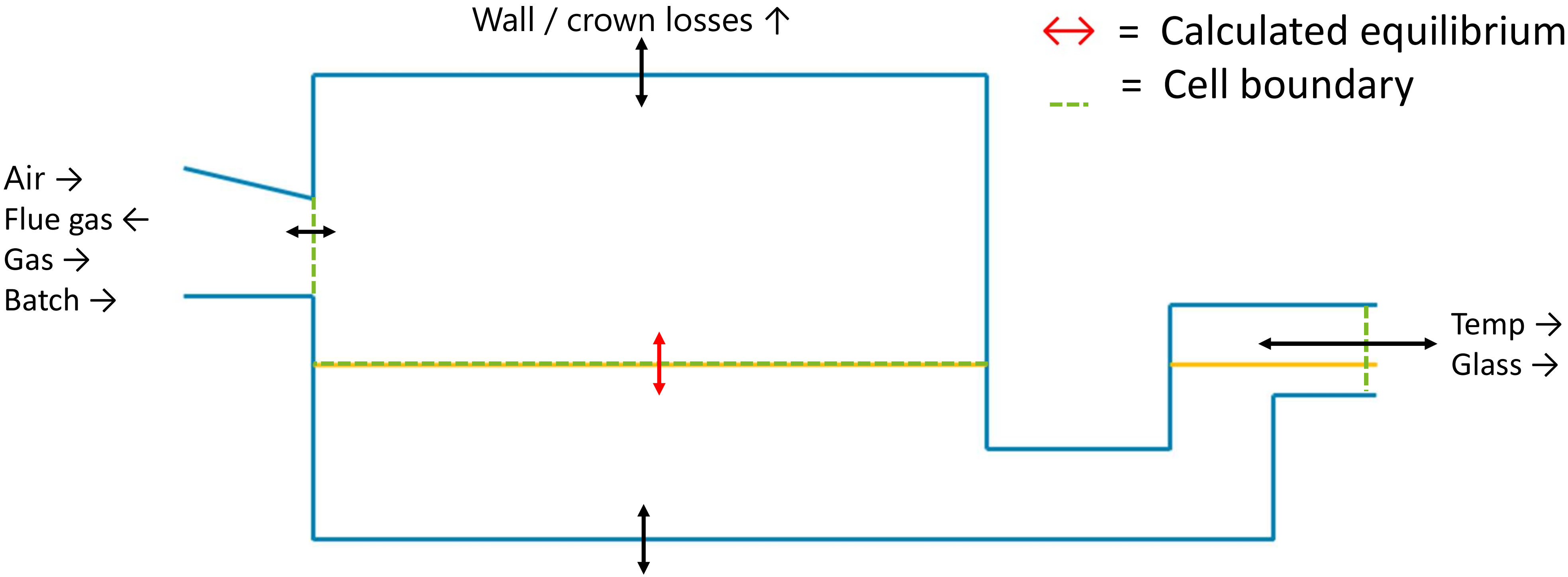
3.12 t/m²/day

What can we do now?

Quantify the influence of the heat transfer on the efficiency and combine everything to estimate the achievable pull rate

2 cell furnace

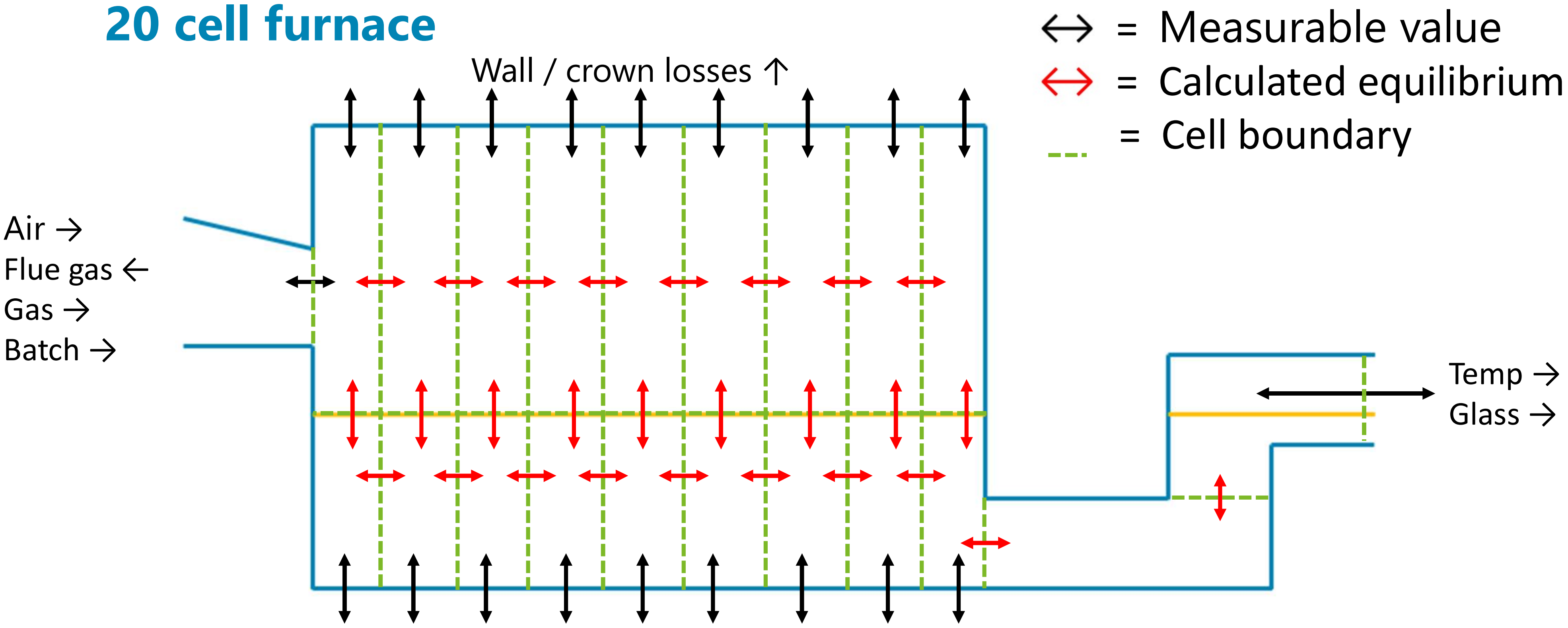
↔ = Measurable value
↔ = Calculated equilibrium
- - - = Cell boundary


Wall / crown losses ↑

Air →
Flue gas ←
Gas →
Batch →

Temp →
Glass →

20 cell furnace



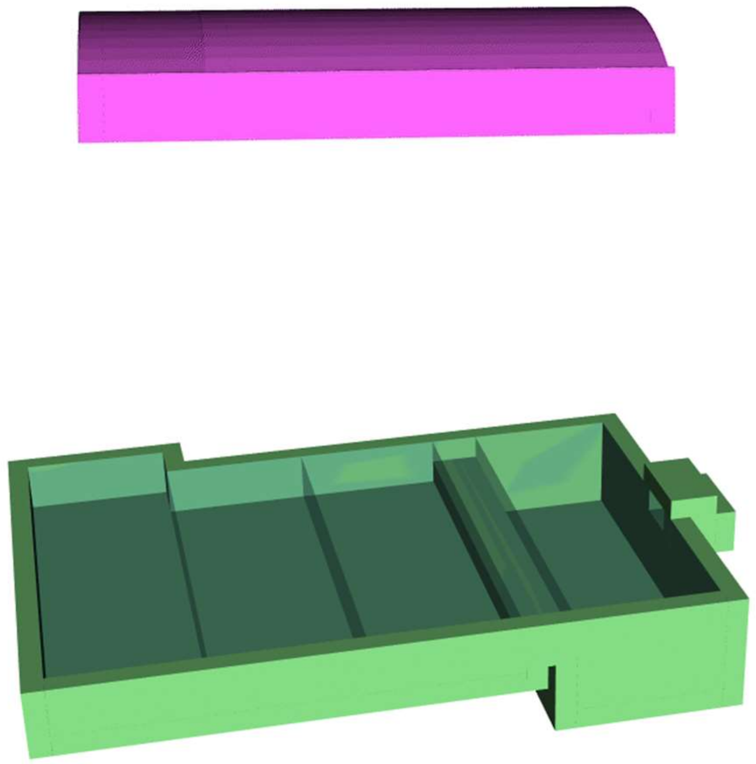
↔ = Measurable value

🟥↔ = Calculated equilibrium

-- = Cell boundary

Energy Balance Model

- "Fast" (1-2 min) calculations
- Potential energy savings and CO_2 reduction potential
- Detailed picture where to save energy
- Quantify impact of implementing energy saving-measures
- Training tool !



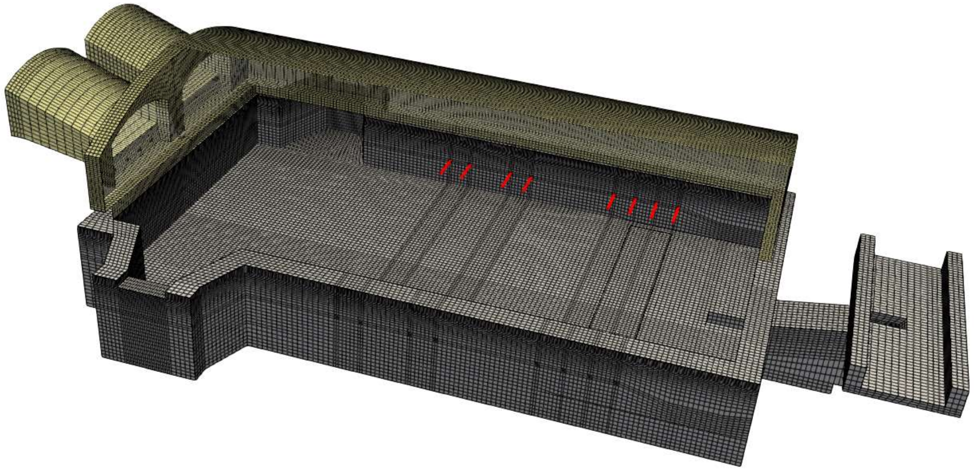
Have we solved the problem?

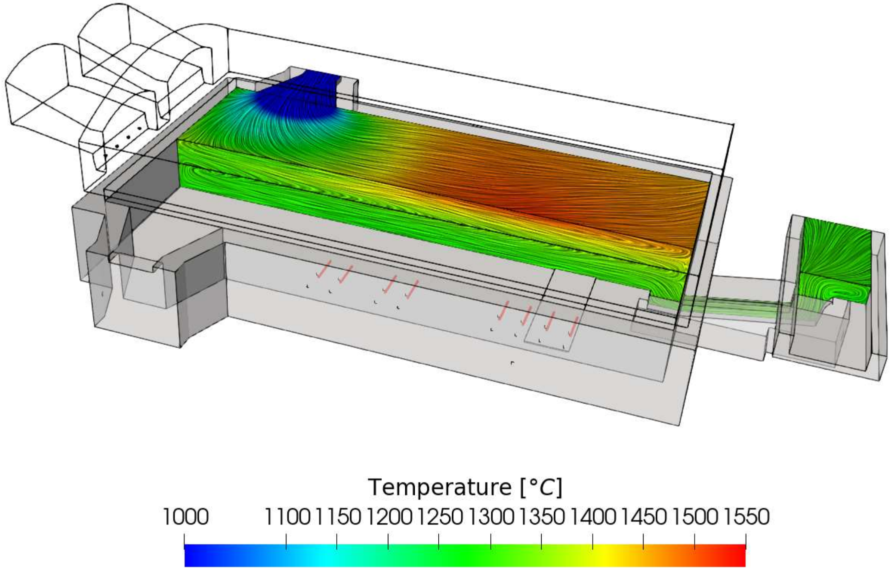
Saving energy BUT keeping quality

Thermodynamics + flow

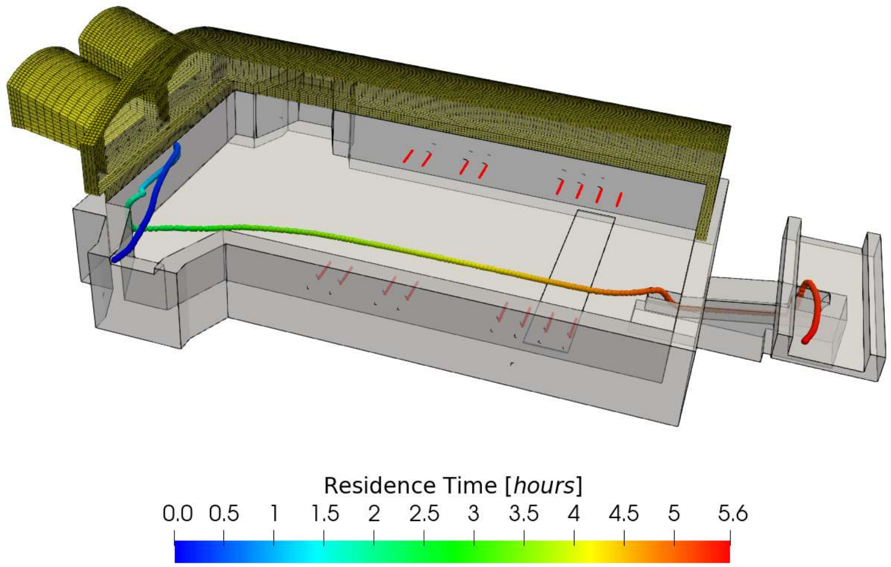
Computational Fluid Dynamics

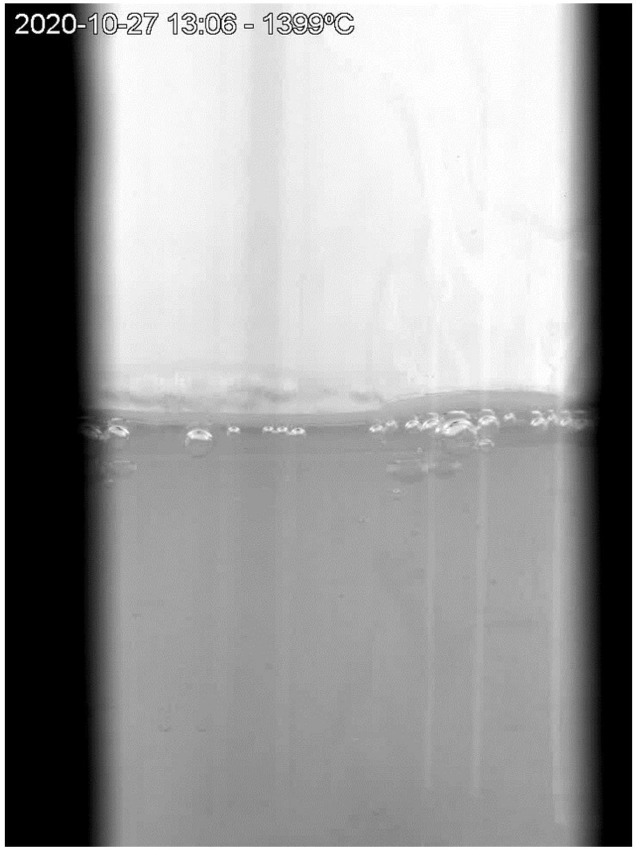
CFD simulation – domain discretization





Classic sources of bubbles : shortcut flow and reboil





Conclusion

- Elegant and efficient approach to accurately describe the energy exchanges taking place in furnaces.
- Powerful to quantify potential energy savings and optimize furnaces.
- For quality issues, the additional understanding of flows is a necessity.
- Excellent educational tool.

DO IT !

CelSian

Thank you for your kind attention!