WORKSHOP ON ENERGY CALCULATION IN THE GLASS INDUSTRY

Reinhard Conradt

Department of Mineral Engineering, RWTH Aachen Univbersity, Germany

Department of Materials Science, Faculty of Science, Chulalongkorn University

&

Department of Science Service

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conradt@ghi.rwth-aachen.de

the heat balance

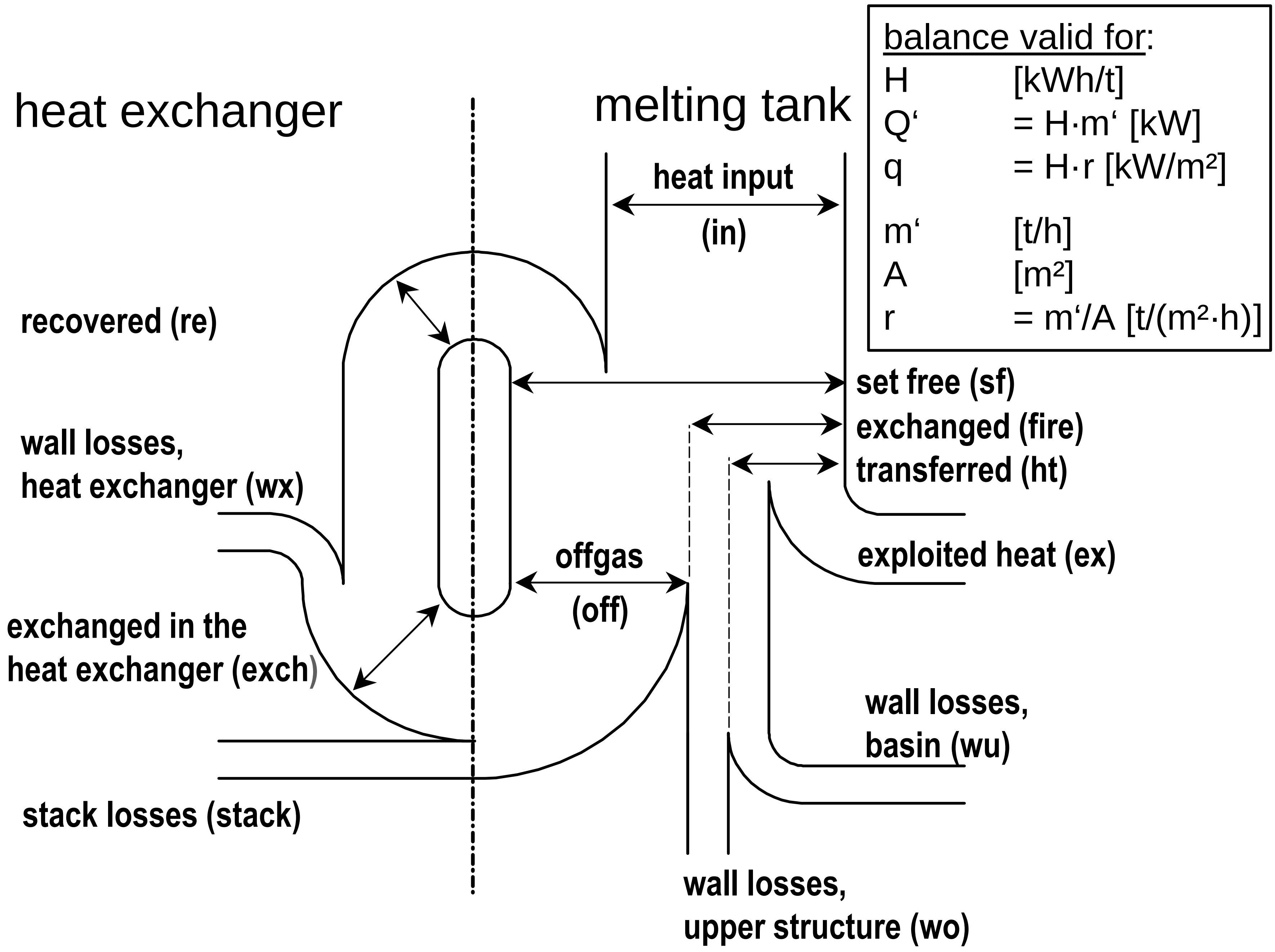
$$Q_{12} = \Delta H = H_2 - H_1$$

two types of heat:

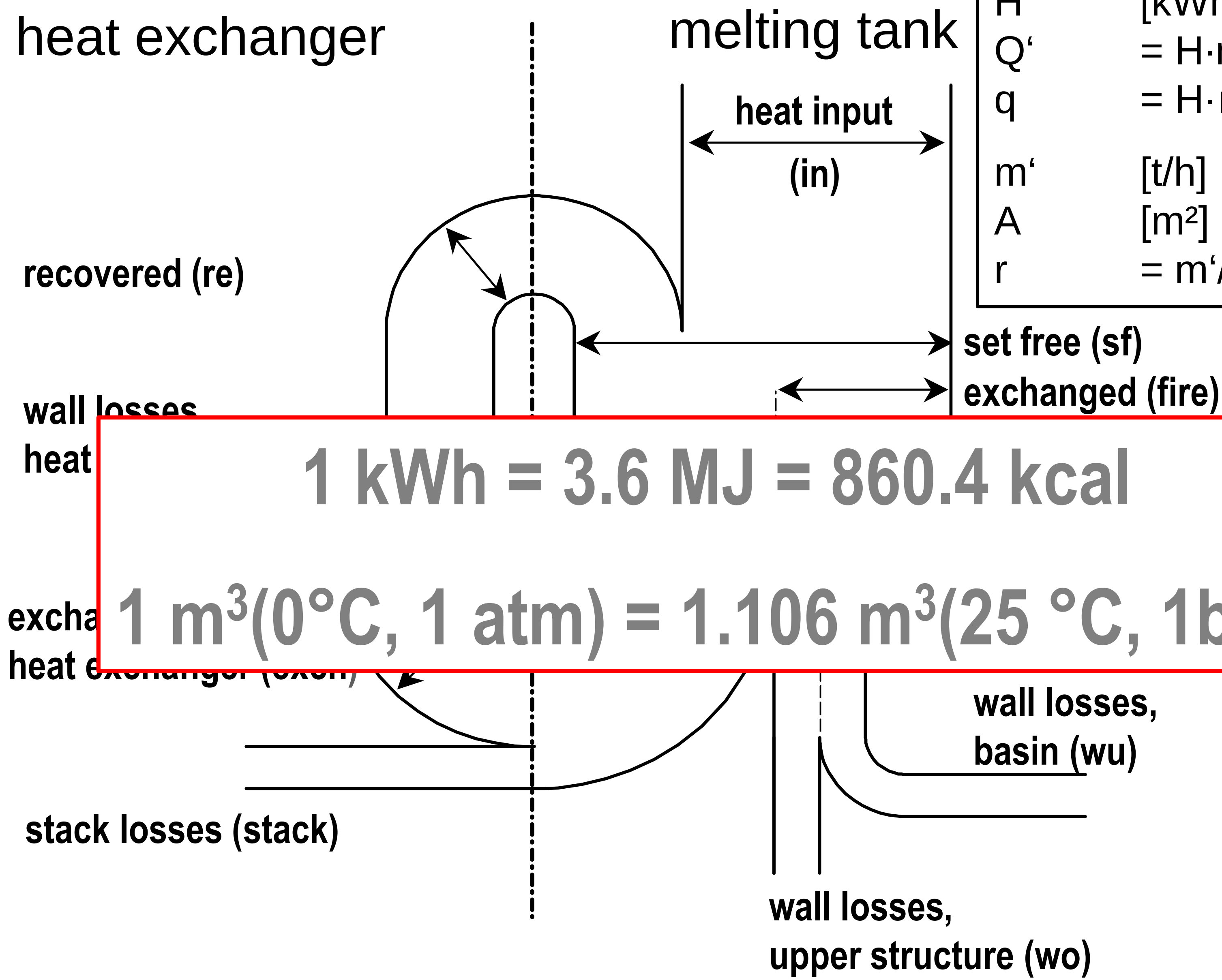
$$Q_r = H^{\circ}_{products} - H^{\circ}_{educts} \Big| T = 25°C$$

$$Q_T = H_{products}(T_2) - H_{products}(T_1)$$

$$Q_r + Q_T = H_{ex}$$



heat exchanger
melting tank
balance valid for:
H [kWh/t]
Q‘ = H·m‘ [kW]
q = H·r [kW/m²]
m‘ [t/h]
A [m²]
r = m‘/A [t/(m²·h)]
heat input
(in)
recovered (re)
set free (sf)
exchanged (fire)
transferred (ht)
wall losses,
heat exchanger (wx)
exploited heat (ex)
offgas
(off)
exchanged in the
heat exchanger (exch)
wall losses,
basin (wu)
stack losses (stack)
wall losses,
upper structure (wo)

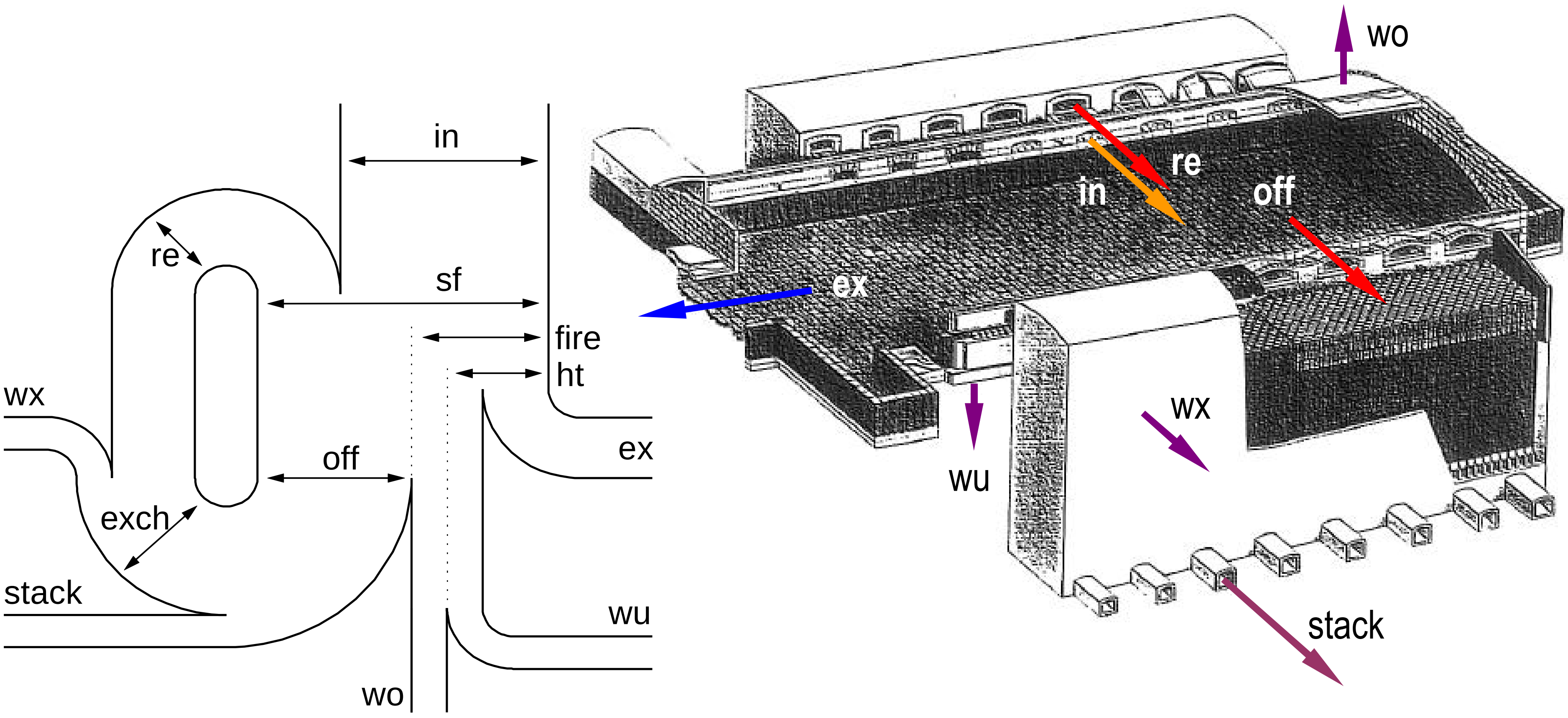


balance valid for:

H	[kWh/t]
Q‘	$= H \cdot m‘$ [kW]
q	$= H \cdot r$ [kW/m²]
m‘	[t/h]
A	[m²]
r	$= m‘/A$ [t/(m²·h)]

1 kWh = 3.6 MJ = 860.4 kcal

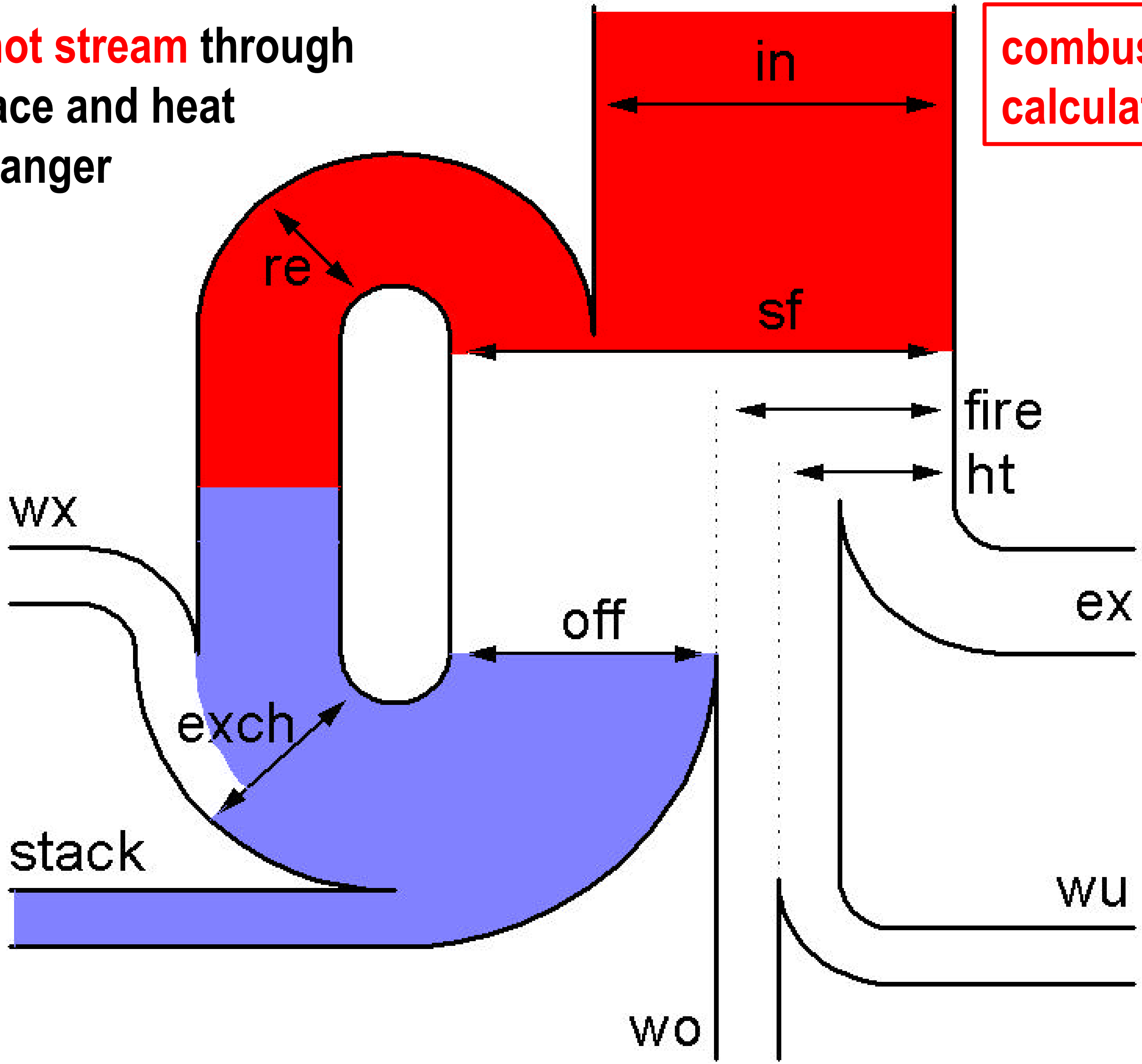
1 m^3(0°C, 1 atm) = 1.106 m^3(25 °C, 1bar)



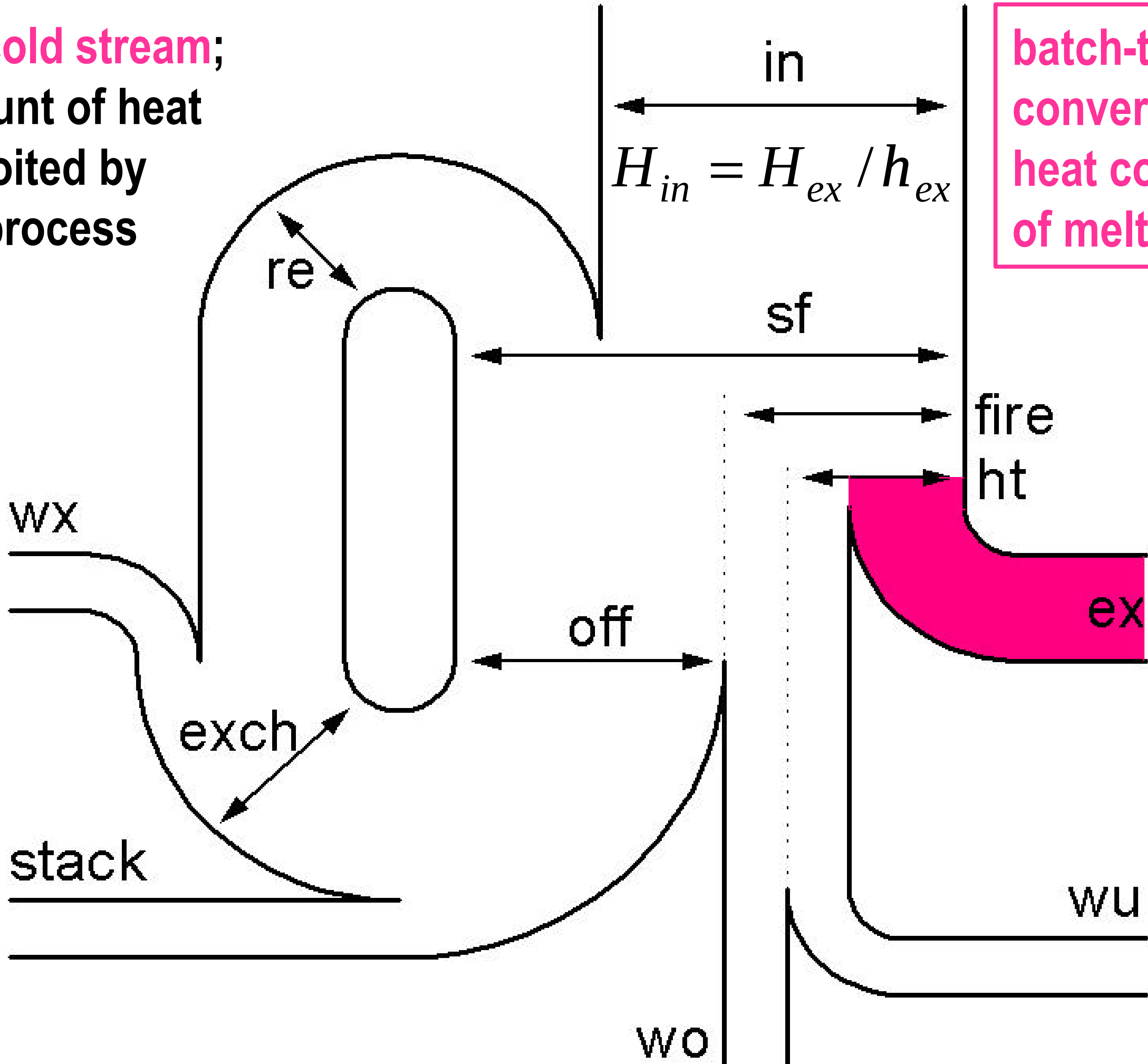
in
re
sf
fire
ht
wx
off
ex
exch
stack
wu
wo
wo
re
in
off
ex
wu
wx
stack

the hot stream through furnace and heat exchanger

combustion calculations

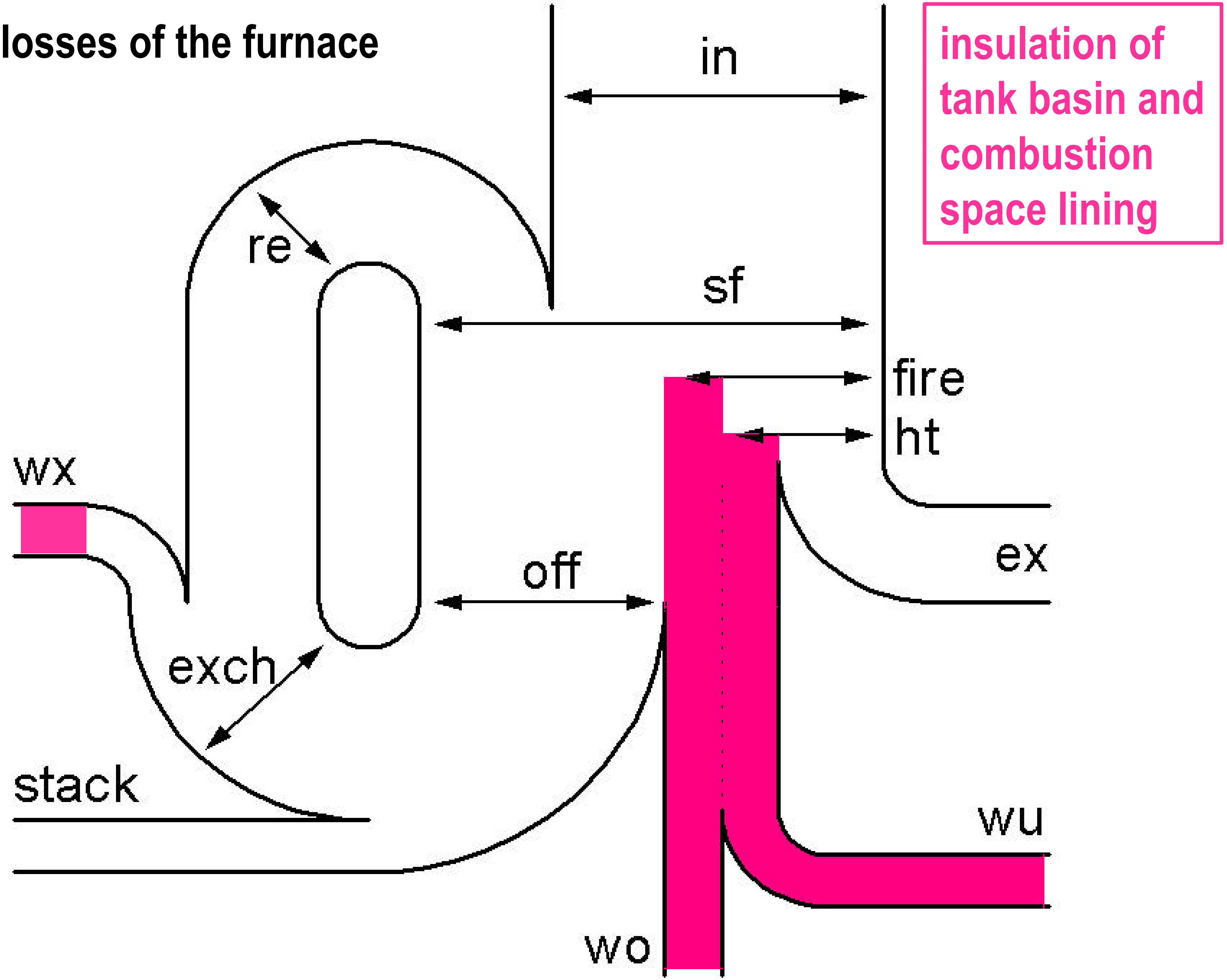


the cold stream; amount of heat exploited by the process

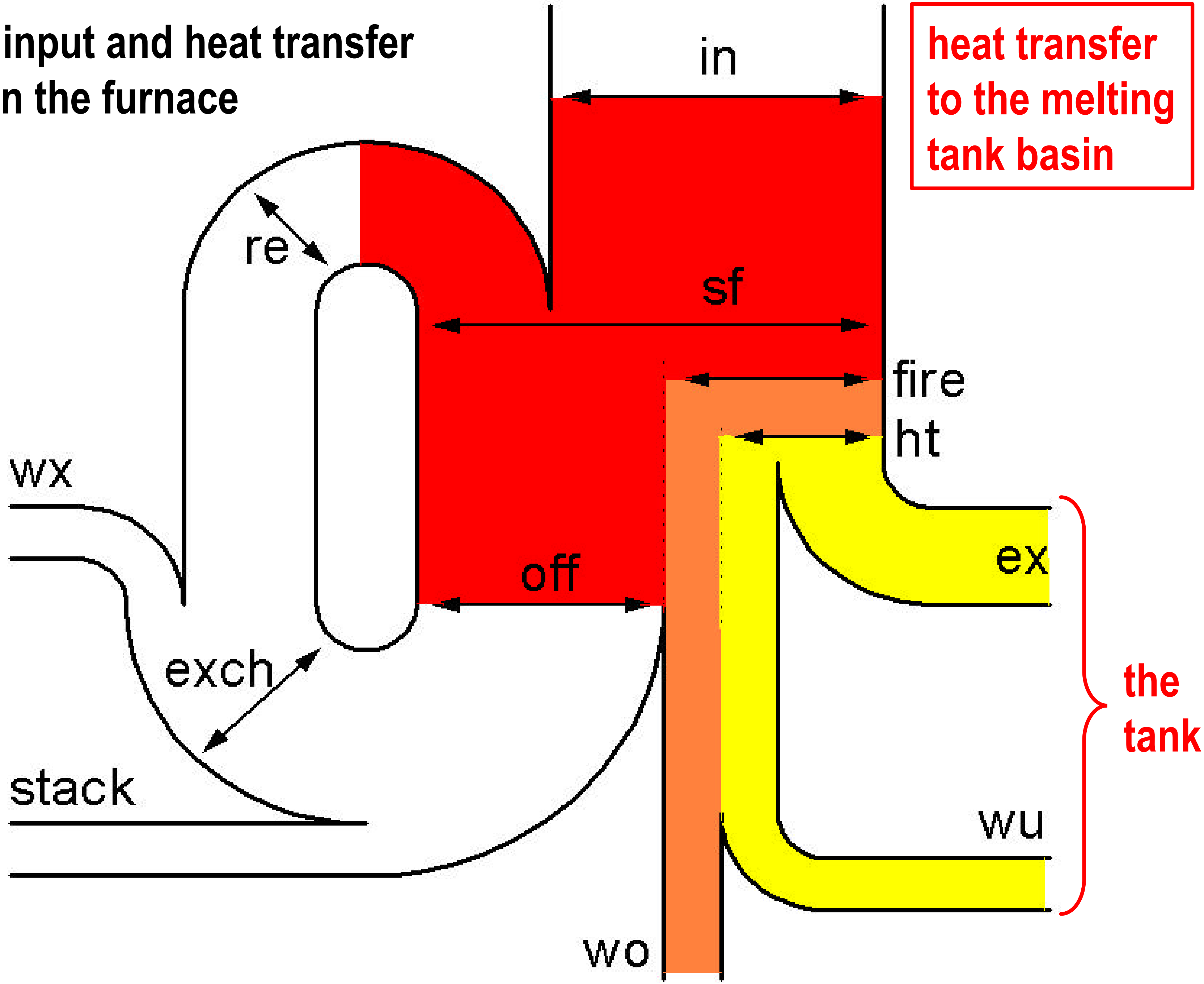


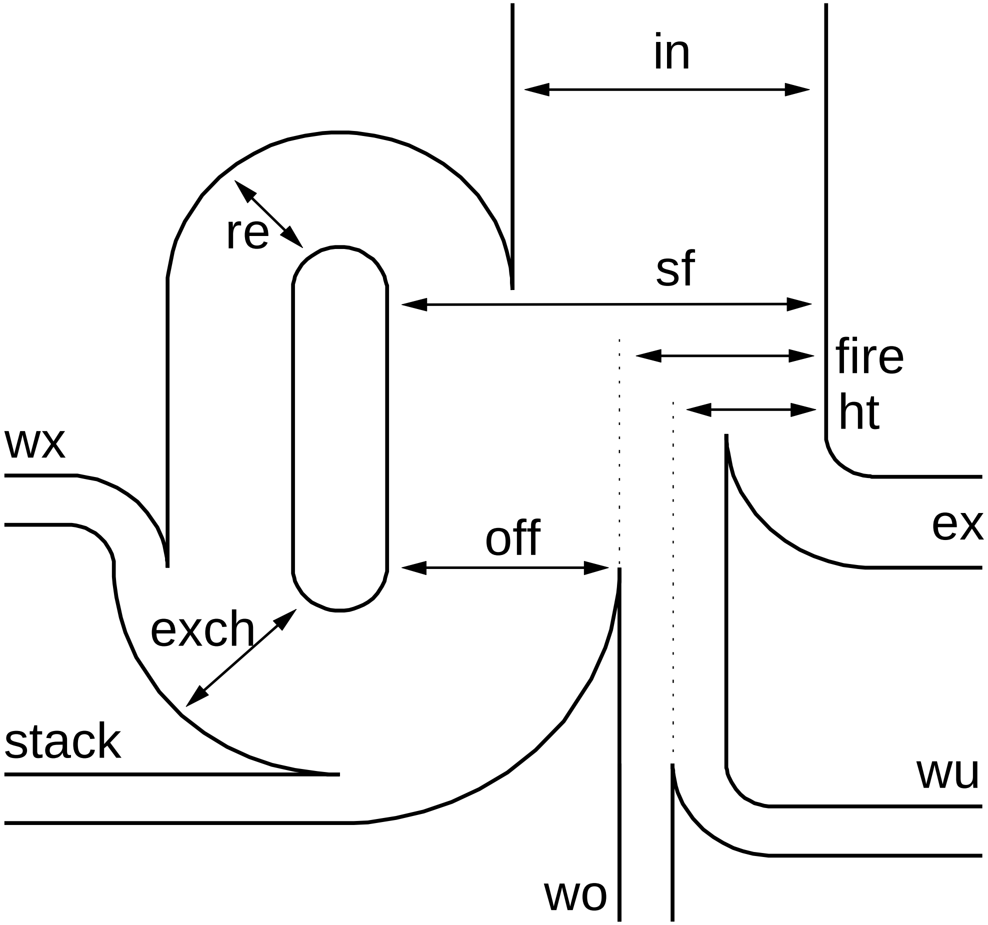
batch-to-melt conversion; heat content of melt

wall losses of the furnace



heat input and heat transfer within the furnace





$$H_{sf} = H_{in} + H_{re} = H_{off} + H_{ex} + H_{wo} + H_{wu}$$

$$H_{fire} = H_{sf} - H_{off} = H_{ex} + H_{wo} + H_{wu}$$

$$H_{ht} = H_{ex} + H_{wu}$$

$$H_{off} = H_{stack} + H_{re} + H_{wx}$$

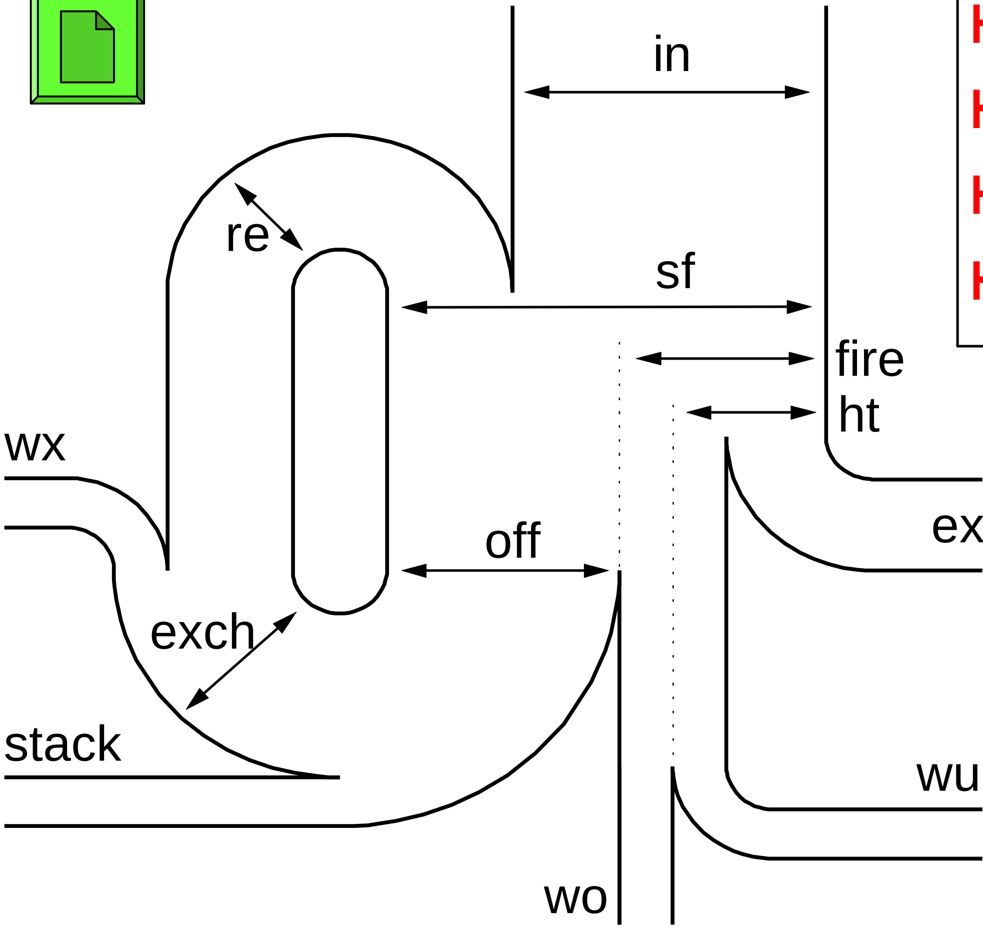
$$H_{exch} = H_{off} - H_{stack} = H_{re} + H_{wx}$$

$H_{in} = V(fuel) \cdot H_{NCV}$

$H_{re} = C_P(air) \cdot V(air) \cdot (T_{re} - 25\ °C)$

$H_{off} = C_P(off) \cdot V(off) \cdot (T_{off} - 25\ °C)$

$H_{stack} = C_P(off) \cdot V(off) \cdot (T_{stack} - 25\ °C)$



$H_{sf} = H_{in} + H_{re} = H_{off} + H_{ex} + H_{wo} + H_{wu}$

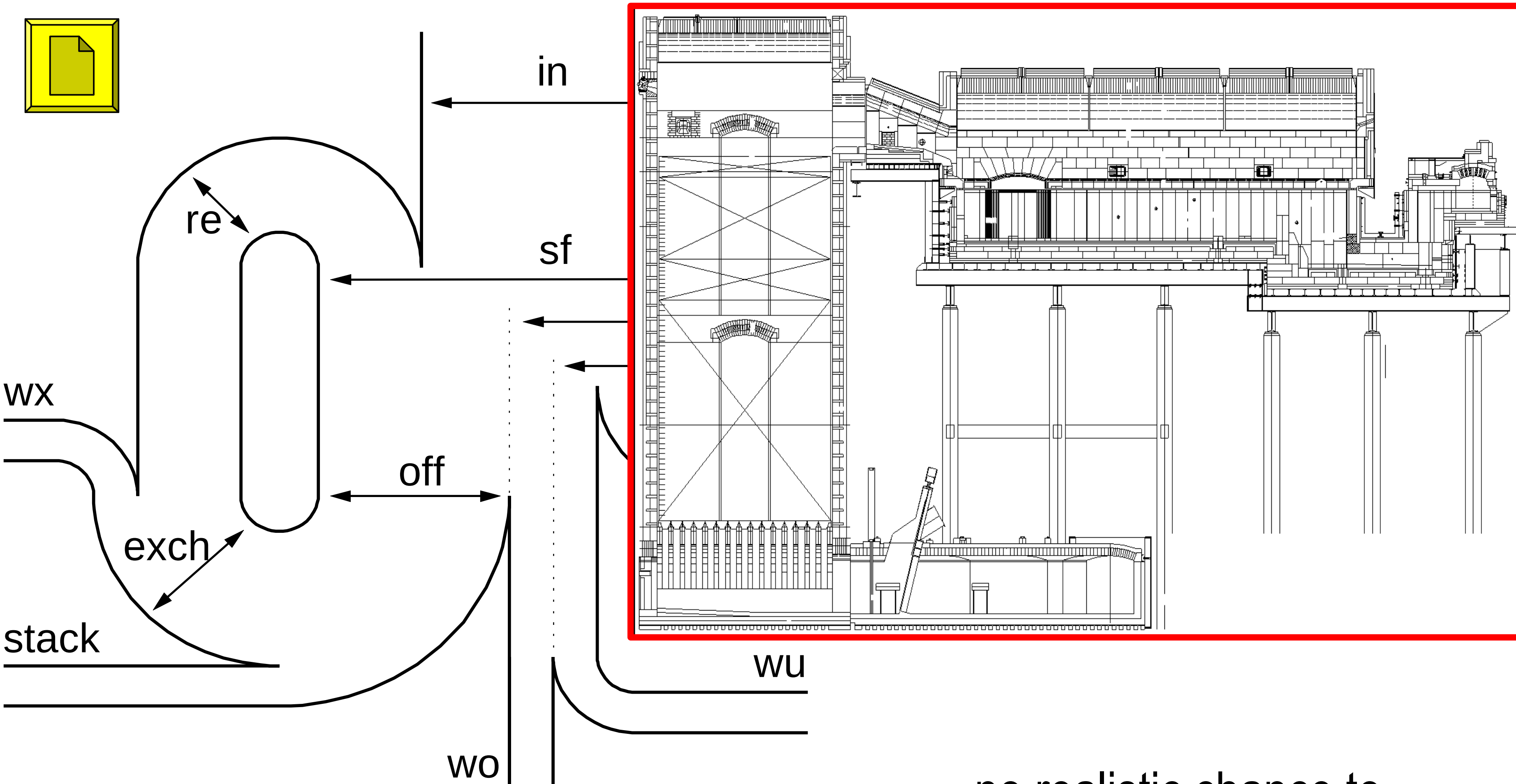
$H_{fire} = H_{sf} - H_{off} = H_{ex} + H_{wo} + H_{wu}$

$H_{ht} = H_{ex} + H_{wu}$

$H_{off} = H_{stack} + H_{re} + H_{wx}$

$H_{exch} = H_{off} - H_{stack} = H_{re} + H_{wx}$

good chance to determine H_{in}, H_{re}, H_{off}, H_{stac} via combustion calculations, and H_{sf}, H_{fire}, H_{wx}, H_{exch} by difference



$$H_{sf} = H_{in} + H_{re} = H_{off} + H_{ex} + H_{wo} + H_{wu}$$

$$H_{fire} = H_{sf} - H_{off} = H_{ex} + H_{wo} + H_{wu}$$

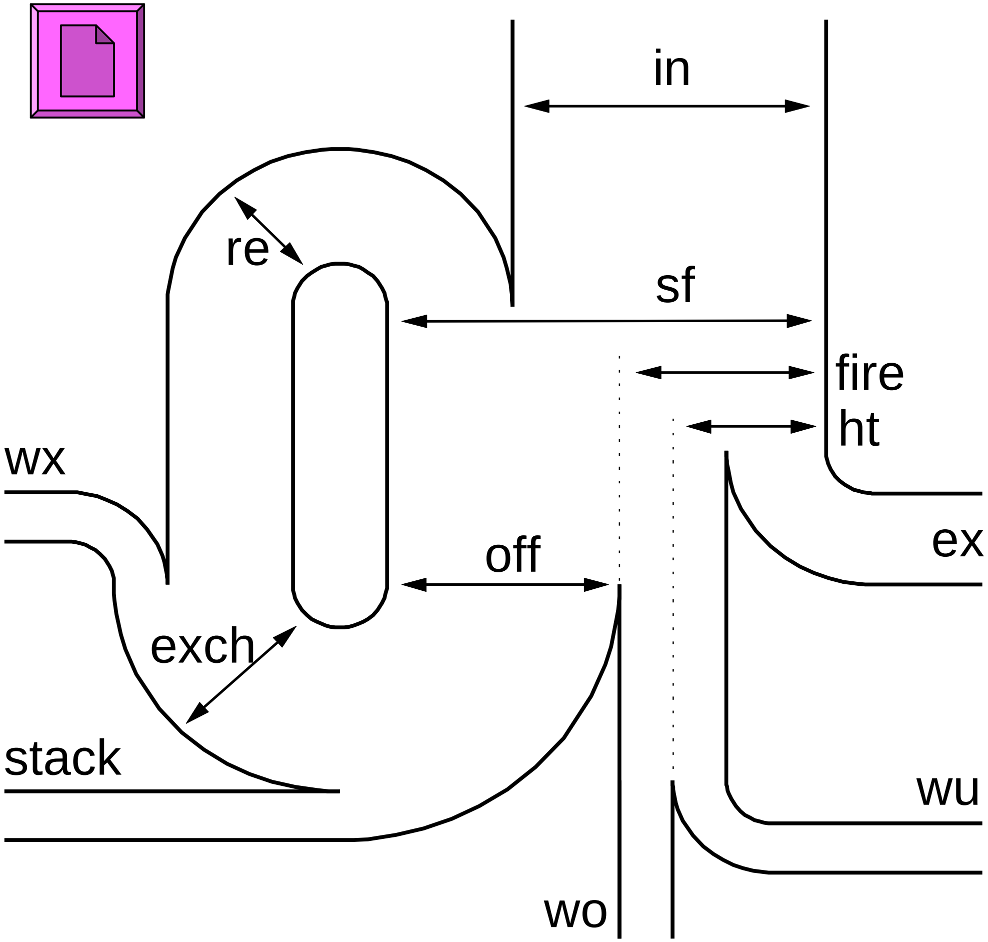
$$H_{ht} = H_{ex} + H_{wu}$$

$$H_{off} = H_{stack} + H_{re} + H_{wx}$$

$$H_{exch} = H_{off} - H_{stack} = H_{re} + H_{wx}$$

no realistic chance to determine H_{wo}, H_{wu}

H_{ex}



$H_{sf} = H_{in} + H_{re} = H_{off} + H_{ex} + H_{wo} + H_{wu}$

$H_{fire} = H_{sf} - H_{off} = H_{ex} + H_{wo} + H_{wu}$

$H_{ht} = H_{ex} + H_{wu}$ ← for the 2nd part, remember this line!

$H_{off} = H_{stack} + H_{re} + H_{wx}$

$H_{exch} = H_{off} - H_{stack} = H_{re} + H_{wx}$

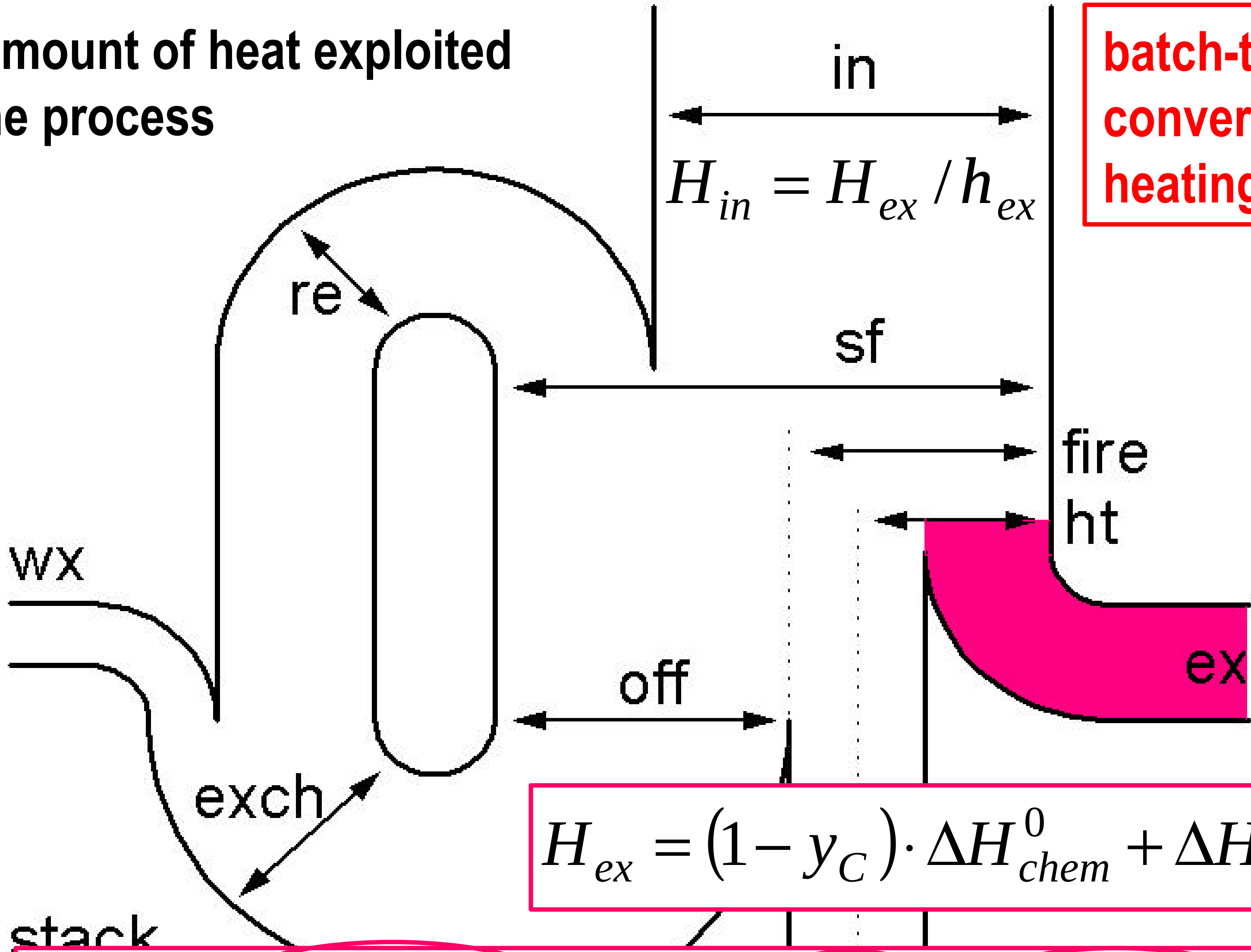
let us focus on the determination of H_{ex}

excursion H_{ex}

the glass
&
the melt

the amount of heat exploited by the process

batch-to-melt conversion and heating to T_{ex}



$$H_{in} = H_{ex} / h_{ex}$$

$$H_{ex} = (1 - y_C) \cdot \Delta H^0_{chem} + \Delta H(T) \Big|_{T_0}^{T_{ex}}$$

DH°$_{chem}$: raw materials (25 °C) ® glass + batch gases (25 °C)

DH(T): glass (25 °C) ® glass melt(T)

$$H^{\circ}_{glass} = \sum_k n_k \cdot (H^{\circ}_k + H^{vit}_k)$$

$$H^{\circ}_{1673,liq} = \sum_k n_k \cdot H^{\circ}_{1673,liq,k}$$

$$c_{P,liq} = \sum_k n_k \cdot c_{P,liq,k}$$

$$H_{T,liq} = H^{\circ}_{1673,liq} + c_{P,liq} \cdot (T - 1673)$$

$$\Delta H_{T,liq} = H_{T,liq} - H^{\circ}_{glass}$$

k for the soda-lime based mass glasses

$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$	=	$5.1440 \cdot Al_2O_3 - 5.5697 \cdot K_2O$
$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	=	$5.9102 \cdot K_2O$
$FeO \cdot Fe_2O_3$	=	$0.6 \cdot Fe_2O_3$
$Feo \cdot SiO_2$	=	$0.7345 \cdot Fe_2O_3$
$Mgo \cdot SiO_2$	=	$2.4907 \cdot MgO$
$Na_2O \cdot 3CaO \cdot 6SiO_2$	=	$3.5112 \cdot CaO$
$Na_2O \cdot 2SiO_2$	=	$2.9386 \cdot Na_2O + 1.9346 \cdot K_2O - 1.7867 \cdot Al_2O_3 - 1.0824 \cdot CaO$
SiO_2	=	rest to the total mass.

oxide amounts in wt. %

Table 1. Thermodynamic data of compounds k employed to represent the crystalline reference systems (c.r.s.) of industrial glasses; enthalpies H in kJ/mol, entropies S and heat capacities c_P in J/(mol·K); superscripts: ° = standard state at 298.15 K, 1 bar; ^{vit} = vitrification; subscripts: $_{liq}$ = liquid state; $_{1673}$ = 1673.15 K

k	$-H°$	$S°$	H^{vit}	S^{vit}	$-H_{1673,liq}$	$S_{1673,liq}$	$c_{P,liq}$
$P_2O_5·3CaO$	4117.1	236.0	135.1	51.5	3417.1	898.7	324.3
P_2O_5	1504.9	114.4	18.2	9.5	1151.5	586.6	181.6
Fe_2O_3	823.4	87.4	45.2	17.2	550.2	370.3	142.3
$FeO·Fe_2O_3$	1108.8	151.0	82.8	31.4	677.8	579.9	213.4
$FeO·SiO_2$	1196.2	92.8	36.7	13.8	962.3	342.7	139.7
$2FeO·SiO_2$	1471.1	145.2	55.2	20.5	1118.8	512.1	240.6
$MnO·SiO_2$	1320.9	102.5	40.2	15.1	1085.3	345.2	151.5
$2ZnO·SiO_2$	1643.1	131.4	82.4	31.4	1261.1	494.5	174.5
$ZrO_2·SiO_2$	2034.7	84.5	86.6	32.6	1686.2	381.2	149.4
$CaO·TiO_2$	1660.6	93.7	67.4	25.5	1365.7	360.2	124.7
TiO_2	938.7	49.9	44.8	10.5	766.0	200.7	87.9

k	-H°	S°	H^{vit}	S^{vit}	$-H_{1673,liq}$	$S_{1673,liq}$	$c_{P,liq}$
$BaO \cdot Al_2O_3 \cdot 2SiO_2$	4222.1	236.8	130.5	95.4	3454.3	1198.3	473.2
$BaO \cdot 2SiO_2$	2553.1	154.0	81.6	26.8	2171.1	533.5	241.4
$BaO \cdot SiO_2$	1618.0	104.6	56.5	41.0	1349.8	361.1	146.4
$Li_2O \cdot Al_2O_3 \cdot 4SiO_2$	6036.7	308.8	184.1	12.1	5235.4	1173.2	498.7
$Li_2O \cdot SiO_2$	1648.5	79.9	16.7	6.3	1416.7	339.7	167.4
$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	7914.0	439.3	106.3	29.3	6924.9	1559.4	765.7
$K_2O \cdot Al_2O_3 \cdot 2SiO_2$	4217.1	266.1	80.4	22.1	3903.7	666.5	517.6
$K_2O \cdot 4SiO_2$	4315.8	265.7	26.4	21.3	3697.8	983.7	410.0
$K_2O \cdot 2SiO_2$	2508.7	190.6	12.6	23.9	2153.1	595.4	275.3
$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$	7841.2	420.1	125.0	28.4	6870.1	1512.5	648.1
$Na_2O \cdot Al_2O_3 \cdot 2SiO_2$	4163.5	248.5	92.0	27.9	3614.1	856.9	423.8
B_2O_3	1273.5	54.0	18.2	11.3	1088.7	271.1	129.7
$Na_2O \cdot B_2O_3 \cdot 4SiO_2$	5710.9	270.0	42.7	21.1	4988.0	1090.2	637.6
$Na_2O \cdot 4B_2O_3$	5902.8	276.1	58.3	40.1	4986.7	1275.5	704.2
$Na_2O \cdot 2B_2O_3$	3284.9	189.5	48.8	26.6	2735.9	780.3	444.8
$Na_2O \cdot B_2O_3$	1958.1	147.1	43.6	19.5	1585.7	538.7	292.9

k	$-H°$	$S°$	H^{vit}	S^{vit}	$-H_{1673,liq}$	$S_{1673,liq}$	$c_{P,liq}$
$2MgO\cdot 2Al_2O_3\cdot 5SiO_2$	9113.2	407.1	135.8	41.4	7994.8	1606.2	1031.8
$MgO\cdot SiO_2$	1548.5	67.8	46.6	13.6	1318.0	296.2	146.4
$2MgO\cdot SiO_2$	2176.9	95.4	61.4	11.0	1876.1	402.9	205.0
$CaO\cdot MgO\cdot 2SiO_2$	3202.4	143.1	92.3	25.7	2733.4	621.7	355.6
$2CaO\cdot MgO\cdot 2SiO_2$	3876.9	209.2	106.7	32.0	3319.2	775.3	426.8
$CaO\cdot Al_2O_3\cdot 2SiO_2$	4223.7	202.5	103.0	37.7	3628.8	791.2	380.7
$2CaO\cdot Al_2O_3\cdot SiO_2$	3989.4	198.3	129.9	49.4	3374.0	787.8	299.2
$3Al_2O_3\cdot 2SiO_2$	6820.8	274.9	188.3	71.5	5816.2	1231.8	523.4
$CaO\cdot SiO_2$	1635.1	83.1	49.8	18.8	1382.0	329.7	146.4
$2CaO\cdot SiO_2$	2328.4	120.5	101.3	38.5	1868.2	509.2	174.5
$Na_2O\cdot 2SiO_2$	2473.6	164.4	29.3	13.2	2102.5	588.7	261.1
$Na_2O\cdot SiO_2$	1563.1	113.8	37.7	9.8	1288.3	415.1	179.1
$Na_2O\cdot 3CaO\cdot 6SiO_2$	8363.8	461.9	77.3	20.5	7372.6	1555.6	786.6
$Na_2O\cdot 2CaO\cdot 3SiO_2$	4883.6	277.8	57.7	13.4	4240.9	990.4	470.3
$2Na_2O\cdot CaO\cdot 3SiO_2$	4763.0	309.6	87.0	22.6	4029.6	1107.9	501.2
SiO_2	908.3	43.5	6.9	4.0	809.6	157.3	86.2

(1) Take the glass composition in wt. %..

(2) Calculate the glass composition in n(j) = mol per 1 kg of glass:
$n(j) = 10 \times \text{wt. \%}(j) \times M(j)$

(3) Find the compounds k.

(4) Calculate the mass of k.

(5) Sum up to get H^o(glass) and H_T(melt).

the raw materials

sand and feldspar at 25° C

H° in MJ/kg; oxide amounts in wt. %

$$
\begin{aligned}
-H^\circ = \; & 15.174 \cdot SiO_2 + 17.100 \cdot Al_2O_3 + 4.633 \cdot Fe_2O_3 \\
& + 15.030 \cdot MgO \\
& + 12.035 \cdot CaO \\
& + 10.52 \cdot Na_2O + 7.639 \cdot K_2O
\end{aligned}
$$

dolomite and limestone

$Ca_{1+x}(Fe_{(1-x)\cdot y}Mg_{(1-x)\cdot(1-y)})(CO_3)_2$

$x = 1 \quad\quad \Rightarrow \quad Ca_2(CO_3)_2$

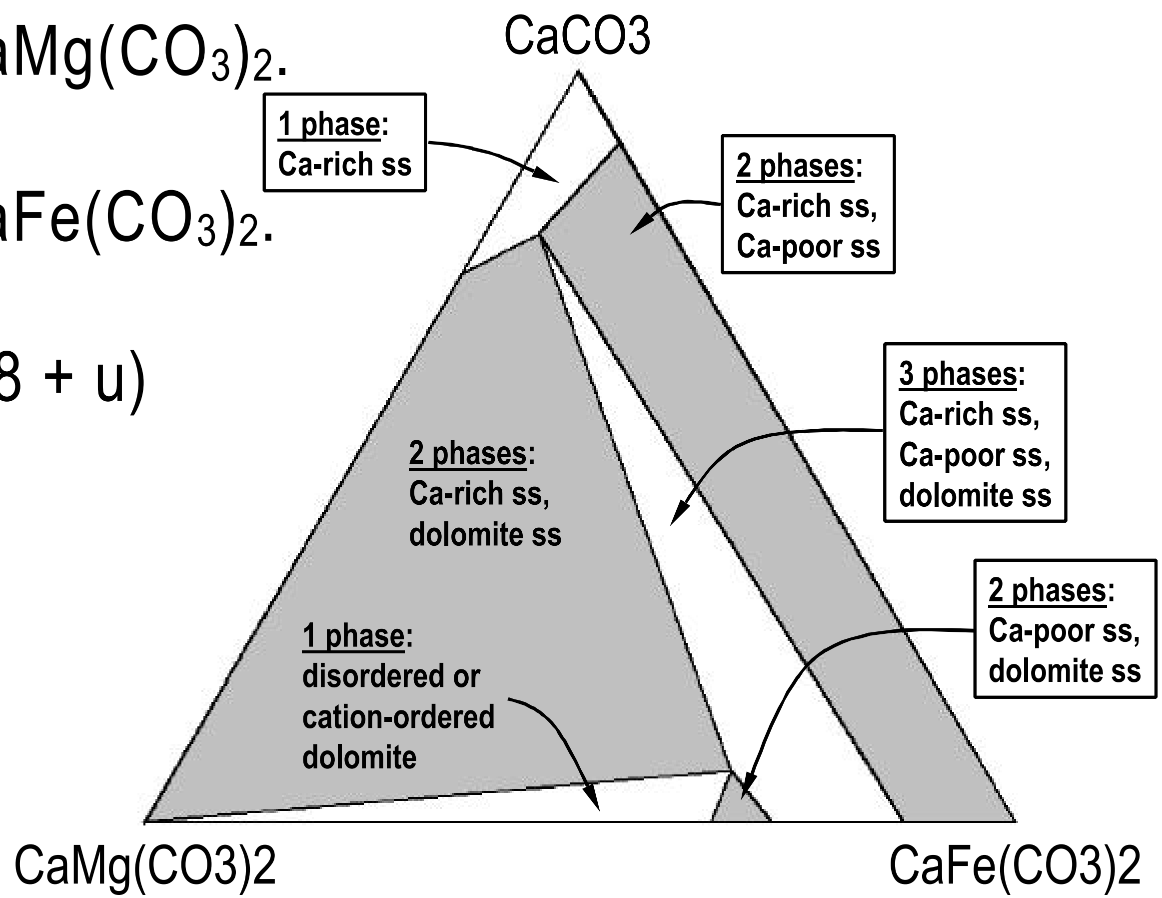
$x = 0 \begin{cases} y = 0 \Rightarrow & CaMg(CO_3)_2. \\ y = 1 \Rightarrow & CaFe(CO_3)_2. \end{cases}$

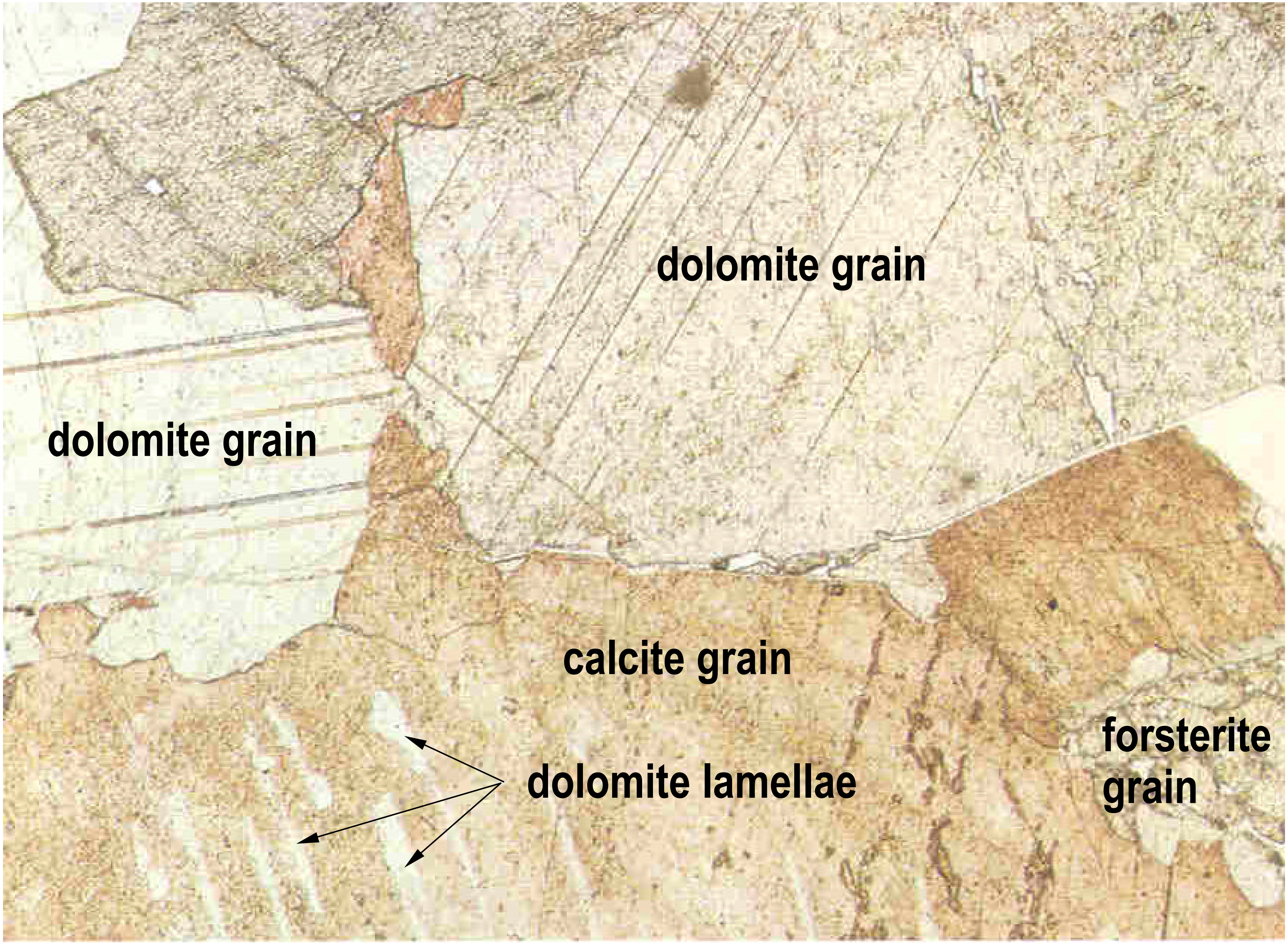
$x = (0.7188 - u)/(0.7188 + u)$

$u = Fe / Mg$

$y = v/(1.7832 + v)$

$v = Mg / Ca$




dolomite grain
dolomite grain
calcite grain
dolomite lamellae
forsterite grain

dolomite and limestone at 25° C

$$H^{o}_{dolomite} = \frac{-2413.8 - 9.97 \cdot (1 - x)}{184.411 + 15.768 \cdot x + 31.535 \cdot y \cdot (1 - x)}$$

$$H^{o}_{limestone} = \frac{-2314.2 + 129.4 \cdot x + 74.0 \cdot y}{184.411 + 15.768 \cdot x + 31.535 \cdot y \cdot (1 - x)}$$

H° in MJ/kg; x, y, as calculated before

chemical grade raw materials at 25° C

		– H° in MJ/kg
sulfate	Na_2SO_4	9.783
Chili saltpeter	$NaNO_3$	5.509
coal	C	0.000
soda ash	Na_2CO_3	10.659
potash	K_2CO_3	8.343
	$BaCO_3$	6.169
	PbO	0.983
	Pb_3O_4	1.048

the batch gases

batch gases at 25° C

	– H° in MJ/kg
CO_2	2.482
H_2O	3.728
O_2	0.000
N_2	0.000
SO_2	1.287

$\Delta H_T(gl) = C_P(gl) \cdot (T_{ex} - 25\ °C)$

$C_P(gl)$ in kWh/(t·K) $= 1.163 \cdot (T \cdot \Sigma A_j \cdot y_j + \Sigma C_j \cdot y_j)/(1 + 1.46 \cdot T)$

oxide j	A_j	C_j		oxide j	A_j	C_j
SiO_2	0.468	0.1657		MnO	0.294	0.1498
Al_2O_3	0.453	0.1765		ZnO	0.486	0.2020
B_2O_3	0.598	0.1935		PbO	0.013	0.0490
Fe_2O_3	0.380	0.1449		Li_2O	1.183	0.2665
MgO	0.514	0.2142		Na_2O	0.829	0.2992
CaO	0.410	0.1707		K_2O	0.455	0.1756
BaO	0.300	0.1251		SO_3	0.830	0.1890

practice

#GLASS.xls

#SAND & FELDSPAR.xls

#DOLOMITE & LIMESTONE.xls

#SODA & BORATES & KAOLIN.xls

#BATCH-TO-MELT CONVERSION.xls

excursion

combustion

fuels, air demand, offgas volume

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2} \right) \cdot O_2 = x \cdot CO_2 + \frac{y}{2} \cdot H_2O$$

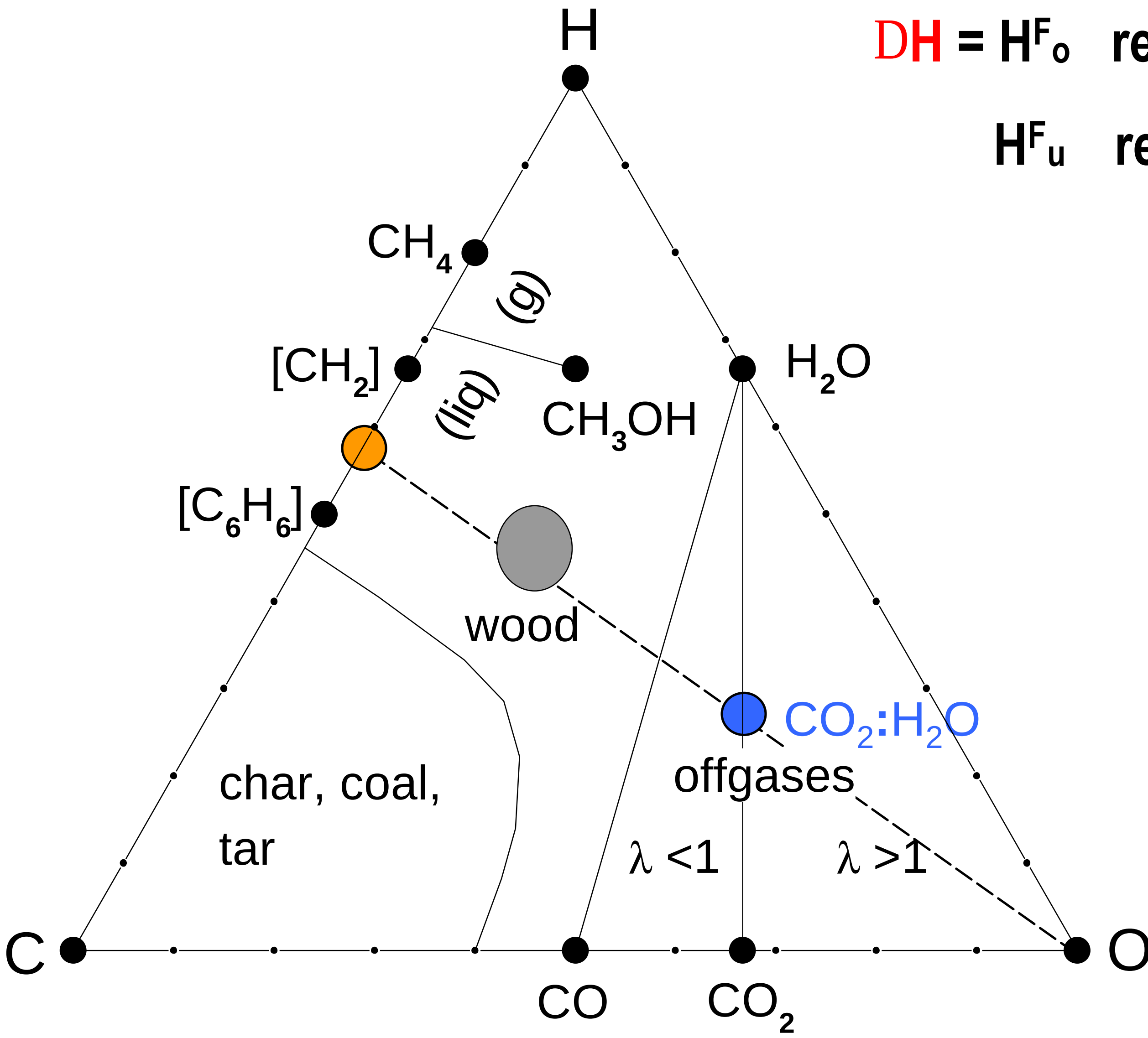
fuels

DH

$C_xH_yO_z + ¼·(4·x + y - 2·z)\ O_2$ ® $x·CO_2 + 1/2·y·H_2O$

DH = $H^F{}_o$ referred to H_2O(liq),

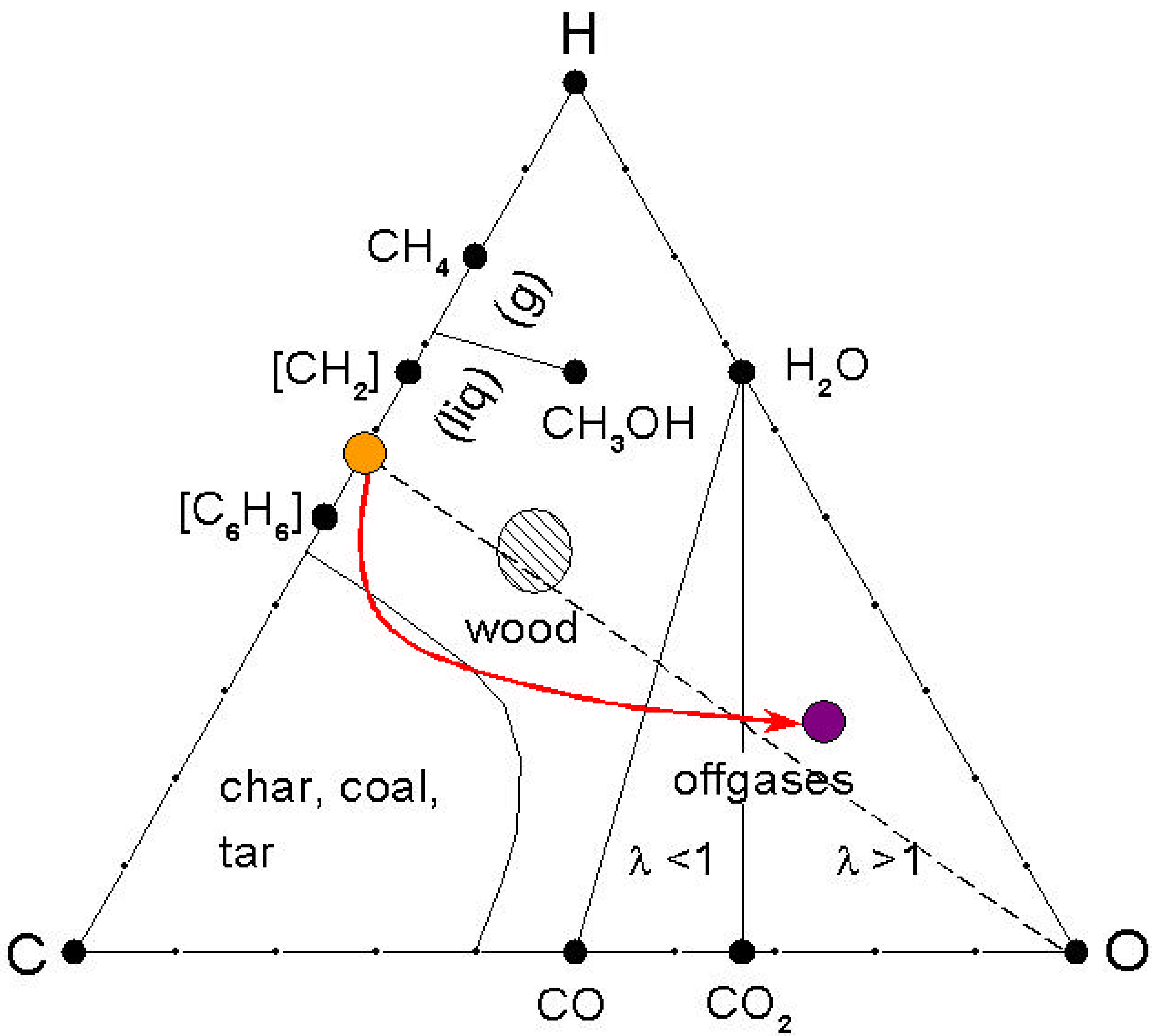
$H^F{}_u$ referred to H_2O(gas)



fuels

DH

$C_xH_yO_z + \frac{1}{4}\cdot(4\cdot x + y - 2\cdot z)\ O_2$ ® $x\cdot CO_2 + 1/2\cdot y\cdot H_2O$



$V^F(air)$, $V^F(off)$ in m^3_{NTP} **per m^3 fuel**

density d in kg/m³

$V^F(air)$, $V^F(off)$ in m^3_{NTP} **per kg fuel**

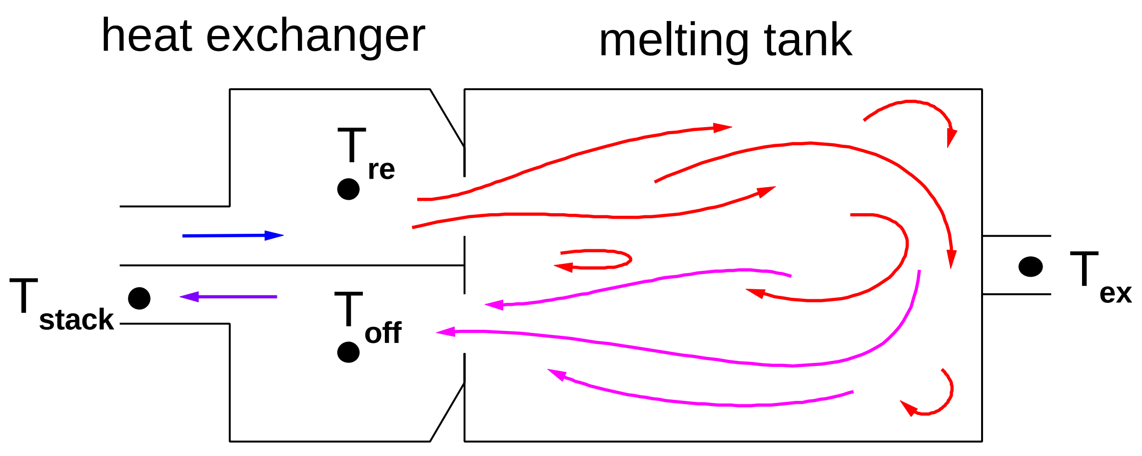
m_F = fuel demand in kg per t glass

$V(air)$, $V(off)$ in m^3_{NTP} **per t glass**

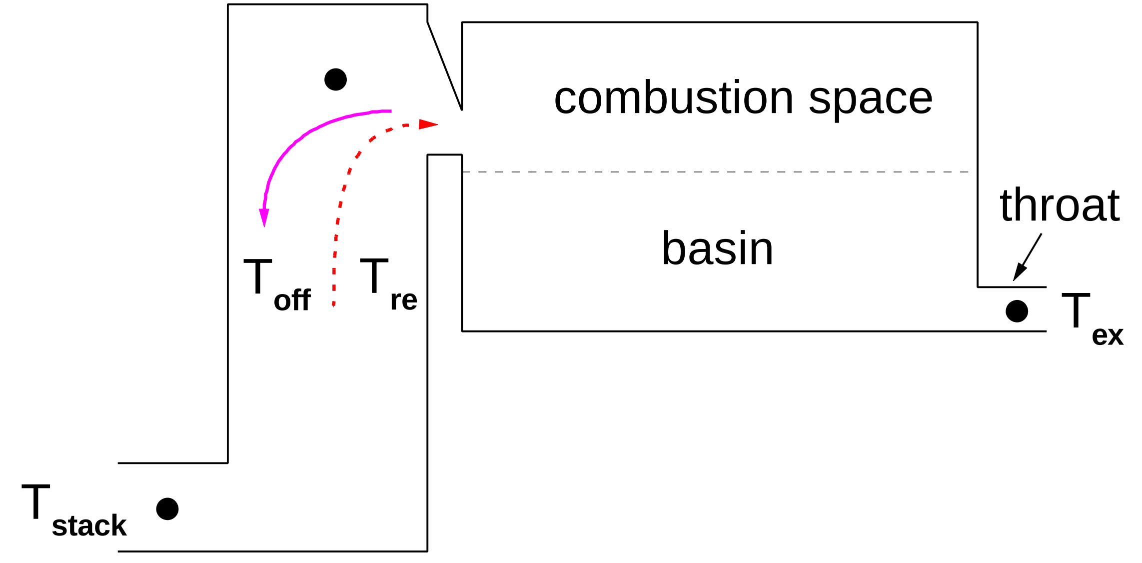
$$V(air) = m_F \cdot V^F(air)$$

$$V(off) = m_F \cdot V^F(off)$$

horizontal projection



vertical projection (longitudinal axis)



composition of different fuels:

gas:

volume fractions of all species C_xH_y and CO_2, N_2 are provided by the supplier

$$\Rightarrow \quad \text{Vol. \% } C_xH_y$$

oil:

wt. fractions of elements C, H, O, S are provided by the supplier; conversion to $[CH_2]$ und C_6H_6 required:

$$\Rightarrow \quad m_{CH2} = -1.1678 \cdot m_C + 13.916 \cdot m_H$$

$$m_{C6H6} = 2.1678 \cdot m_C - 12.916 \cdot m_H$$

coal:

wt. fractions of elements C, H, O, S and humidity are provided by the supplier

heat capacities of air and offgas:

C_P in $Wh/(m^3_{NTP} \cdot K) = S\, X_k \cdot v_k + (S\, Y_k \cdot v_k)\, T + (S\, Z_k \cdot v_k)/T^2$

calculation according to the actual gas composition					fast calculation			
k	X_k	Y_k	Z_k		k	X_k	Y_k	Z_k
O_2	0.3357	0.0468	-0.00187		air	0.3398	0.0323	-0.00249
N_2	0.3409	0.0285	-0.00266		gas-off	0.3546	0.0528	-0.00274
CO_2	0.4946	0.1013	-0.00957		oil-EL-off	0.3606	0.0499	-0.00318
H_2O	0.3362	0.1199	0.00037		oil-S-off	0.3609	0.0497	-0.00320

example: air at 1200 °C (1473 K) :

$$C_P = 0.3398 + 0.0323 \cdot 1.473 - 0.00249 \cdot 1.473^{-2}$$

$$= 0.382\ Wh/(m^3_{NTP} \cdot K)$$

c_P √

example CH_4

V^F

air: $0.21\ O_2 + 0.79\ N_2$ resp. $1\ O_2 + 3.76\ N_2$

$1\ CH_4 + 2\ O_2 + 7.52\ N_2 = 1\ CO_2 + 2\ H_2O + 7.52\ N_2$ | mol oder m^3

9.52 m^3 air

10.52 m^3 offgas wet

9.5 % CO_2
19.0 % H_2O
71.5 % N_2

8.52 m^3 offgas dry

air: $0.21\ O_2 + 0.79\ N_2$ resp. $1\ O_2 + 3.76\ N_2$

air excess $l = 1.08$

$$1\ CH_4 + l \cdot 2\ O_2 + l \cdot 7.52\ N_2 = 1\ CO_2 + 2\ H_2O + l \cdot 7.52\ N_2 + (l - 1)\ O_2$$

$7.52\ N_2 + (l - 1)$ air

$l \cdot 9.52 = 10.28\ m^3$ air

$10.52\ m^3 + (l - 1)$ air $= 11.28\ m^3$ offgas wet

8.9 % CO_2

17.7 % H_2O

72.0 % N_2

0.14 % O_2

batch gases V_b *[*m^3*/t glass]:*

V_b » $0.269\cdot dolo + 0.248\cdot lime$

$+ 0.234\cdot soda$ *[kg/t glass]*

» $0.6\cdot(m_{batch} - 1000)$

$V(air) = m_F\cdot l\cdot V^F(air)$

$V(off) = m_F\cdot(V^F(off) + (l\text{-}1)\, V°(air)) + V_b$

$$l = \frac{V^F(dry) + V_b / m_F}{V^F(air)} \cdot \frac{P_{O2}}{0.21 - P_{O2}}$$

density d_k at 298 K, partial NCV h_k and volumes of oxygen, air, and offgas components for fuel species from the system C-H-O-S

species k	d_k kg/m³	h_k kWh/kg	volumes V^F in m³NTP per kg species						
			air	off	dry	O_2	N_2	CO_2	H_2O
CO gas	1.130	2.81	2.11	2.55	2.55	0.44	1.66	0.88	0.00
H_2 gas	0.081	33.32	29.26	35.42	23.10	6.15	23.13	0.00	12.30
CH_4 gas	0.647	13.89	14.71	16.26	13.17	3.09	11.63	1.55	3.09
C_2H_6 gas	1.213	13.19	13.74	14.97	12.50	2.89	10.85	1.65	2.47
C_3H_8 gas	1.779	12.88	13.38	14.51	12.26	2.81	10.57	1.69	2.25
C_4H_{10} gas	2.345	12.70	13.20	14.26	12.13	2.77	10.43	1.71	2.13
C_5H_{12} gas	2.911	12.60	13.09	14.12	12.06	2,75	10.34	1.72	2.06
C_6H_{14} gas	3.477	12.53	13.01	14.02	12.00	2.73	10.28	1.73	2.01
C_5H_{12} liq	626.2	12.49	13.09	14.12	12.06	2.75	10.34	1.72	2.06
C_6H_{14} liq	659.4	12.43	13.01	14.02	12.00	2.73	10.28	1.73	2.01
$[CH_2]$ liq	780.0	12.14	12.62	13.51	11.74	2.65	9.97	1.77	1.77
C_6H_6 liq	873.7	11.15	11.33	11.81	10.86	2.38	8.95	1.90	0.95
S [1)] diss.	≈1920	2.57	3.68	3.68	3.68	0.77	2.91	0.00	0.00
C solid	≈1800	9.10	9.83	9.83	9.83	2.06	7.76	2.06	0.00

[1)] dissolved sulfur generates 0.77 m³ SO_2 per kg S

species k	d_k kg/m^3	h_k kWh/kg	volumes V^F in m^{3}NTP per kg of species						
			air	off	dry	O_2	N_2	CO_2	H_2O
generator gases									
CO gas	1.130	2.81	2.11	2.55	2.55	0.44	1.66	0.88	0.00
H_2 gas	0.081	33.32	29.26	35.42	23.10	6.15	23.13	0.00	12.30
mineral gases									
CH_4 gas	0.647	13.89	14.71	16.26	13.17	3.09	11.63	1.55	3.09
:	:	:	:	:	:	:	:	:	:
C_6H_{14} gas	3.477	12.53	13.01	14.02	12.00	2.73	10.28	1.73	2.01
mineral oils									
$[CH_2]$ liq	780.0	12.14	12.62	13.51	11.74	2.65	9.97	1.77	1.77
C_6H_6 liq	873.7	11.15	11.33	11.81	10.86	2.38	8.95	1.90	0.95

$$H^F_u = \Sigma\, x_k \cdot h_k \cdot d_k \qquad V^F(air) = \Sigma\, x_k \cdot d_k \cdot V_k(air)$$

$$V^F(off) = \Sigma\, x_k \cdot d_k \cdot V_k(off) \qquad V^F(dry) = \Sigma\, x_k \cdot d_k \cdot V_k(dry)$$

species	v_j %	d_j kg/m3	Hu_j kWh/kg	Ho_j kWh/kg	O_2 m3/kg	air m3/kg	off m3/kg	dry m3/kg
CH4	86.33	0.647	13.89	15.42	3.09	14.72	16.26	13.17
C2H6	5.73	1.213	13.19	14.41	2.89	13.74	14.98	12.50
C3H8	1.05	1.779	12.88	13.98	2.81	13.38	14.51	12.26
C4H10	0.43	2.345	12.70	13.75	2.77	13.20	14.27	12.13
C5H12	0.10	2.911	12.60	13.61	2.75	13.09	14.12	12.06
C6H14	0.07	3.477	12.53	13.52	2.73	13.01	14.02	12.01
N2	1.72	1.130	0	0	0	0	0.88	0.88
CO2	4.57	1.775	0	0	0	0	0.56	0.56

		$v_j \cdot d_j$			$v_j \cdot d_j \cdot Z_j$			
		kg·m3	kWh/m3	kWh/m3	m3/m3	m3/m3	m3/m3	m3/m3
CH4	86.33	0.559	7.76	8.61	1.73	8.22	9.09	7.36
C2H6	5.73	0.070	0.92	1.00	0.20	0.95	1.04	0.87
C3H8	1.05	0.019	0.24	0.26	0.05	0.25	0.27	0.23
C4H10	0.43	0.010	0.13	0.14	0.03	0.13	0.14	0.12
C5H12	0.10	0.003	0.04	0.04	0.01	0.04	0.04	0.04
C6H14	0.07	0.002	0.03	0.03	0.01	0.03	0.03	0.03
N2	1.72	0.019	0.00	0.00	0.00	0.00	0.02	0.02
CO2	4.57	0.081	0.00	0.00	0.00	0.00	0.05	0.05
S1	**100.00**	**0.763**	**9.11**	**10.09**	**2.02**	**9.63**	**10.68**	**8.71**
S2	**93.71**			**10.76**				

heat transfer,
adiabatic flame temperature

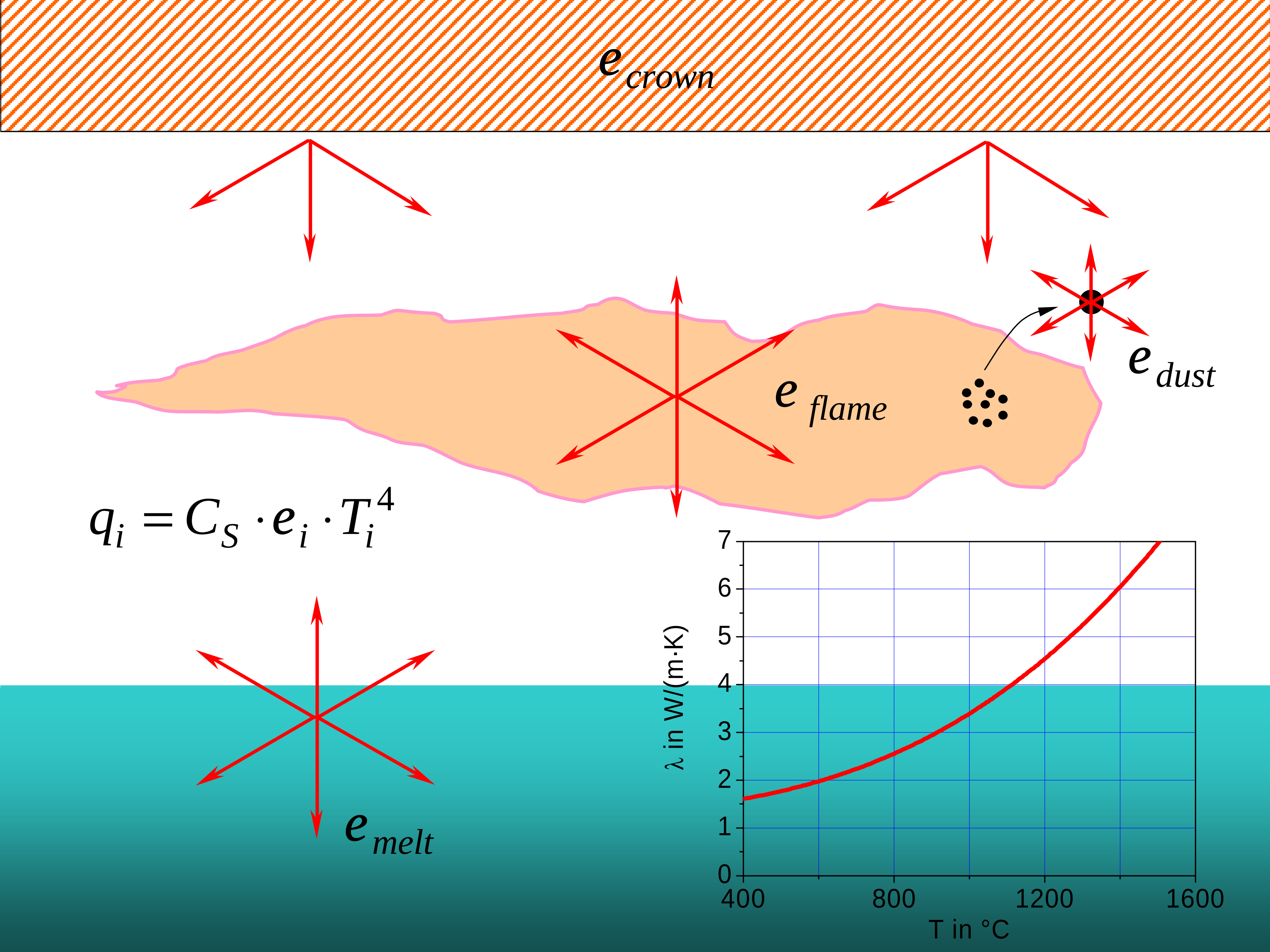
$$\frac{Q_{12}}{T} = \Delta S = S_2 - S_1$$

Heat Q is not „consumed“.
When transferre from T_H to T_L,
it is devaluated.

- *Heat can be transferred over any infinitesimally small temperature difference* $T_H - T_{L,}$.
- *The problem is the transfer rate achieved:*

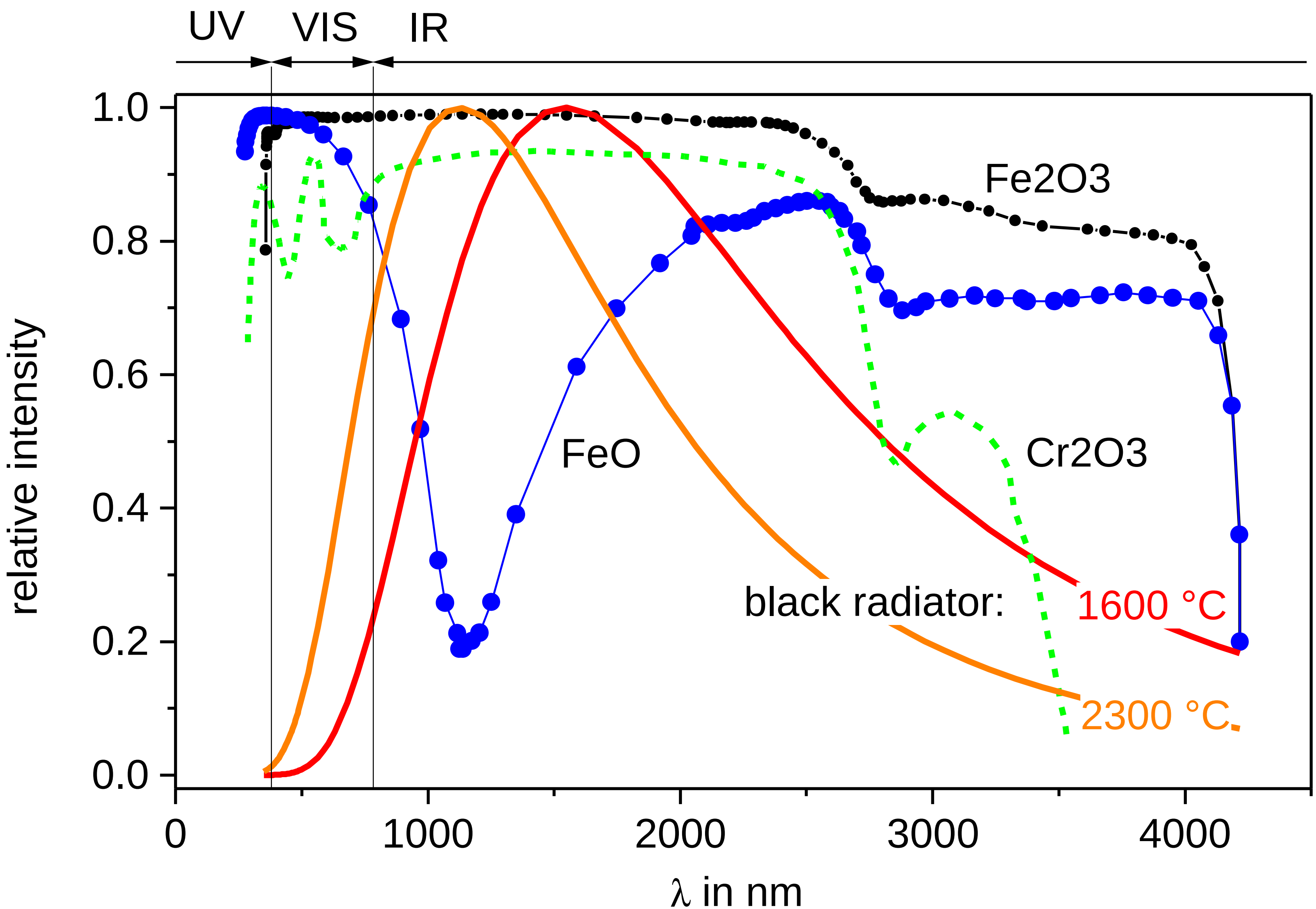
$$\dot{Q} = A \cdot \alpha_{ht} \cdot (T_H - T_L),\ \dot{Q}\ in\ kW$$

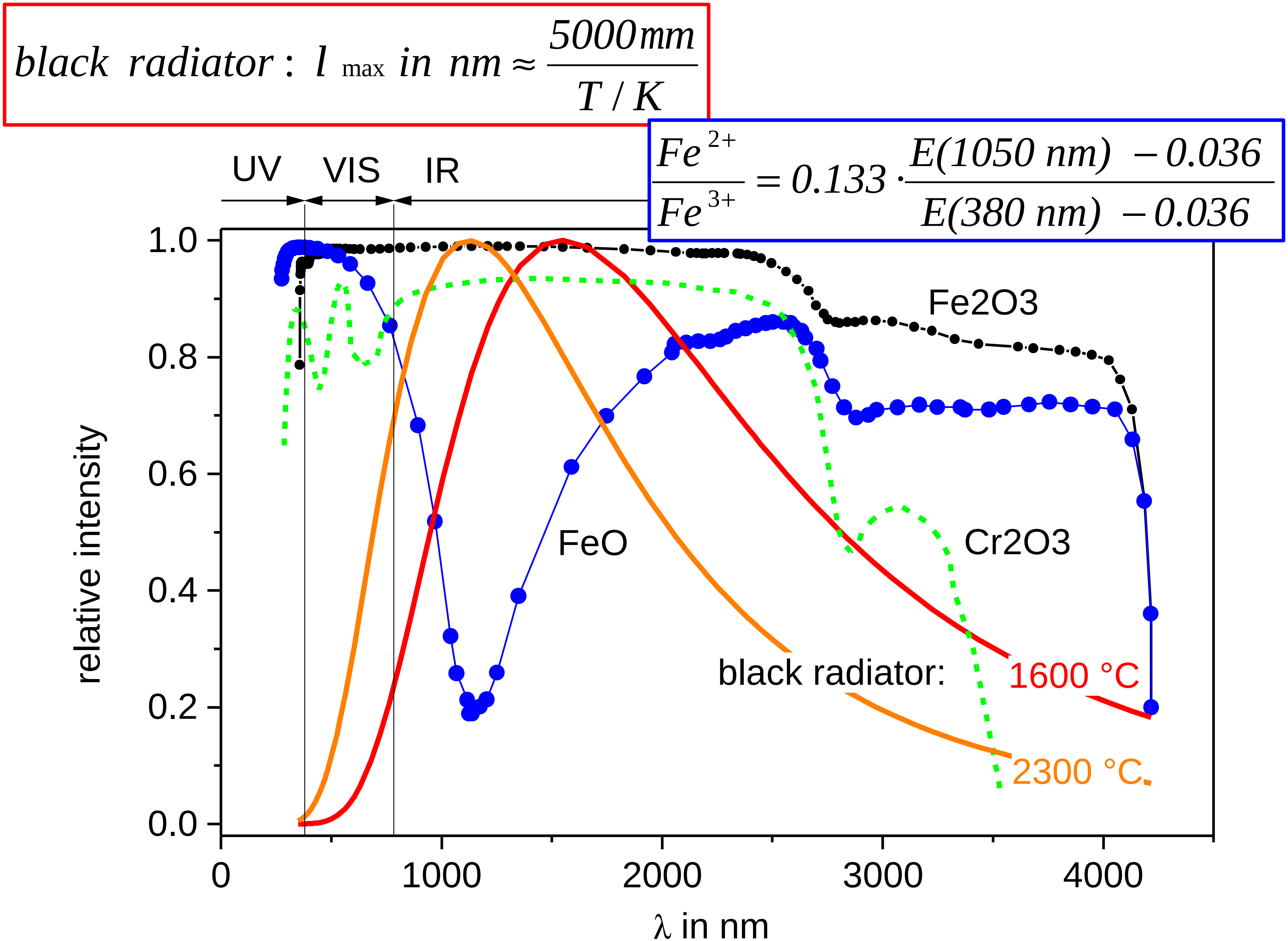
With a given transfer coeff. α_{ht} *and area A,* T_H-T_L *is fixed by the required power* $\dot{Q}$.

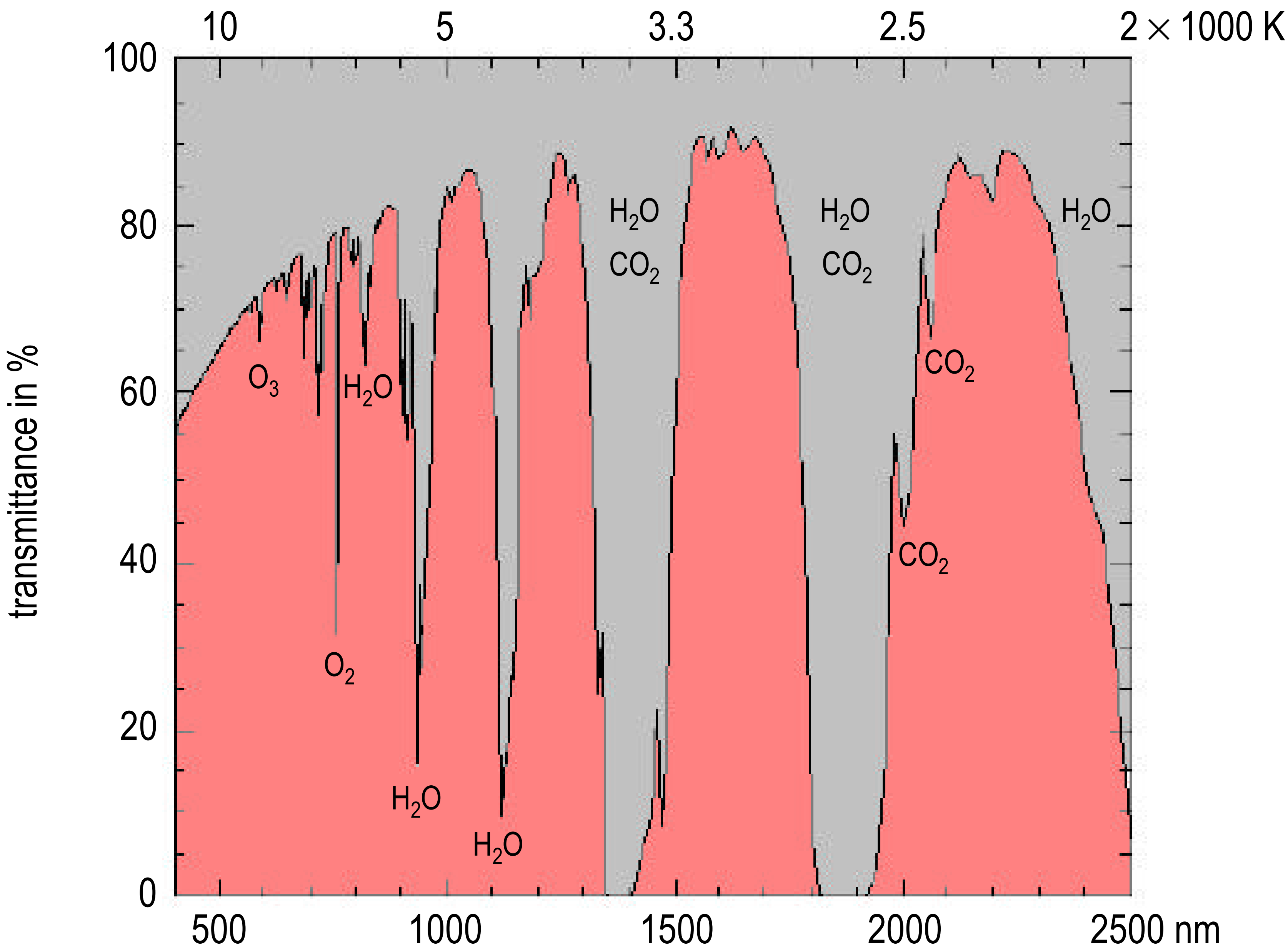


e_{crown}
e_{flame}
e_{dust}
e_{melt}
$q_i = C_S \cdot e_i \cdot T_i^4$
λ in W/(m·K)
T in °C
0
1
2
3
4
5
6
7
400
800
1200
1600

$$black\ \ radiator:\ l_{\max}\ in\ \ nm \approx \frac{5000mm}{T / K}$$

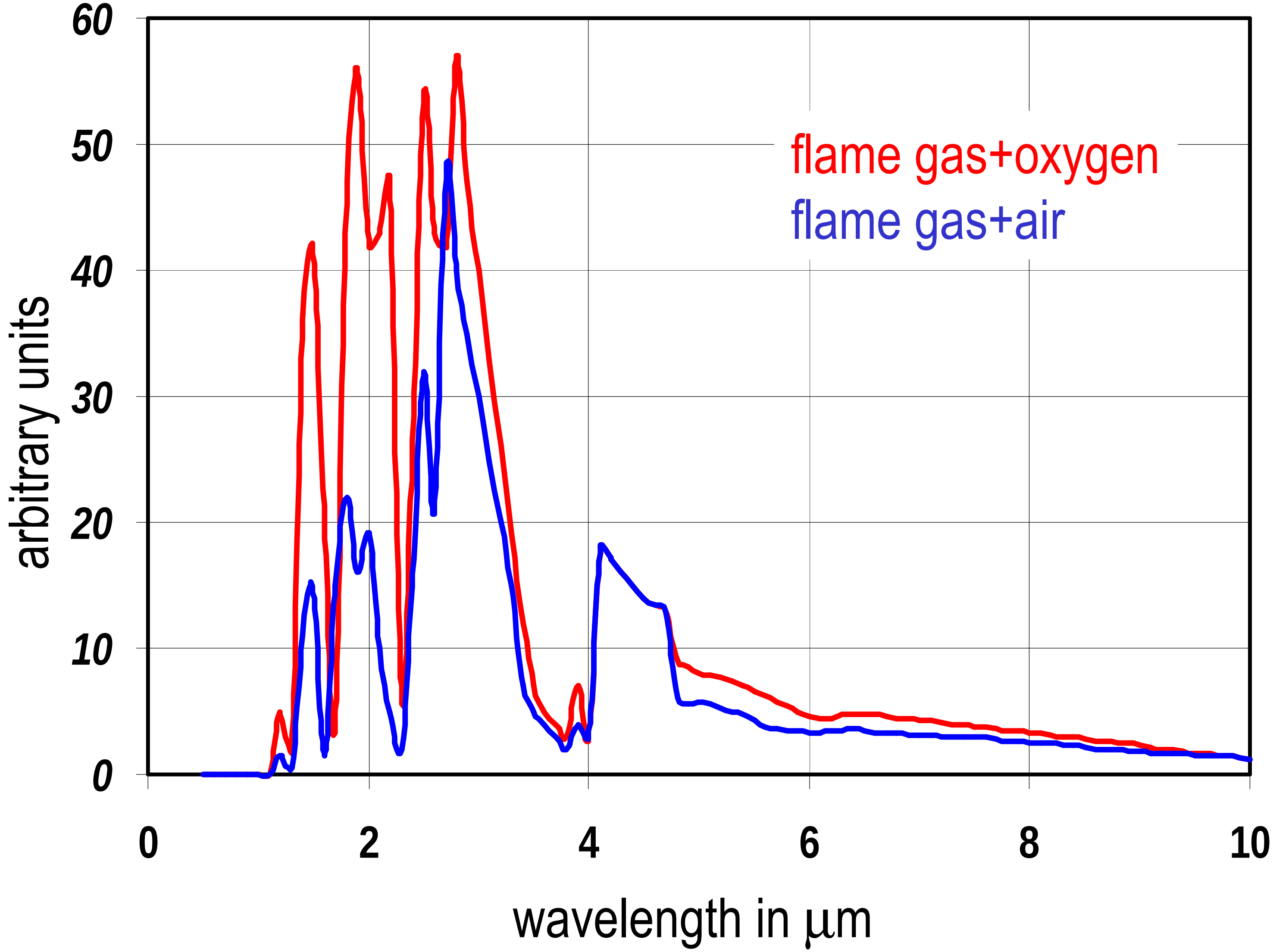


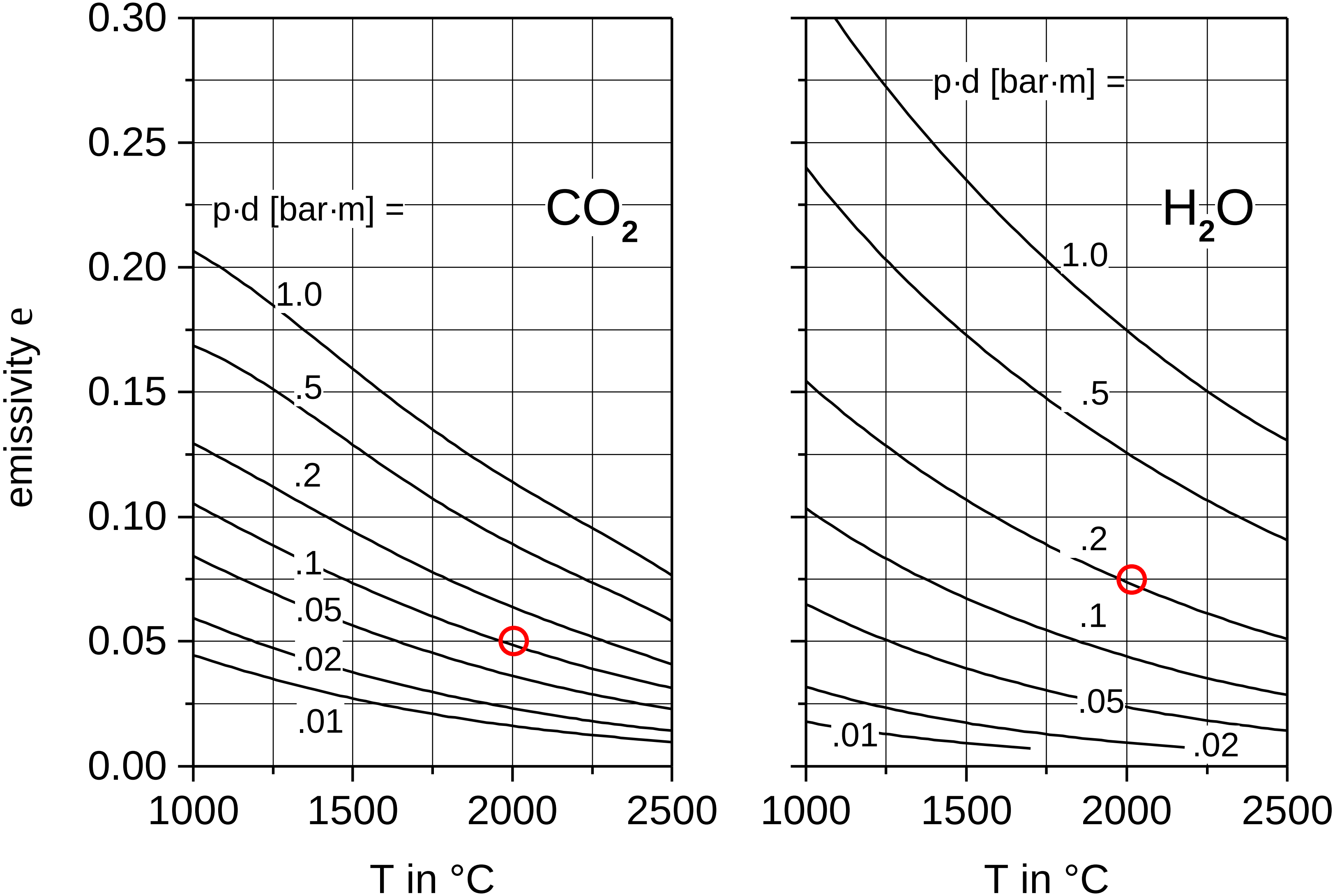

black radiator : l max in nm ≈ 5000mm / T / K
Fe2+ / Fe3+ = 0.133 · (E(1050 nm) − 0.036) / (E(380 nm) − 0.036)
UV
VIS
IR
Fe2O3
FeO
Cr2O3
black radiator:
1600 °C
2300 °C
relative intensity
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
λ in nm



10
5
3.3
2.5
2 × 1000 K
100
80
60
40
20
0
transmittance in %
O_3
H_2O
O_2
H_2O
H_2O
H_2O
CO_2
H_2O
CO_2
H_2O
CO_2
CO_2
500
1000
1500
2000
2500 nm

flame radiation ⇔ oszillation and rotation of molecules with dipoles (i.e., H_2O, CO_2; rest is athermic; no black radiation!)

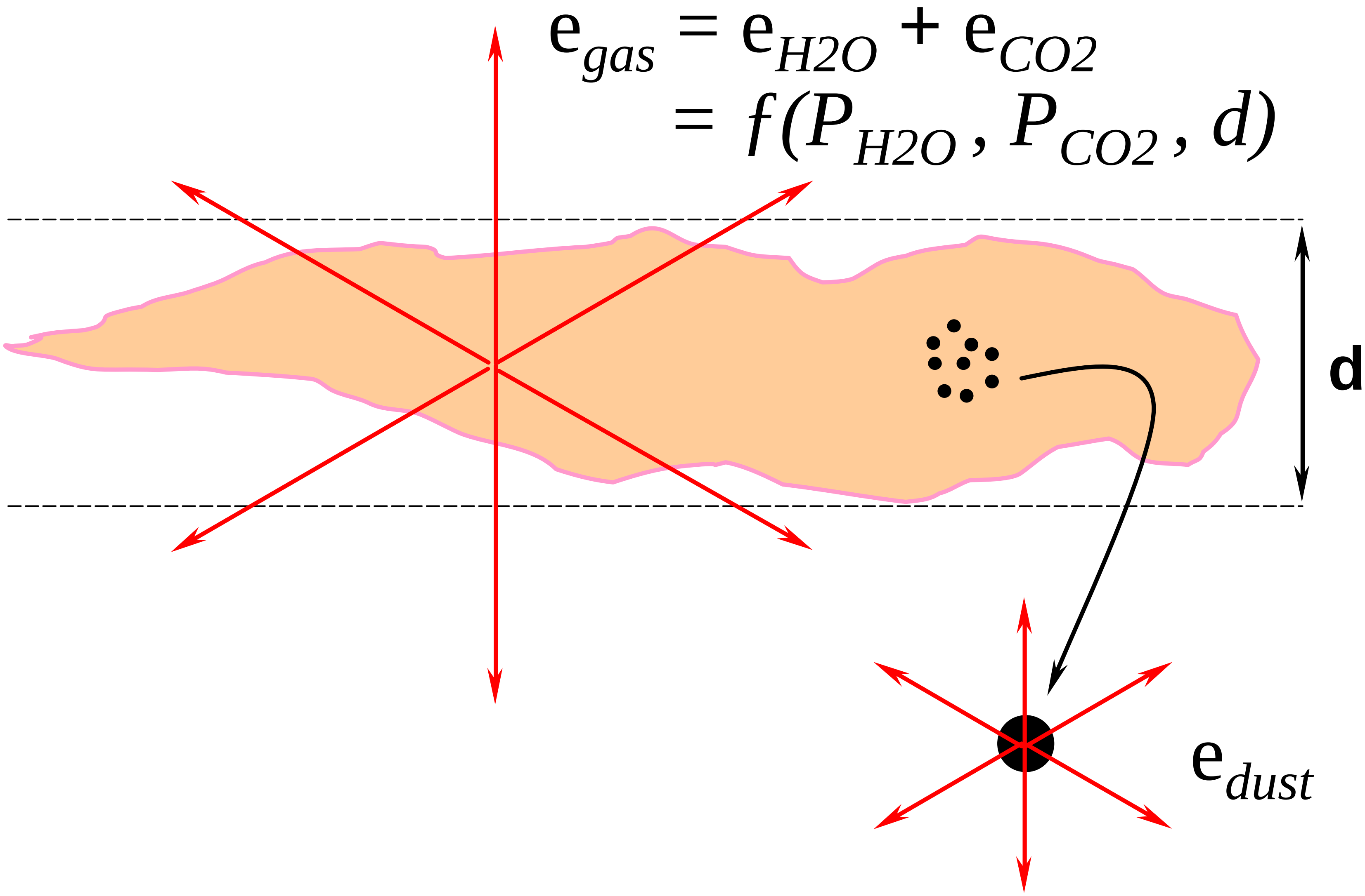




mineral gas flame, d = 1.0 m, $P_{CO2} \approx 0.1$ bar, $P_{H2O} \approx 0.2$ bar

$\varepsilon = \varepsilon_{CO2} + \varepsilon_{H2O} = 0.05 + 0.075 = 0.125$

$$e_{total} = e_{gas} + e_{dust} - e_{gas} \cdot e_{dust}$$

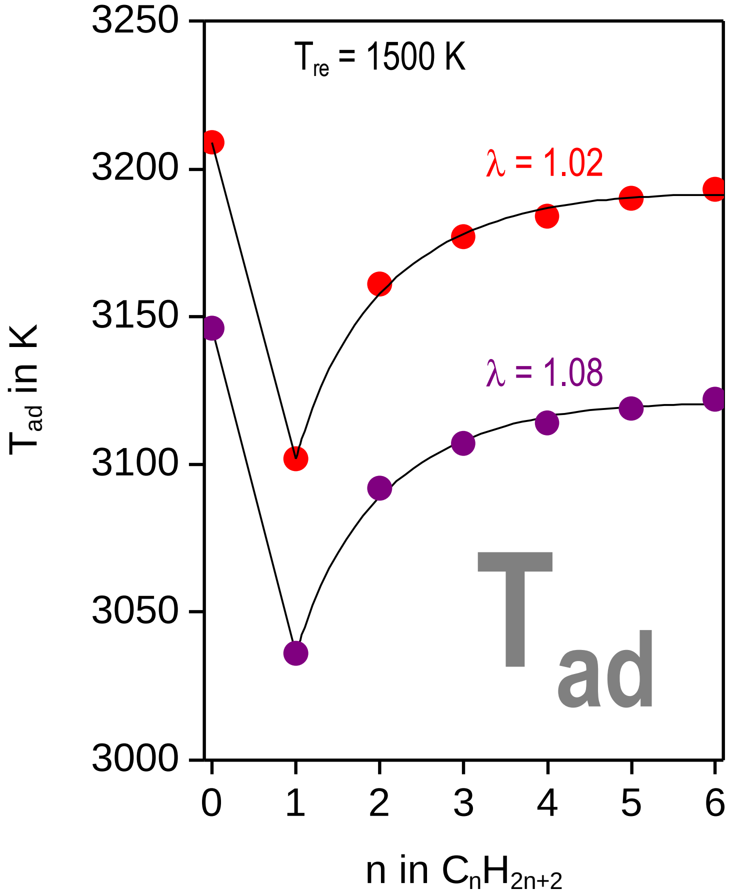


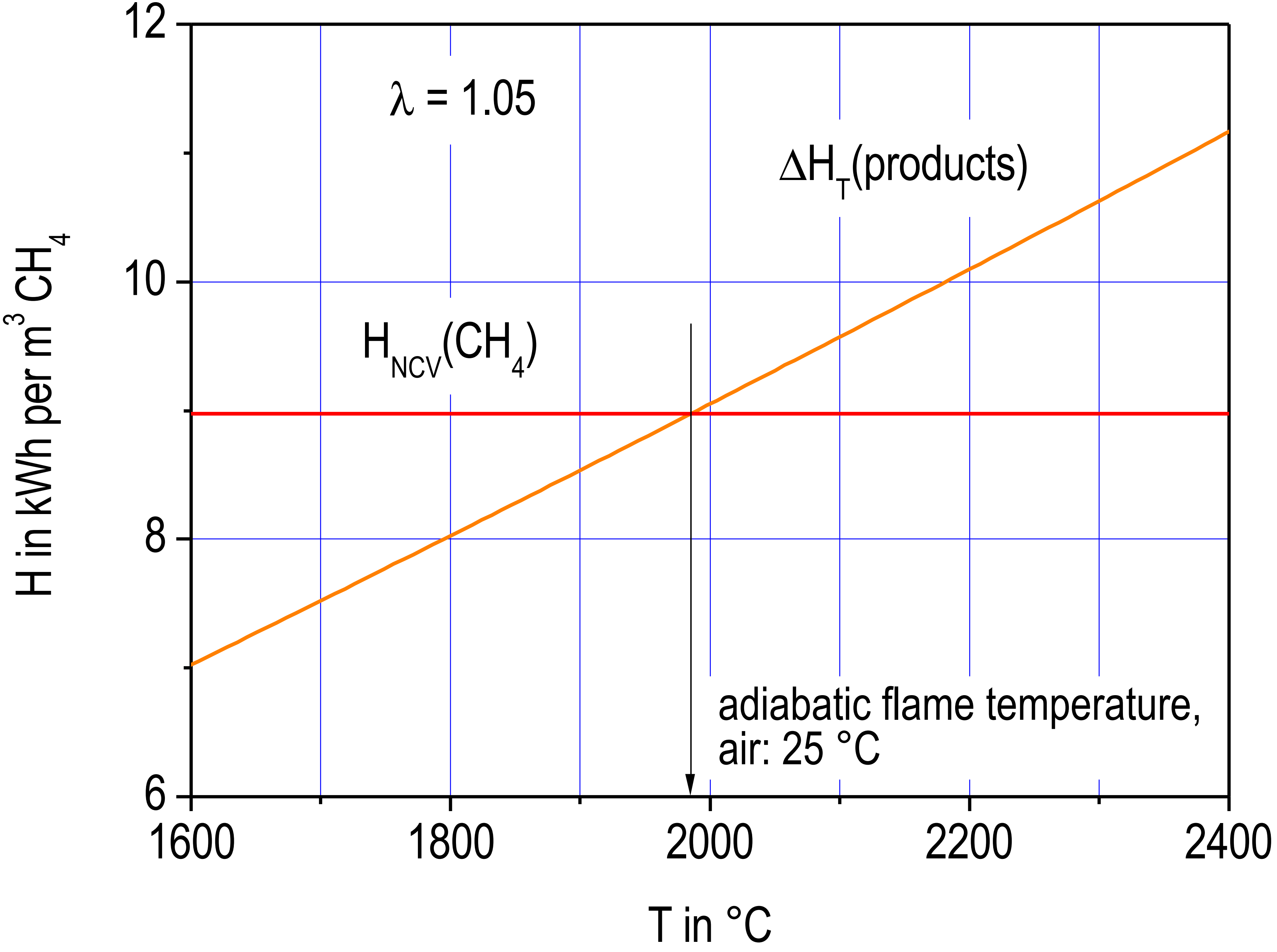
$$\Delta H_{ad} = H_{NCV} + l \cdot n_{O_2} \cdot \left(H_{O_2}(T) + 3.76 \cdot H_{N_2}(T_0) \right) \Big|_{T = T_0}^{T = T_{re}}$$

$$\Delta H_{ad} = \left(n_{CO_2} \cdot H_{CO_2}(T) + n_{H_2O} \cdot H_{H_2O}(T) \right) + n_{O_2} \cdot \left((l - 1) \cdot H_{O_2}(T) + l \cdot 3.76 \cdot H_{N_2}(T) \right) \Big|_{T = T_0}^{T = T_{ad}}$$

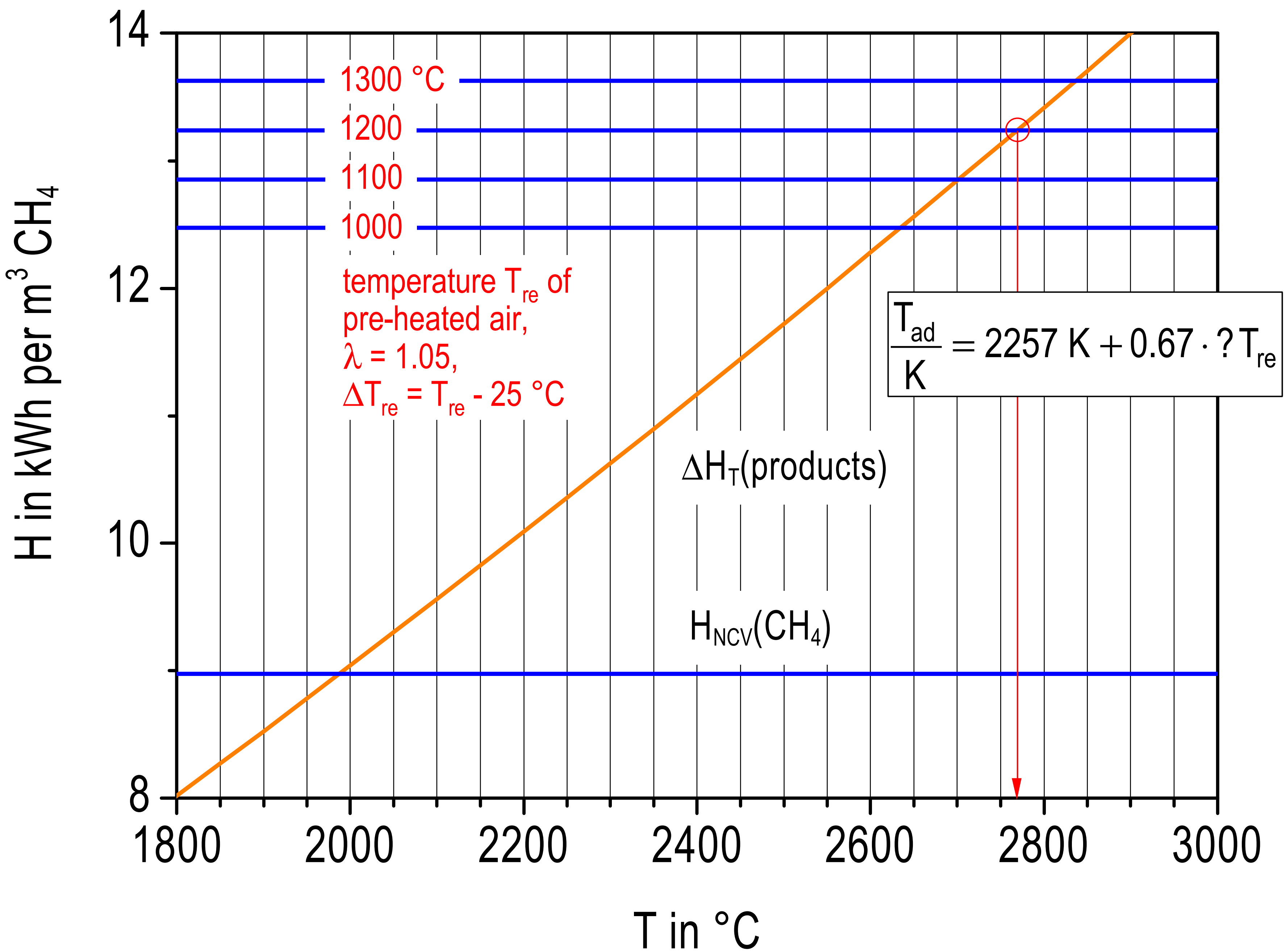
Vary T in the second line until the ΔH_{ad} value maches with the ΔH_{ad} value of the first line. Due to the complicated $c_P(T)$ functions, a straight-forward calculation is not possible.

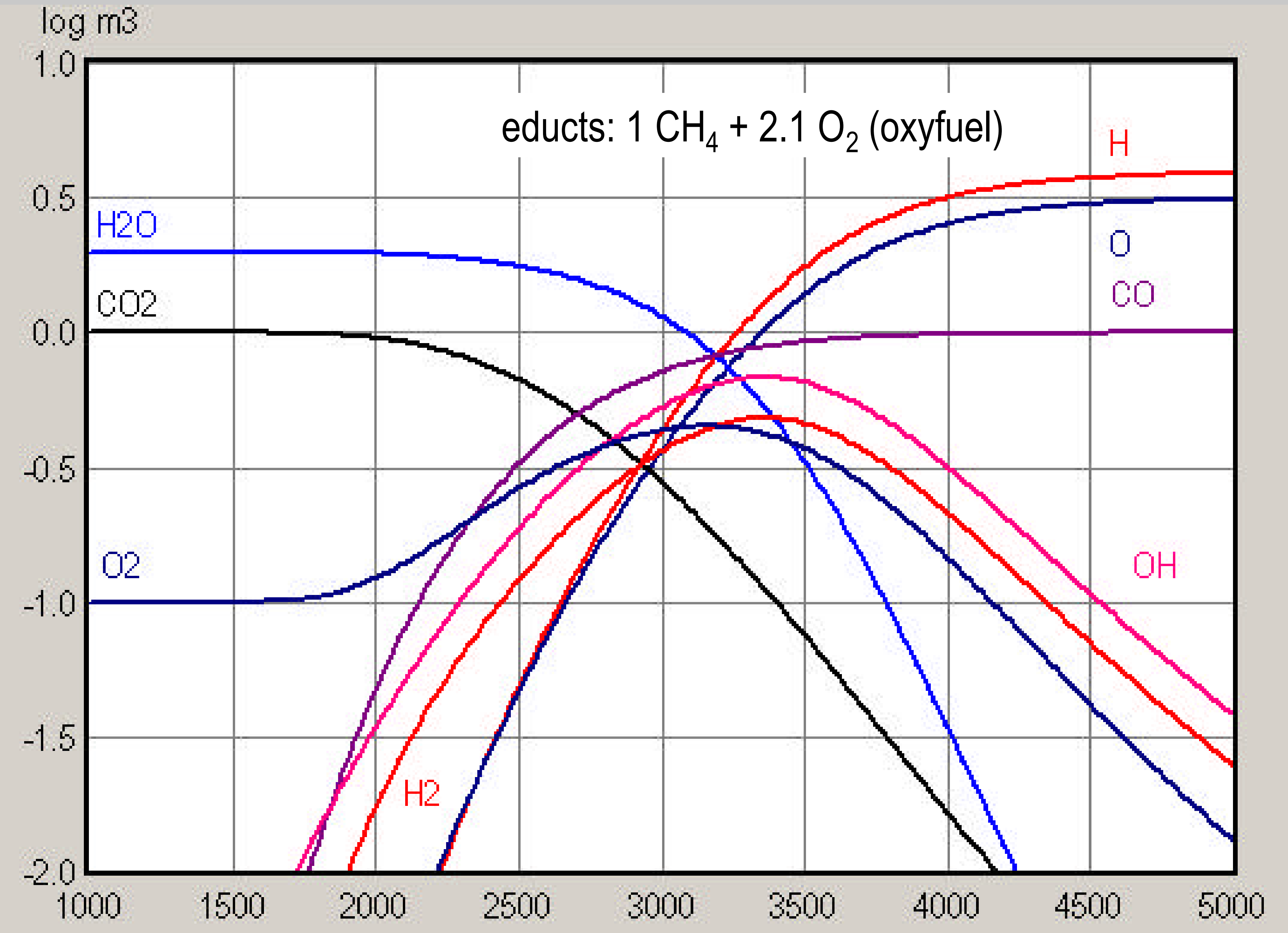
	air-fuel, 298 K	air-fuel, 1500 K	oxy-fuel
λ = 1.02	**2303**	**3102**	**4718**
λ = 1.08	**2221**	**3036**	**4634**

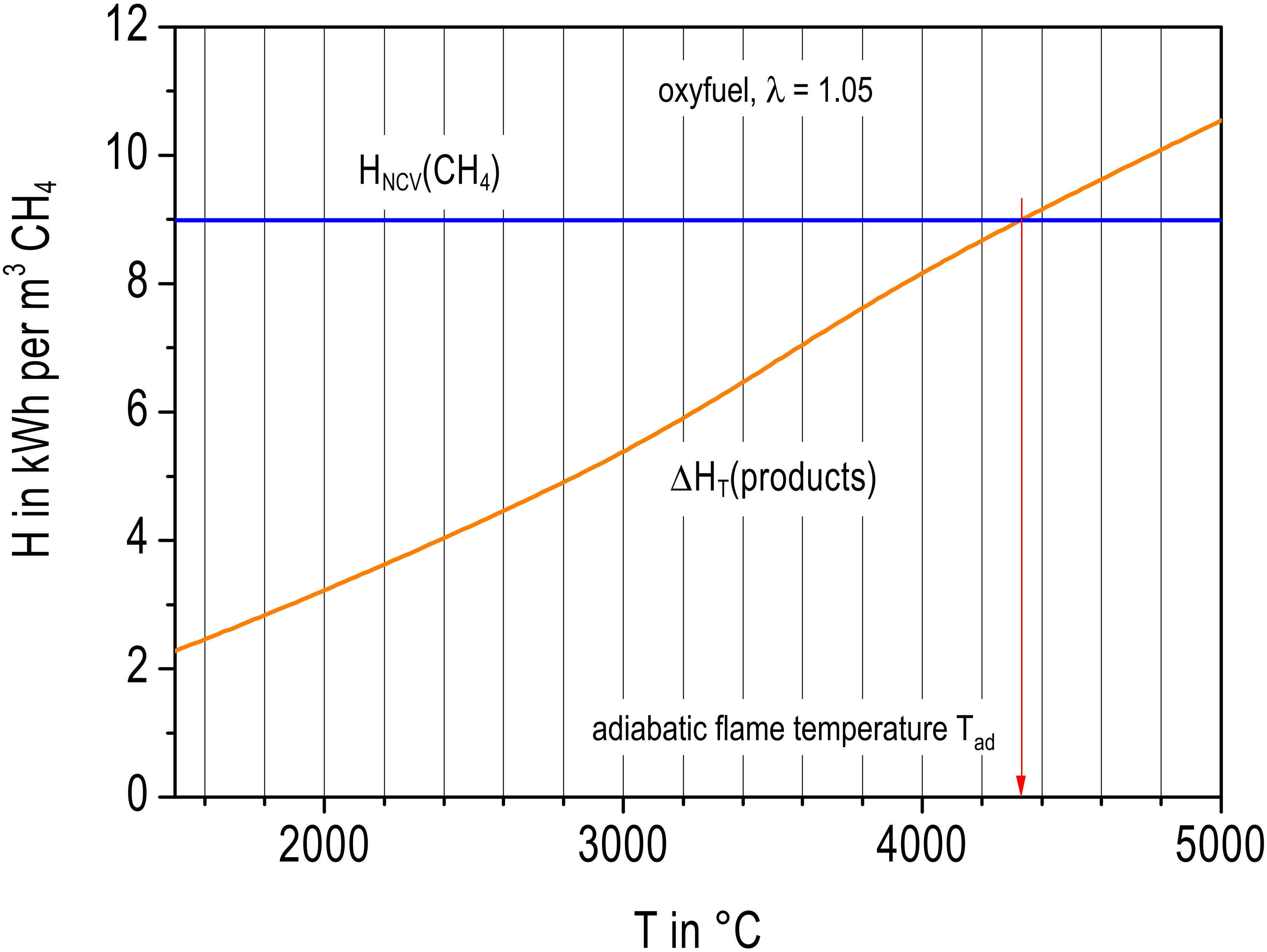




λ = 1.05
ΔH_T(products)
H_NCV(CH_4)
adiabatic flame temperature,
air: 25 °C
H in kWh per m^3 CH_4
T in °C
12
10
8
6
1600
1800
2000
2200
2400


1300 °C
1200
1100
1000
temperature T_re of
pre-heated air,
λ = 1.05,
ΔT_re = T_re - 25 °C
T_ad / K = 2257 K + 0.67 · ? T_re
ΔH_T(products)
H_NCV(CH_4)
H in kWh per m^3 CH_4
T in °C
14
12
10
8
1800
2000
2200
2400
2600
2800
3000


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



oxyfuel, λ = 1.05
H_NCV(CH_4)
ΔH_T(products)
adiabatic flame temperature T_ad
H in kWh per m^3 CH_4
T in °C
0
2
4
6
8
10
12
2000
3000
4000
5000

practice

#FUELTAB-1.xls

#FUELTAB-2.xls

#FUELTAB-3.xls

#THDYN-GAS.xls

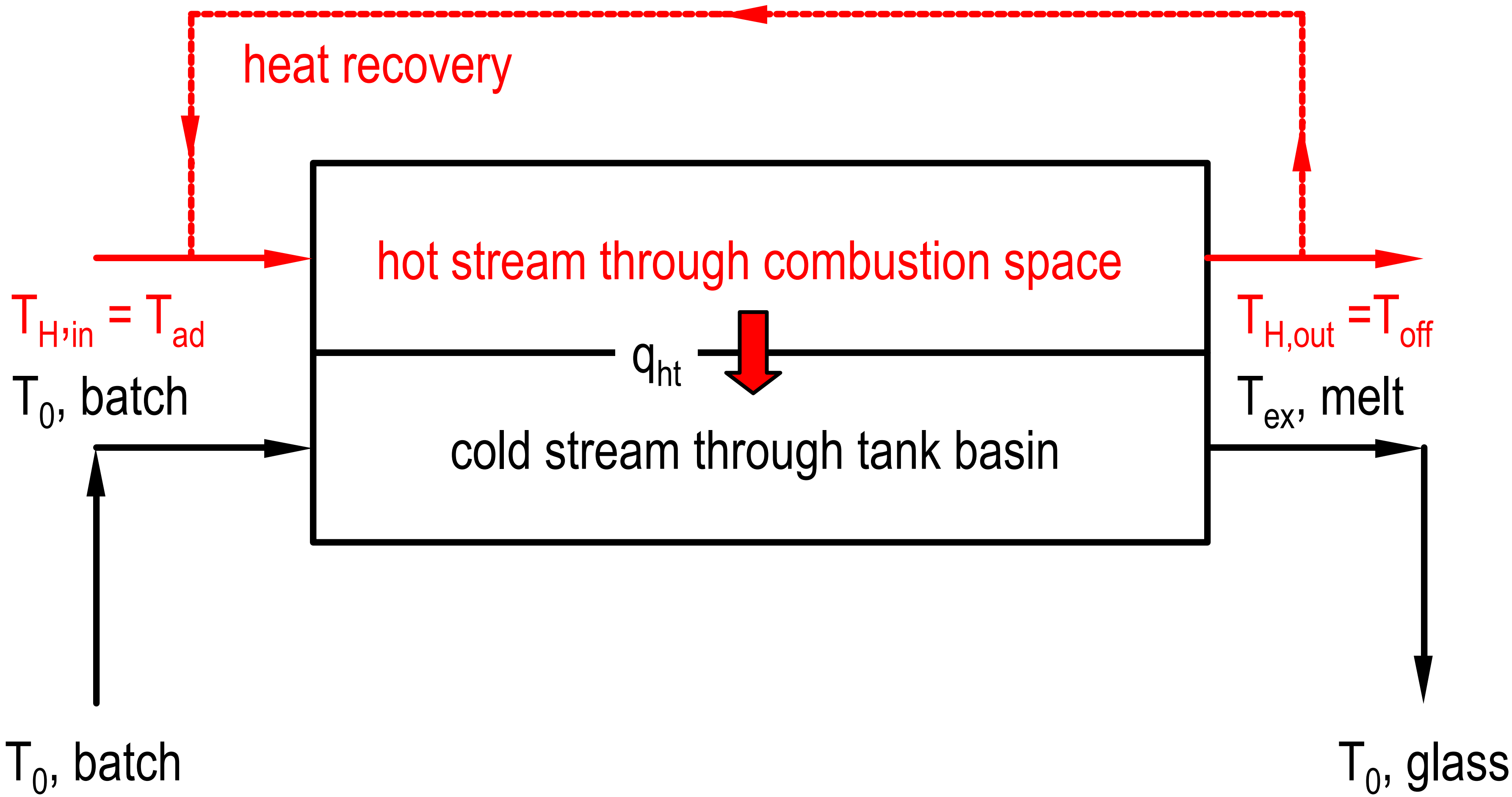
#COMBUSTION.xls

#HEAT IN GASES.xls

the glass furnace -
a thermochemical reactor

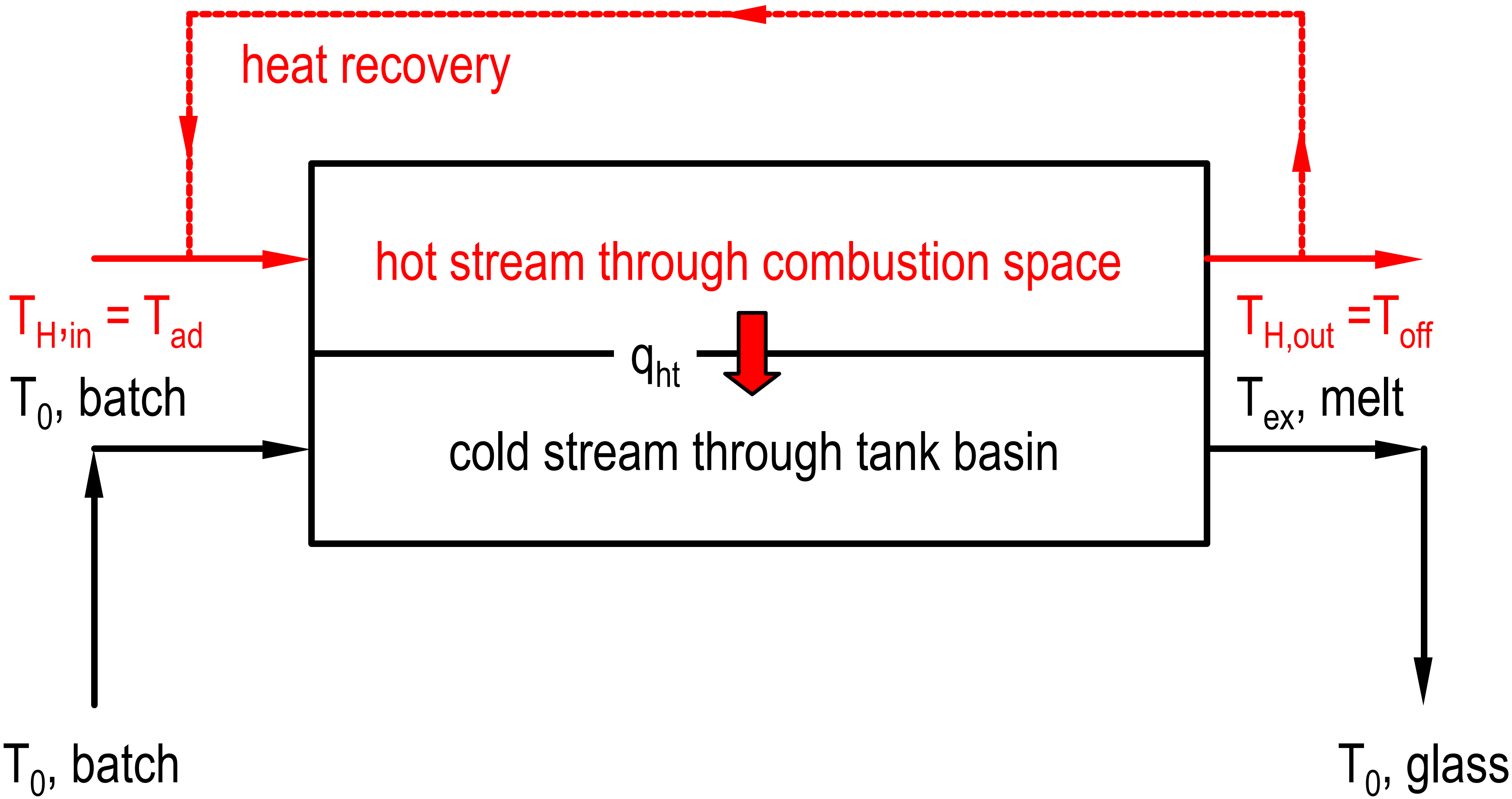
heat transfer problem:

$$\frac{q_{ht}}{q_{in}} = \frac{\dot{m} \cdot c_P \cdot (T_{H,in} - T_{H,out})}{\dot{m} \cdot c_P \cdot (T_{H,in} - T_L)} = \frac{\text{heat extracted from hot stream}}{\text{heat made available by hot stream}}$$

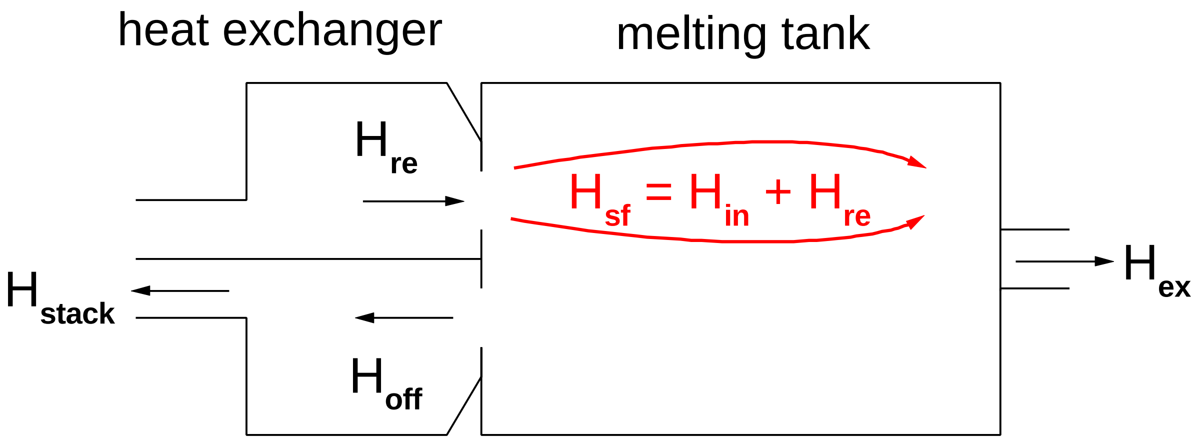


heat transfer problem:

$$\frac{q_{ht}}{q_{in}} = \frac{\Delta T_{ad} - \Delta T_{off}}{\Delta T_{ad} - h_{re} \cdot \Delta T_{off}} \Rightarrow H_{in} = H_{ht} \cdot \frac{1 - h_{re} \cdot h_{ht}}{1 - h_{ht}}; \quad h_{ht} = 1 - \frac{\Delta T_{off}}{\Delta T_{ad}}$$



fuel input: H_{in} [kWh/t], H^F_{NCV} [kWh/m³], m_F [m³/t]



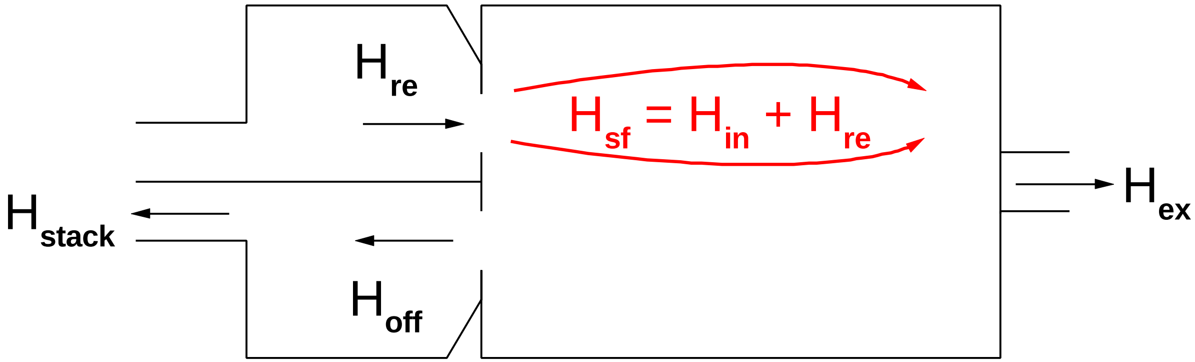
$$m_F = H_{in}/H^F_{NCV}$$

$$H_{in} - (H_{off} - H_{re}) = m_F \cdot H^F_{NCV} - (1 - h_{re}) \cdot H_{off} = H_{wu+wo} + H_{ex}$$

$$H_{off} = \left(V^F(off) \cdot c_{P,off} + (l-1) \cdot V^F(air) \cdot c_{P,air}\right) \cdot \Delta T_{off}$$

resolve for m_F

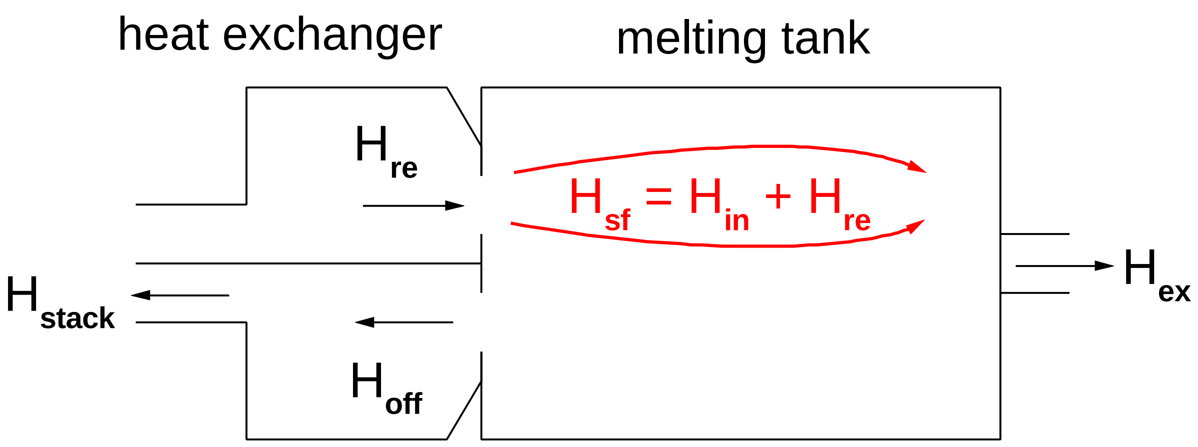
fuel input: H_{in} [kWh/t], H^F_{NCV} [kWh/m³], m_F [m³/t]



$$m_F = H_{in}/H^F_{NCV}$$

$$m_F = \frac{H_{wu+wo} + H_{ex}}{H^F_{NCV} - (1-h_{re}) \cdot \left(V^F(off) \cdot c_{P,off} + (l-1) \cdot V^F(air) \cdot c_{P,air}\right) \cdot \Delta T_{off}}$$

fuel input: H_{in} [kWh/t], H^F_{NCV} [kWh/m³], m_F [m³/t]

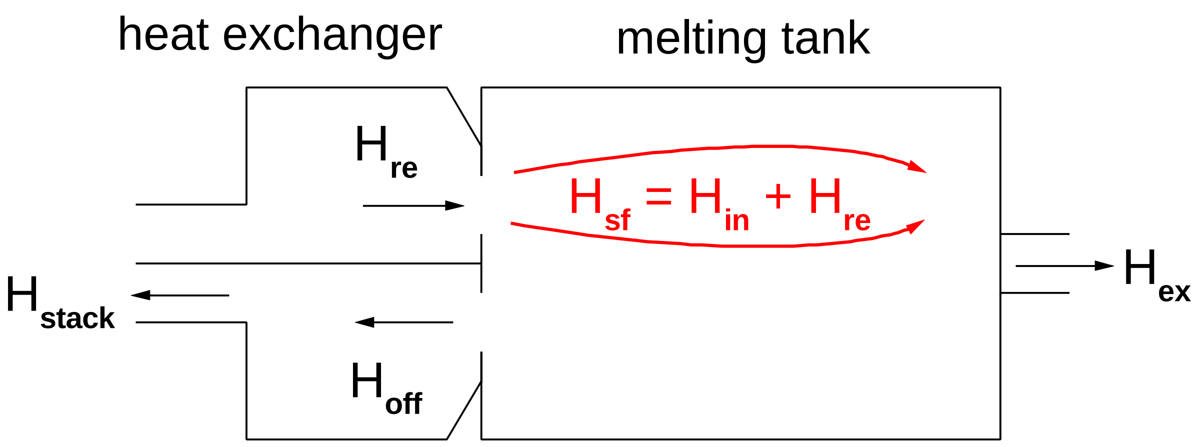


$$m_F = H_{in}/H^F_{NCV}$$

$$\Delta H^0_{chem},\ y_C,\ T_{ex}$$

$$m_F = \frac{H_{wu+wo} + H_{ex}}{H^F_{NCV} - (1-h_{re})\cdot\left(V^F(off)\cdot c_{P,off} + (l-1)\cdot V^F(air)\cdot c_{P,air}\right)\cdot \Delta T_{off}}$$

fuel input: H_{in} [kWh/t], H^F_{NCV} [kWh/m³], m_F [m³/t]

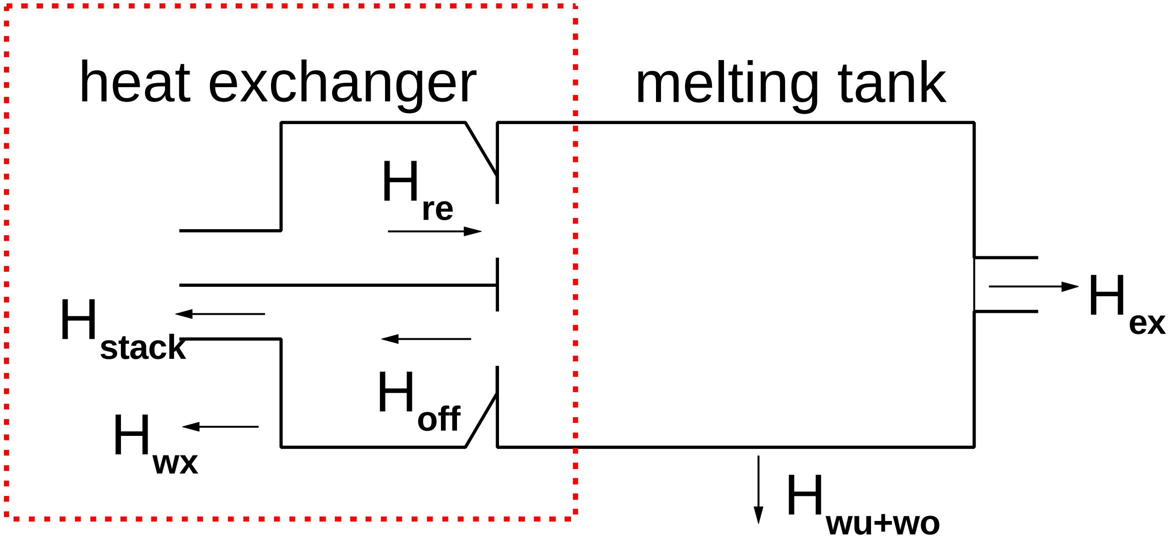


h_{re}

$$m_F = \frac{H_{wu+wo} + H_{ex}}{H^F_{NCV} - (1 - h_{re}) \cdot \left(V^F(off) \cdot c_{P,off} + (l - 1) \cdot V^F(air) \cdot c_{P,air} \right) \cdot \Delta T_{off}}$$

resolve for h_{re}

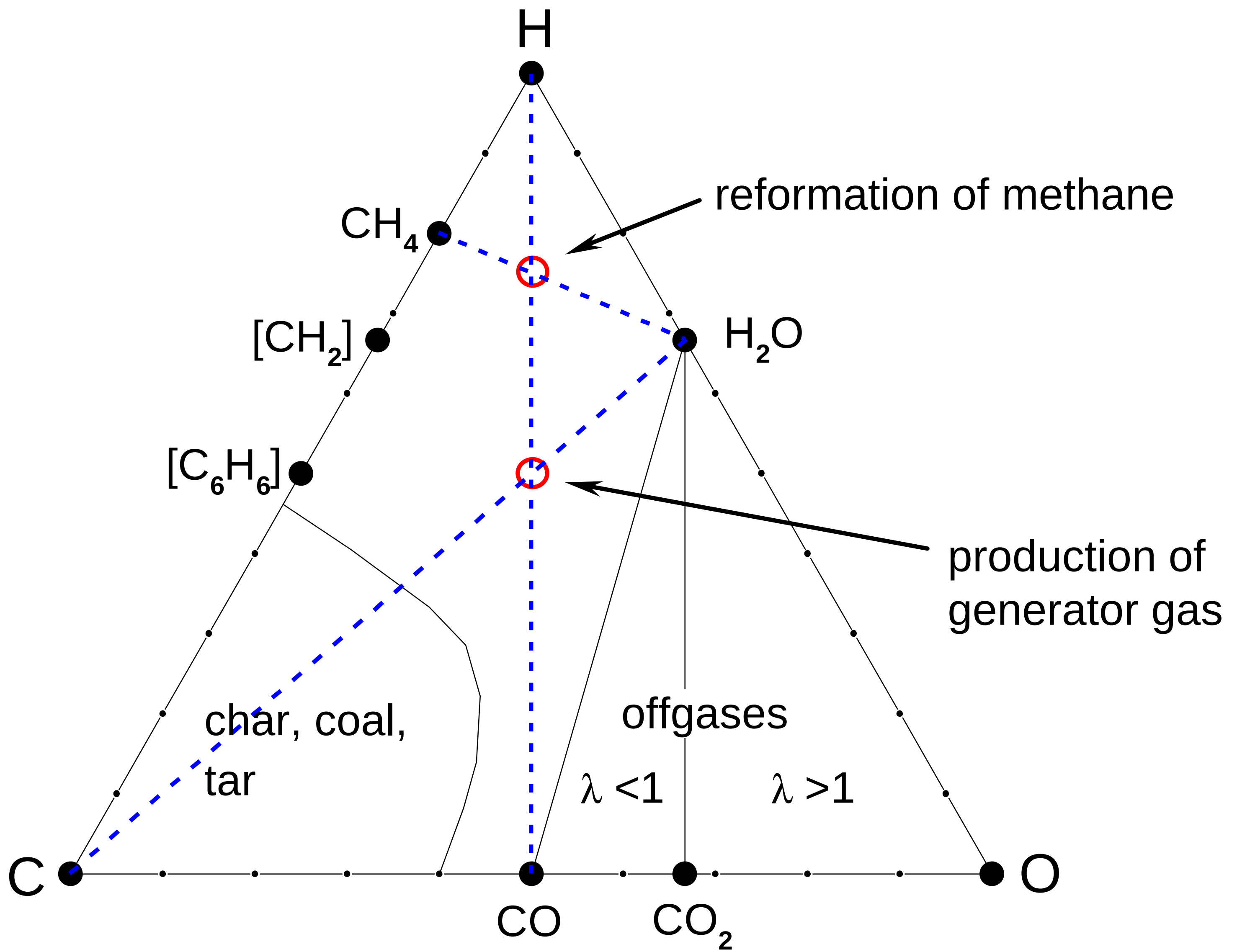
$\eta_{re} = H_{re} / H_{off}$



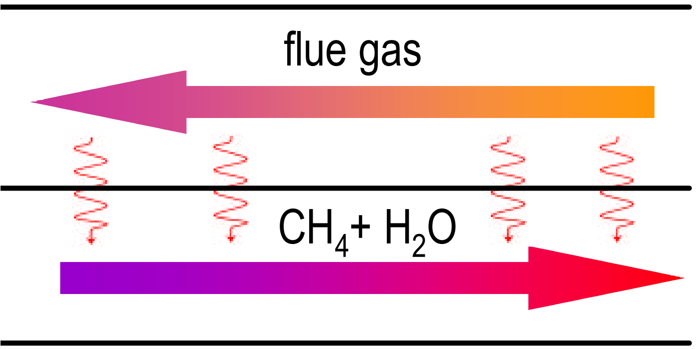
h_{re}

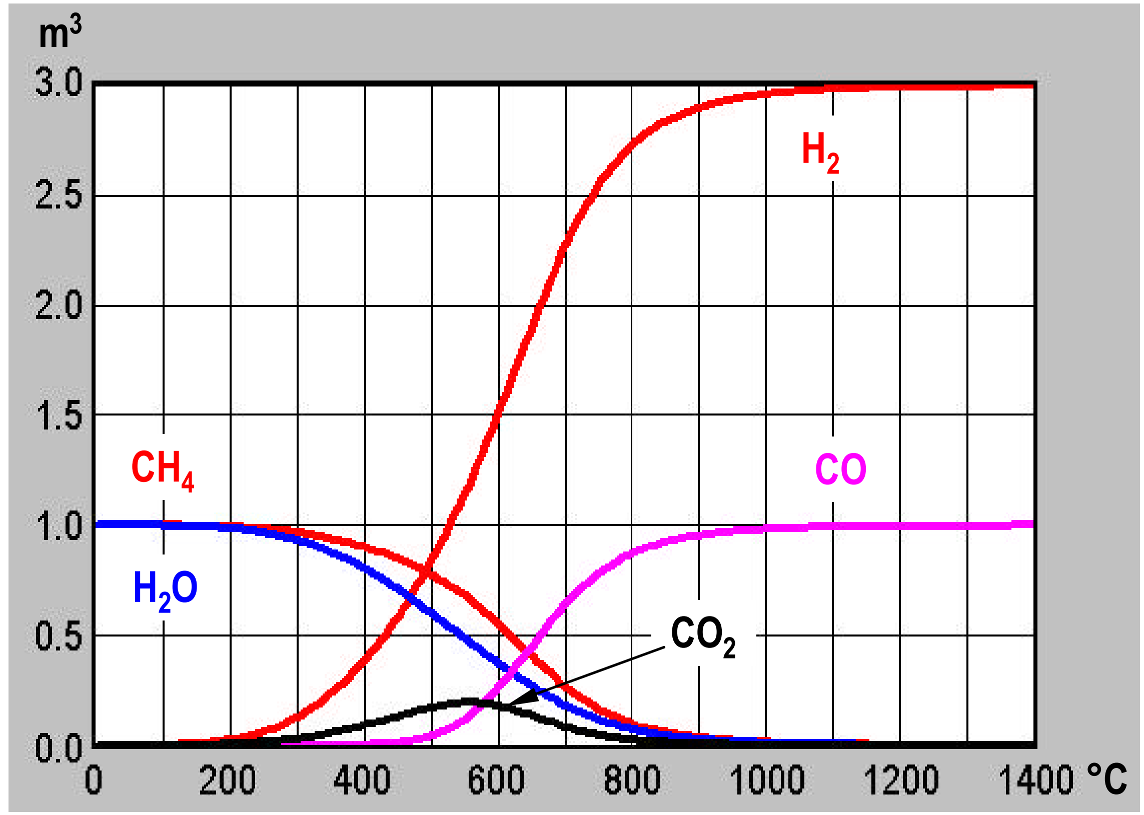
$$h_{re} = \left(\frac{V^F(air)}{V^F(off)} \right) \cdot \left(\frac{c_{P,air}}{c_{P,off}} \right) \cdot \frac{\Delta T_{re}}{\Delta T_{off}} \cdot \frac{1}{1+B} \quad \leq 0.8 \cdot \Delta T_{re} / \Delta T_{off}$$

$$h_{re} \approx 60 - 65\%$$


H
reformation of methane
CH_4
$[CH_2]$
H_2O
$[C_6H_6]$
production of
generator gas
char, coal,
tar
offgases
λ <1
λ >1
C
CO
CO_2
O

thermochemical recuperator

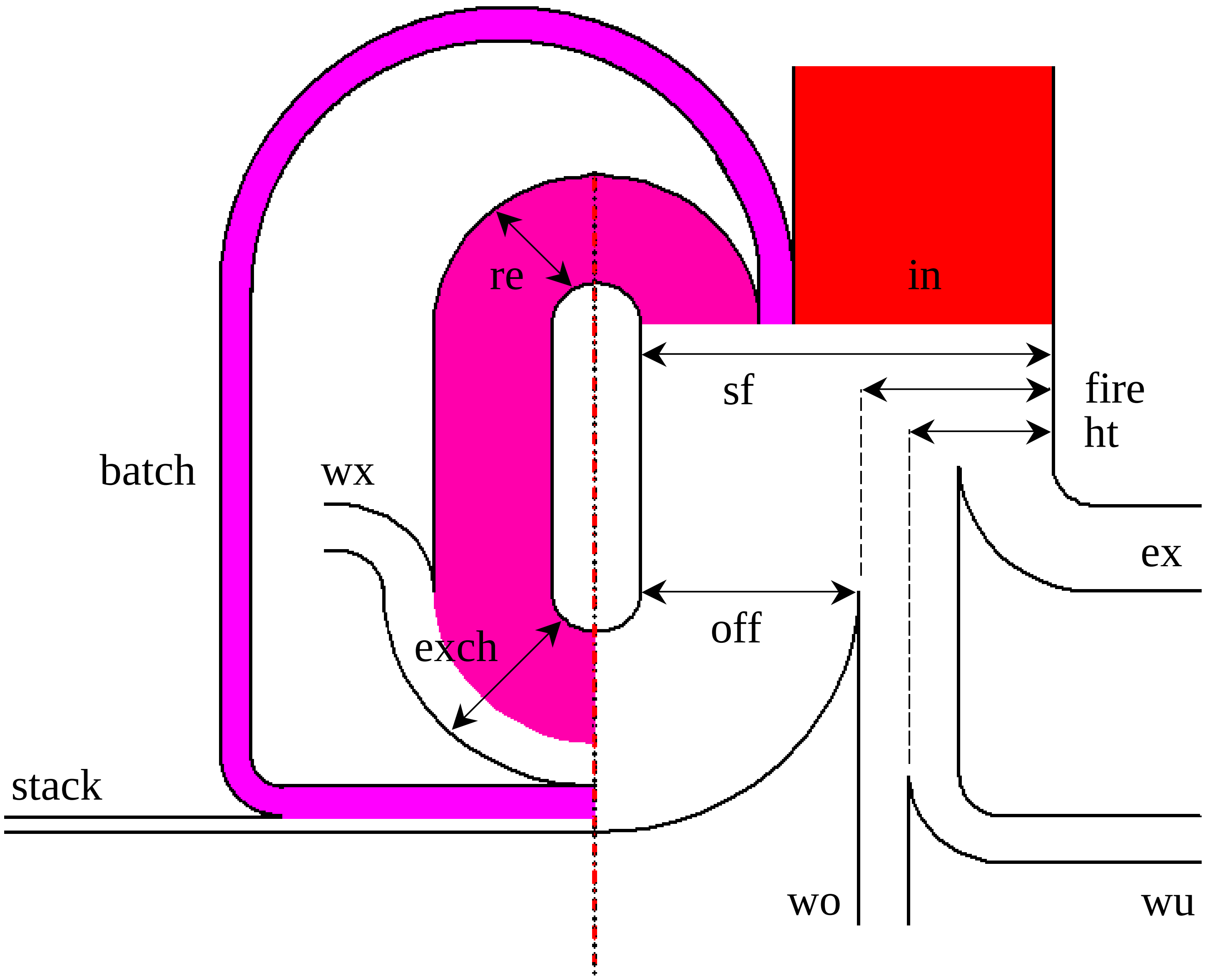


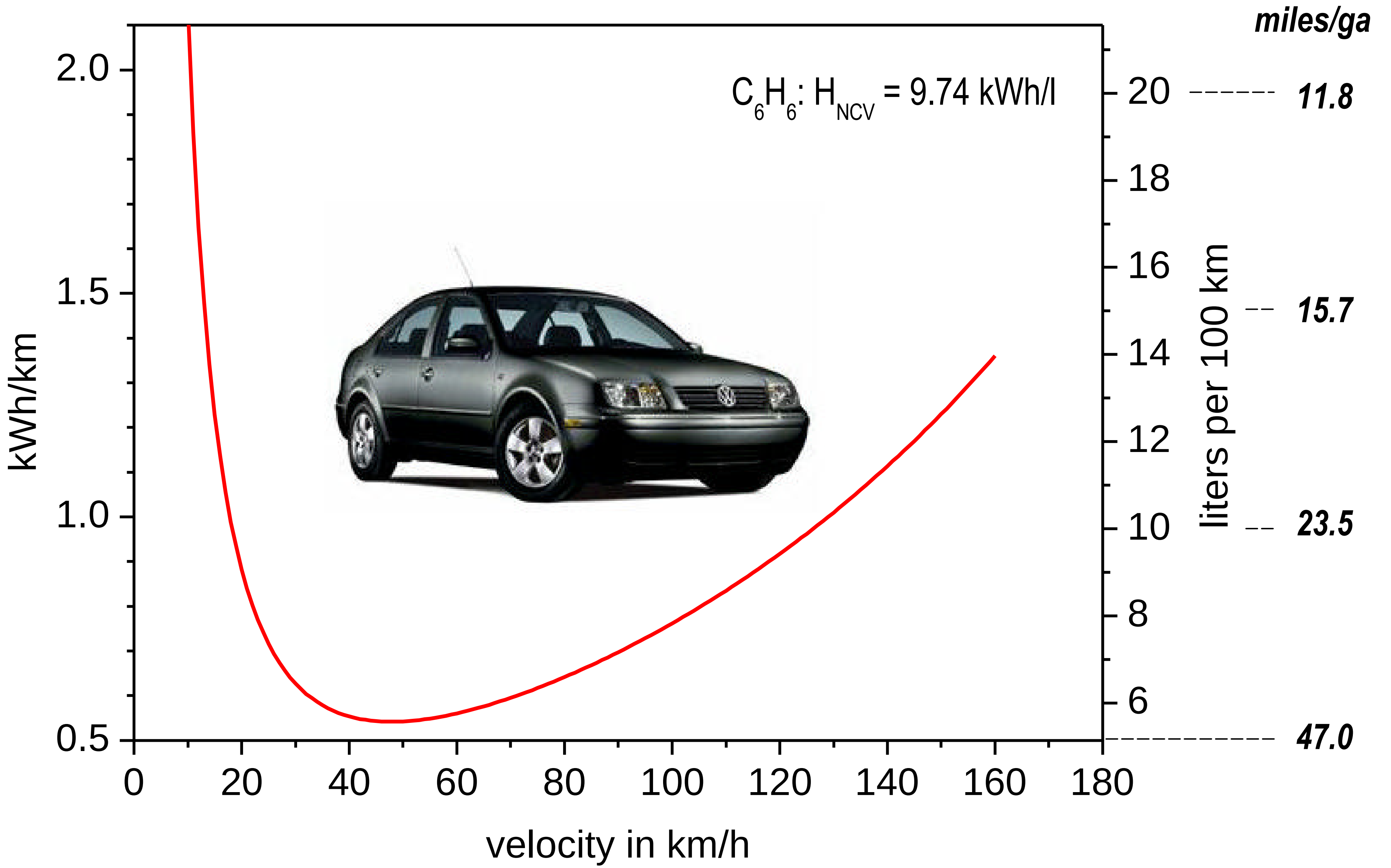


$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	**- 8.99 kWh/m³**
$CH_4 + H_2O \rightarrow CO + 3H_2$	+2.31 kWh/m³
$CO + 1/2O_2 \rightarrow CO_2$	- 3.17 kWh/m³
$3H_2 + 3/2O_2 \rightarrow 3H_2O$	- 8.13 kWh/m³

} **- 11.30 kWh/m³**

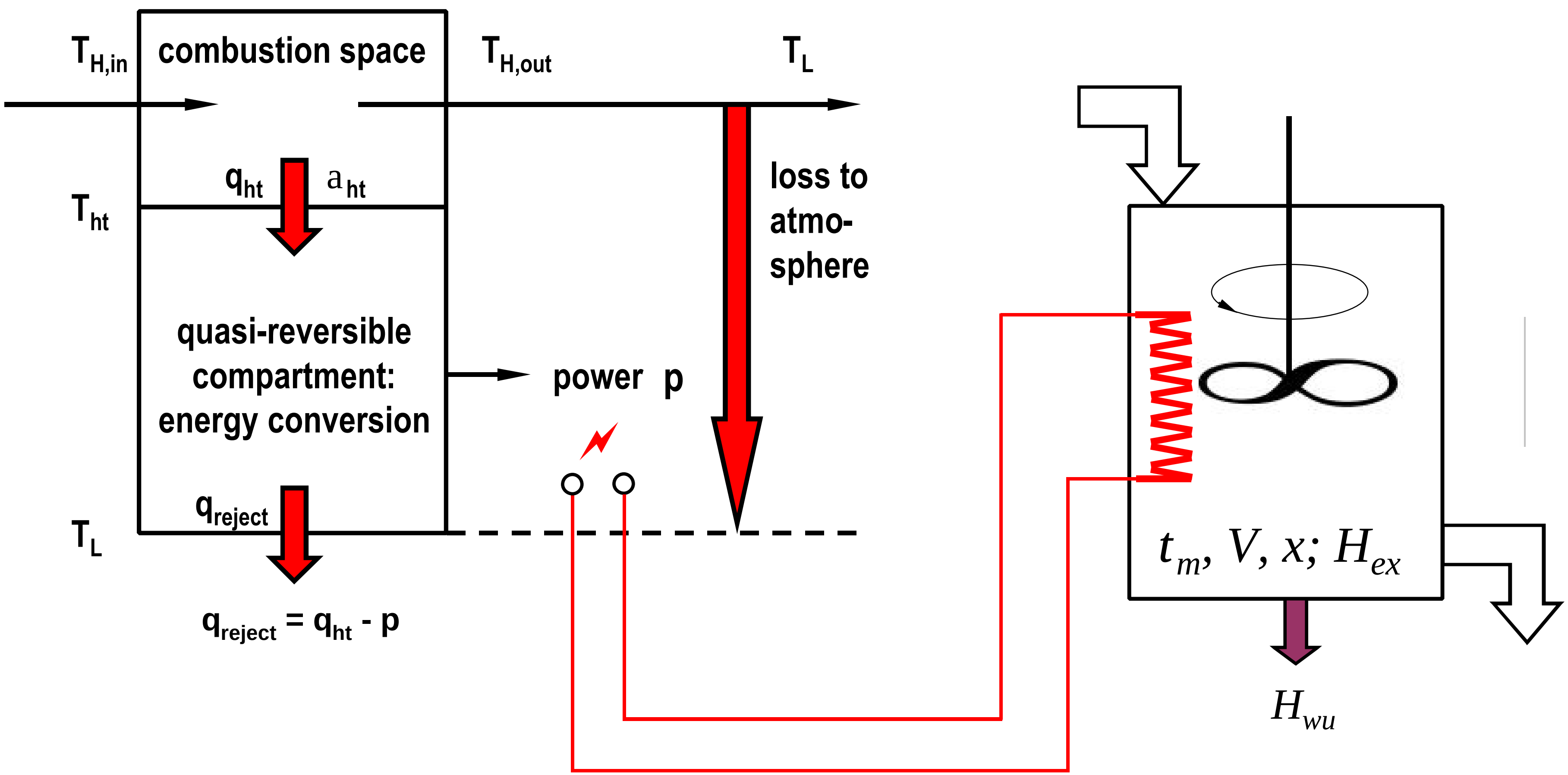
BATCH PREHEATER

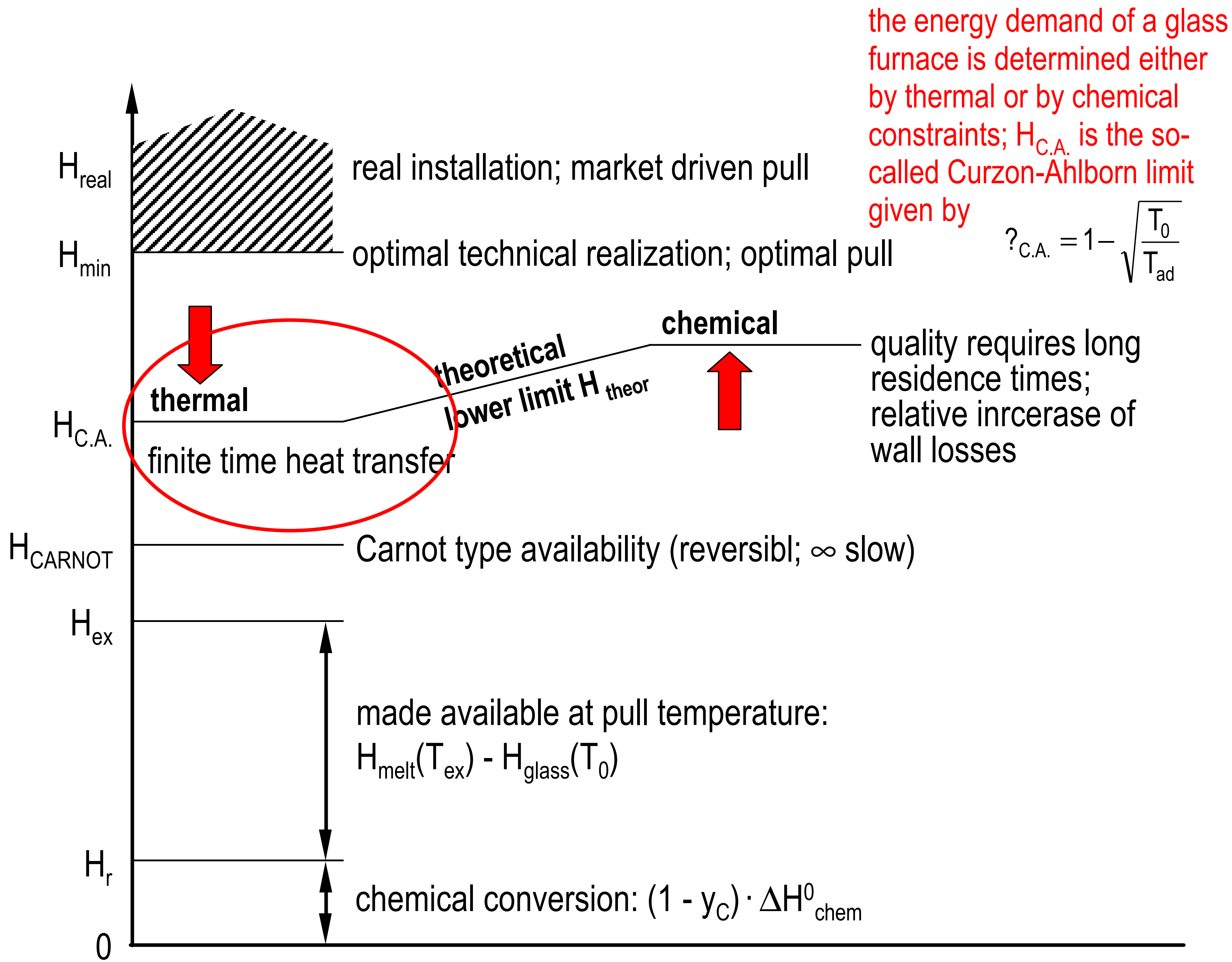




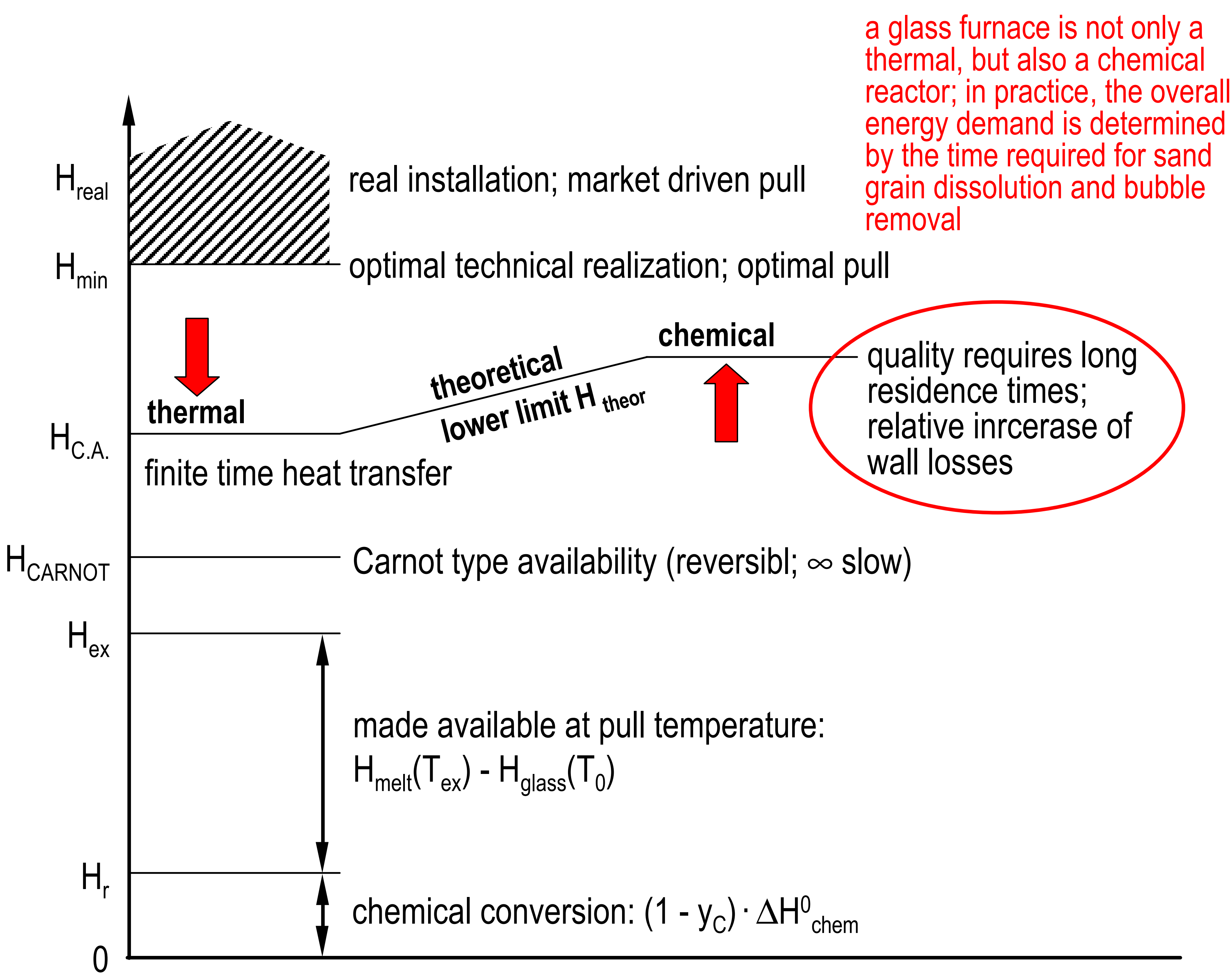
- 100 km/h = 62 mph
- z liters per 100 km correspond to 235.2 / z miles per US gallon

2nd theorem treatment, „finite-time heat thermodynamics“





the energy demand of a glass furnace is determined either by thermal or by chemical constraints; $H_{C.A.}$ is the so-called Curzon-Ahlborn limit given by
$?_{C.A.} = 1 - \sqrt{\frac{T_0}{T_{ad}}}$
H_{real}
real installation; market driven pull
H_{min}
optimal technical realization; optimal pull
chemical
theoretical lower limit H_{theor}
thermal
quality requires long residence times; relative inrcerase of wall losses
$H_{C.A.}$
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



a glass furnace is not only a thermal, but also a chemical reactor; in practice, the overall energy demand is determined by the time required for sand grain dissolution and bubble removal
H_{real}
real installation; market driven pull
H_{min}
optimal technical realization; optimal pull
chemical
theoretical
lower limit H_{theor}
thermal
quality requires long residence times; relative inrcerase of wall losses
$H_{C.A.}$
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

Main influences:

The compiled influences may be attributed to three areas:

physics & chemistry (basics):
nos. 1 - 3, no. 4

product & market:
nos. 5 - 6

technical realization:
nos. 7 - 8

1. $H_{BATCH + CULLET} = (1 - y_C) \cdot \Delta H^0_{chem}$

2. $H_{HEAT\ CAPACITY} = \Delta H_T,\ at\ T = T_{ex}$

3. $H_{EXPLOITATION} = H_{ex}$

4. $H_{HEAT\ TRANSFER} \propto \dfrac{1}{1 - \sqrt{\dfrac{T_0}{T_H}}}$

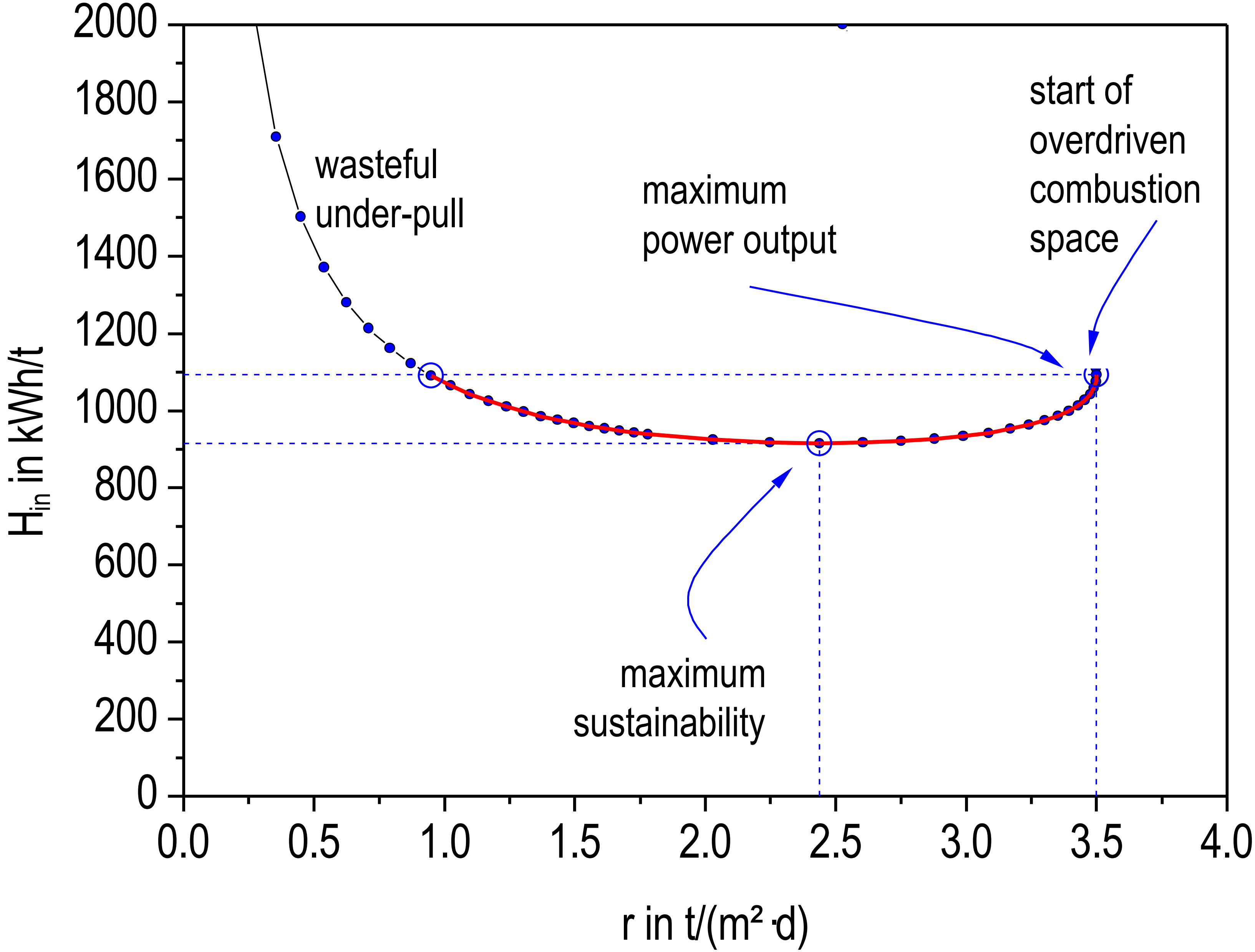
5. $H_{GLASS\ QUALITY} \propto K_Q,\ 1 \leq K_Q \propto \dfrac{1}{1-x}$

6. $H_{UTILIZATION\ OF\ CAPACITY} \propto \dfrac{q}{r},\ q\ in\ kW/m^2,\ r\ in\ t/(m^2 \cdot h)$

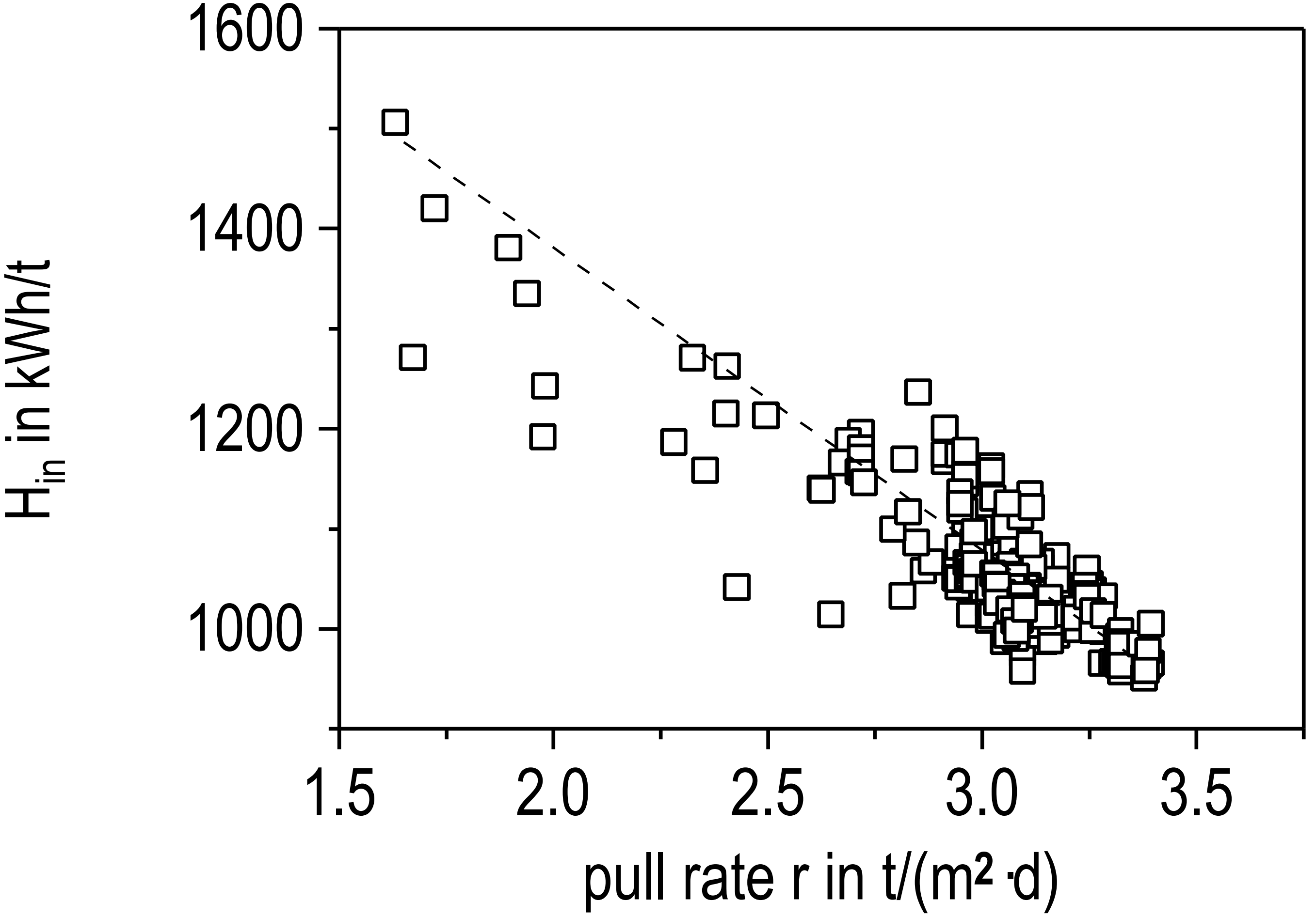
7. $H_{AGE\ OF\ AGGREGATE} \propto (1 + a \cdot t)$

8. $H_{TECHNICAL\ CONSTRAINTS}$

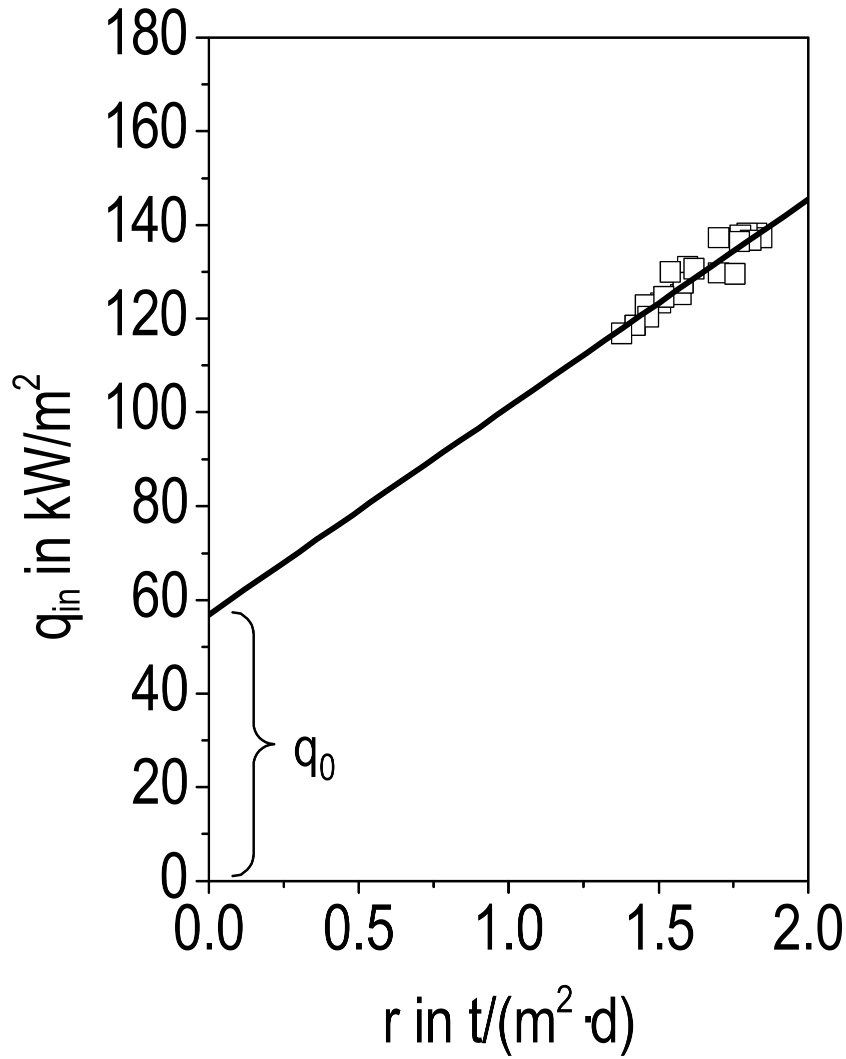
large furnaces with small heat leak show a point of minimum heat demand per t of produced glass



for a small furnace with high heat leak, the minimum is not observed



a plot of $H_{in} \cdot r$ versus r yields a straight line:



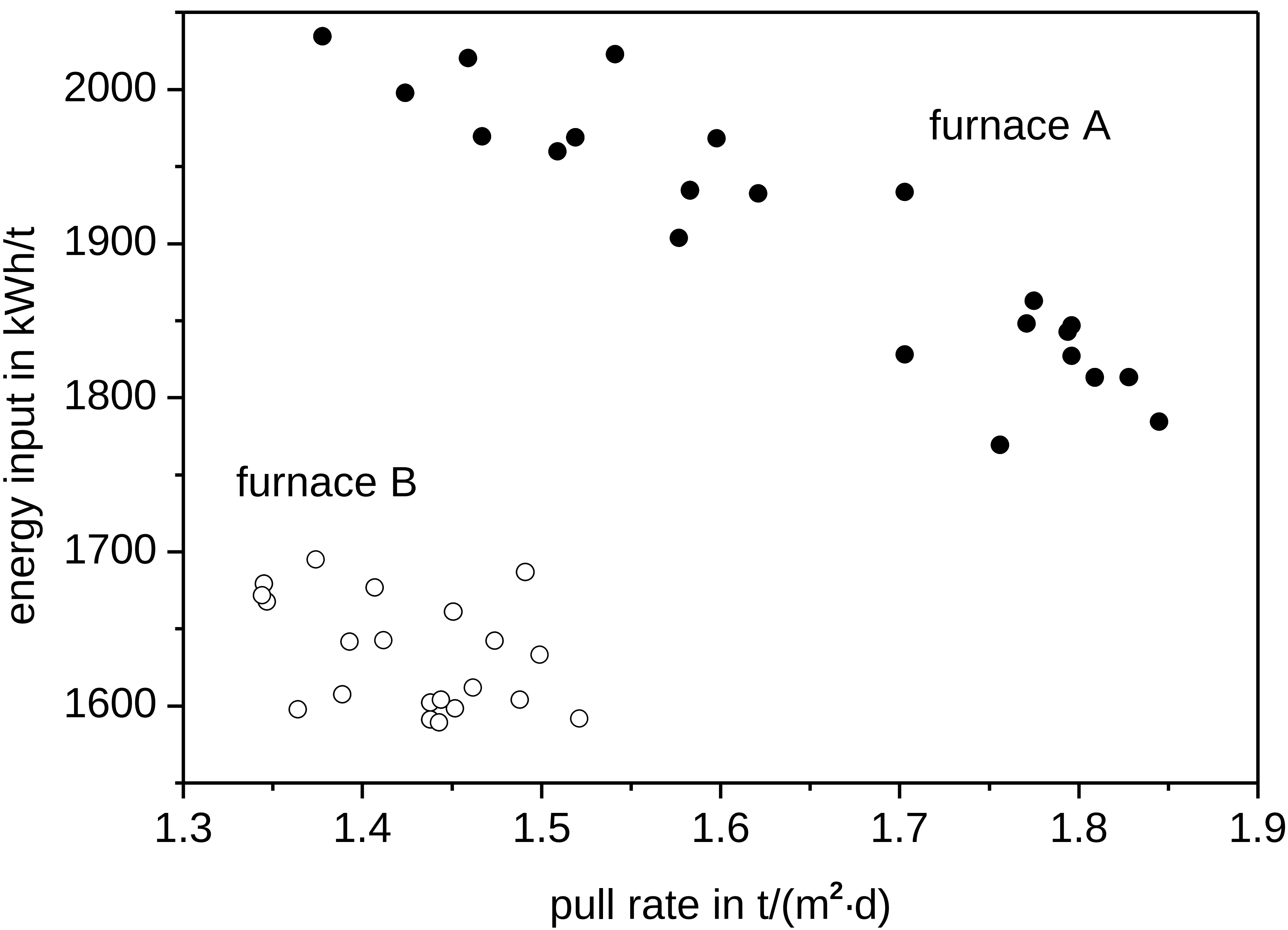
$$q_{in} = q_0 + H_0 \cdot r$$

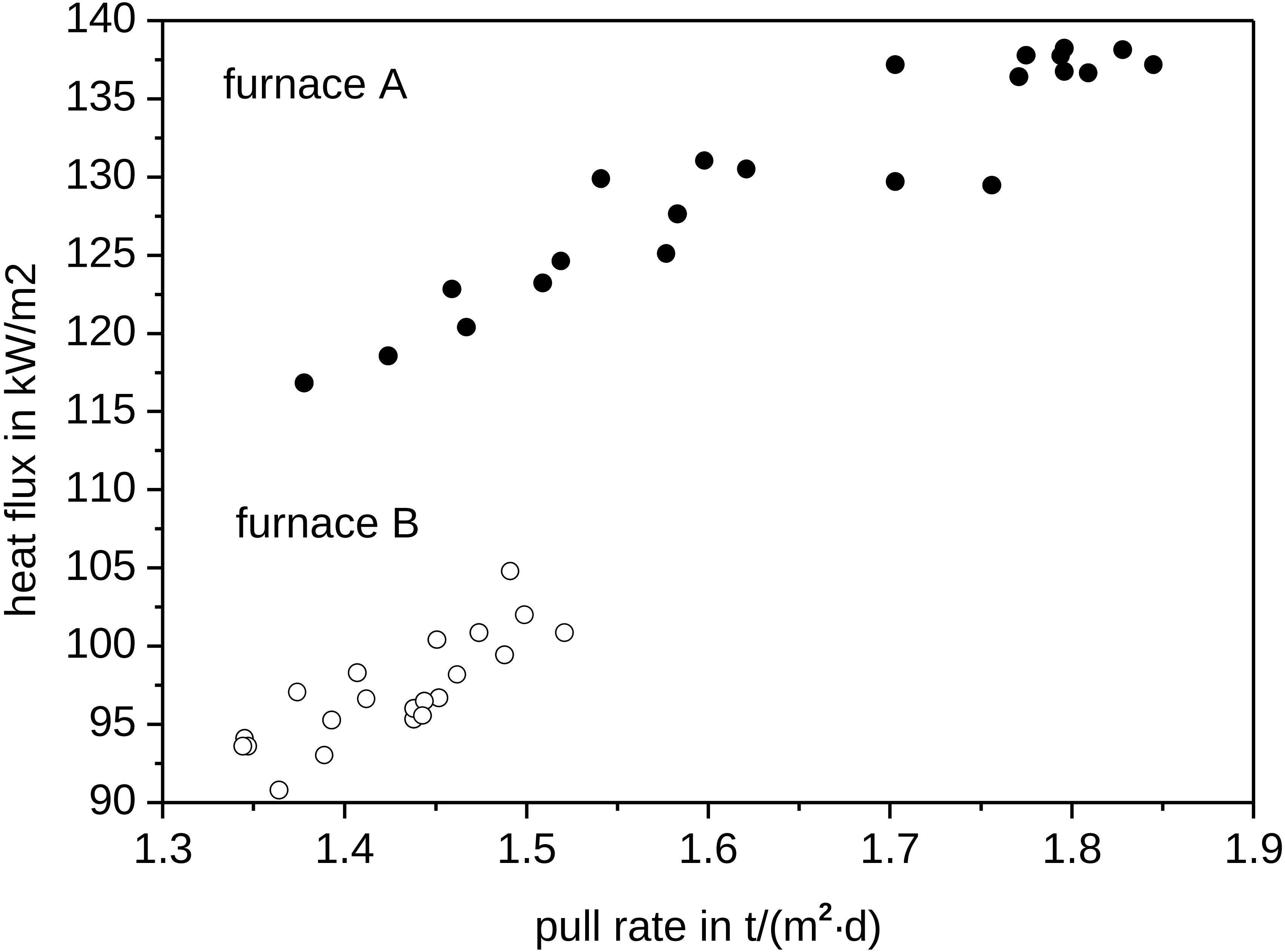
and

$$q_{in} = H_{in} \cdot r$$

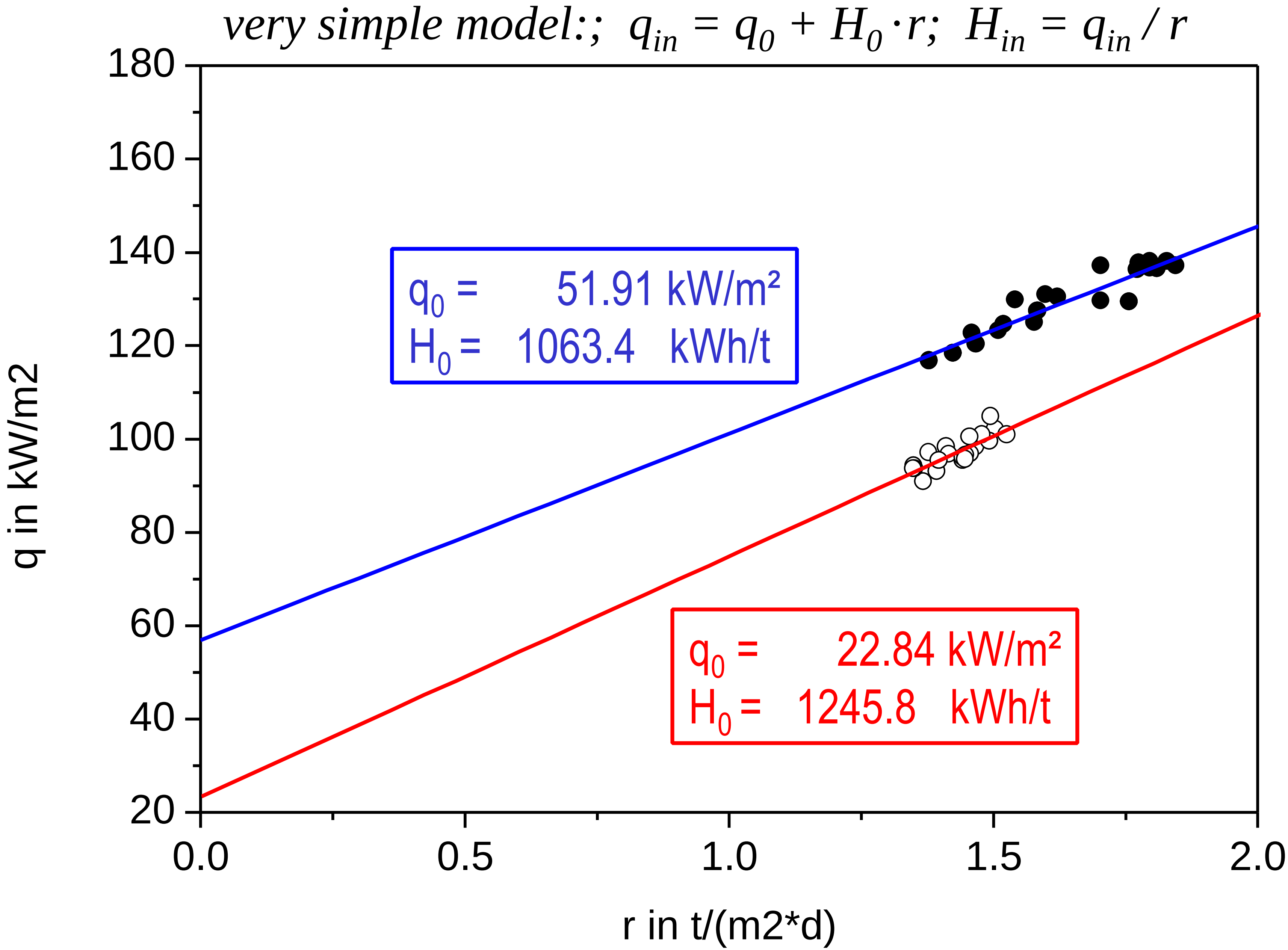
$$\Rightarrow$$

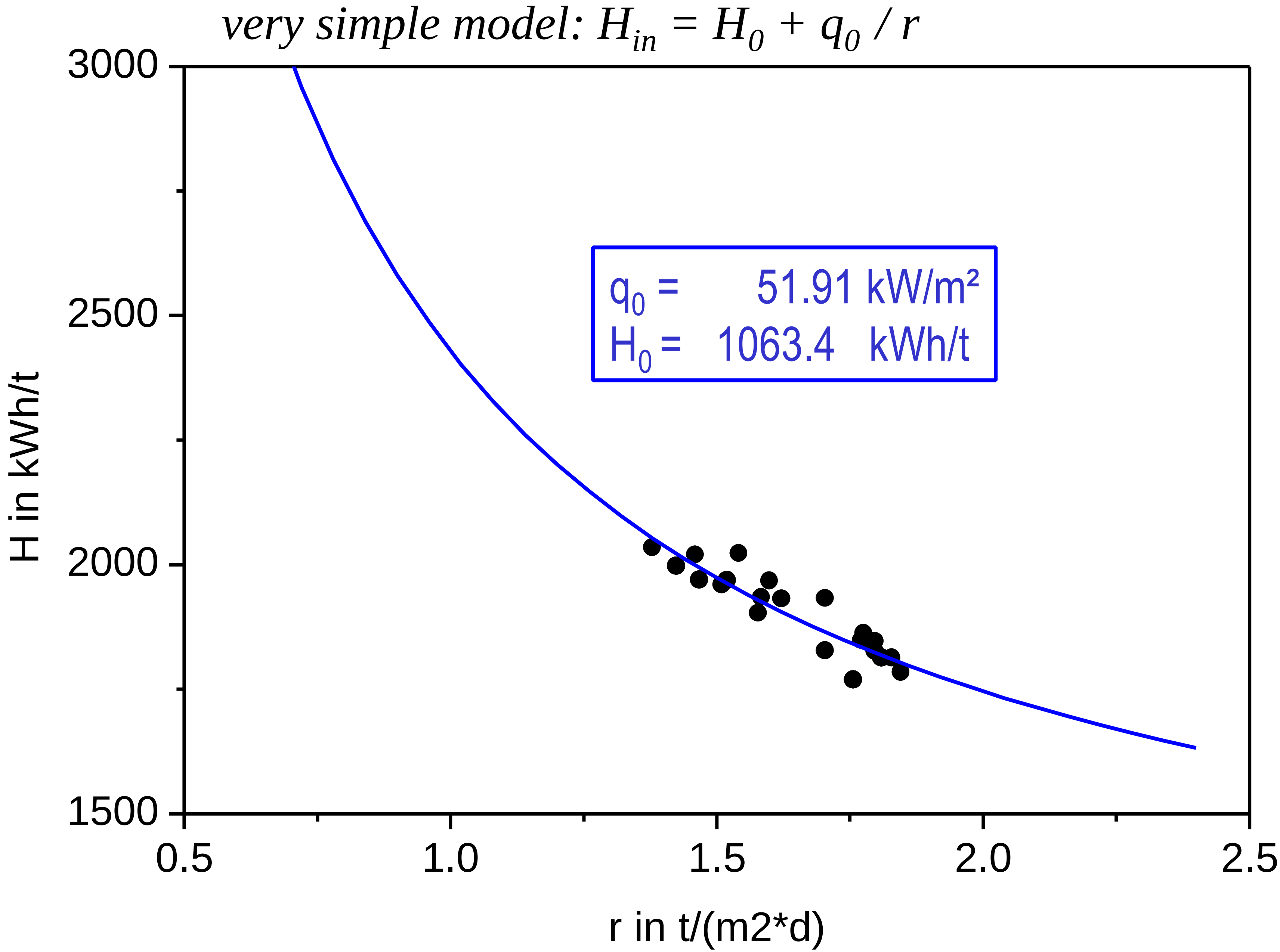
$$H_{in} = H_0 + \frac{q_0}{r} \propto \frac{1}{r}$$

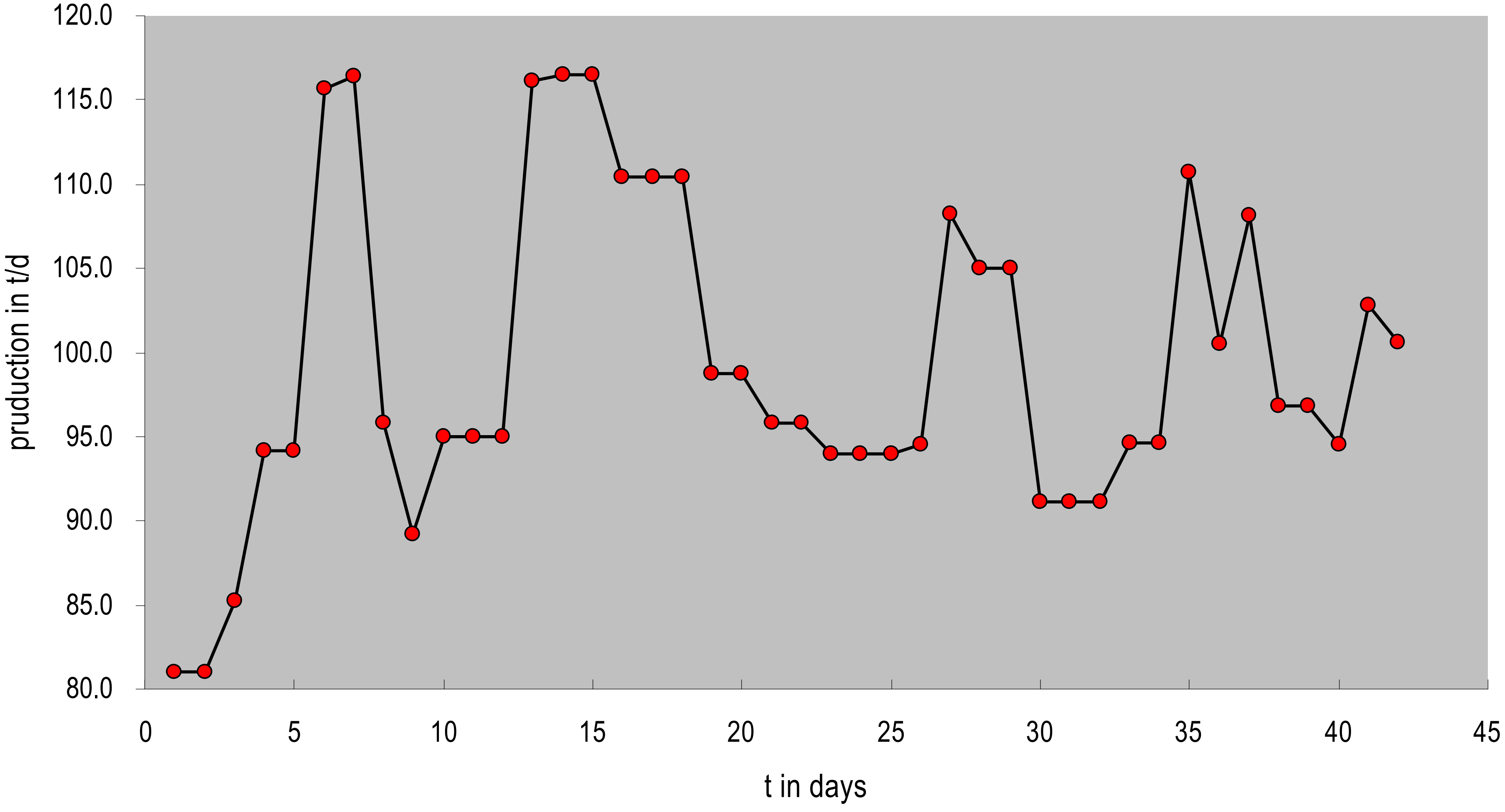

furnace A
furnace B
2000
1900
1800
1700
1600
energy input in kWh/t
1.3
1.4
1.5
1.6
1.7
1.8
1.9
pull rate in t/(m²·d)



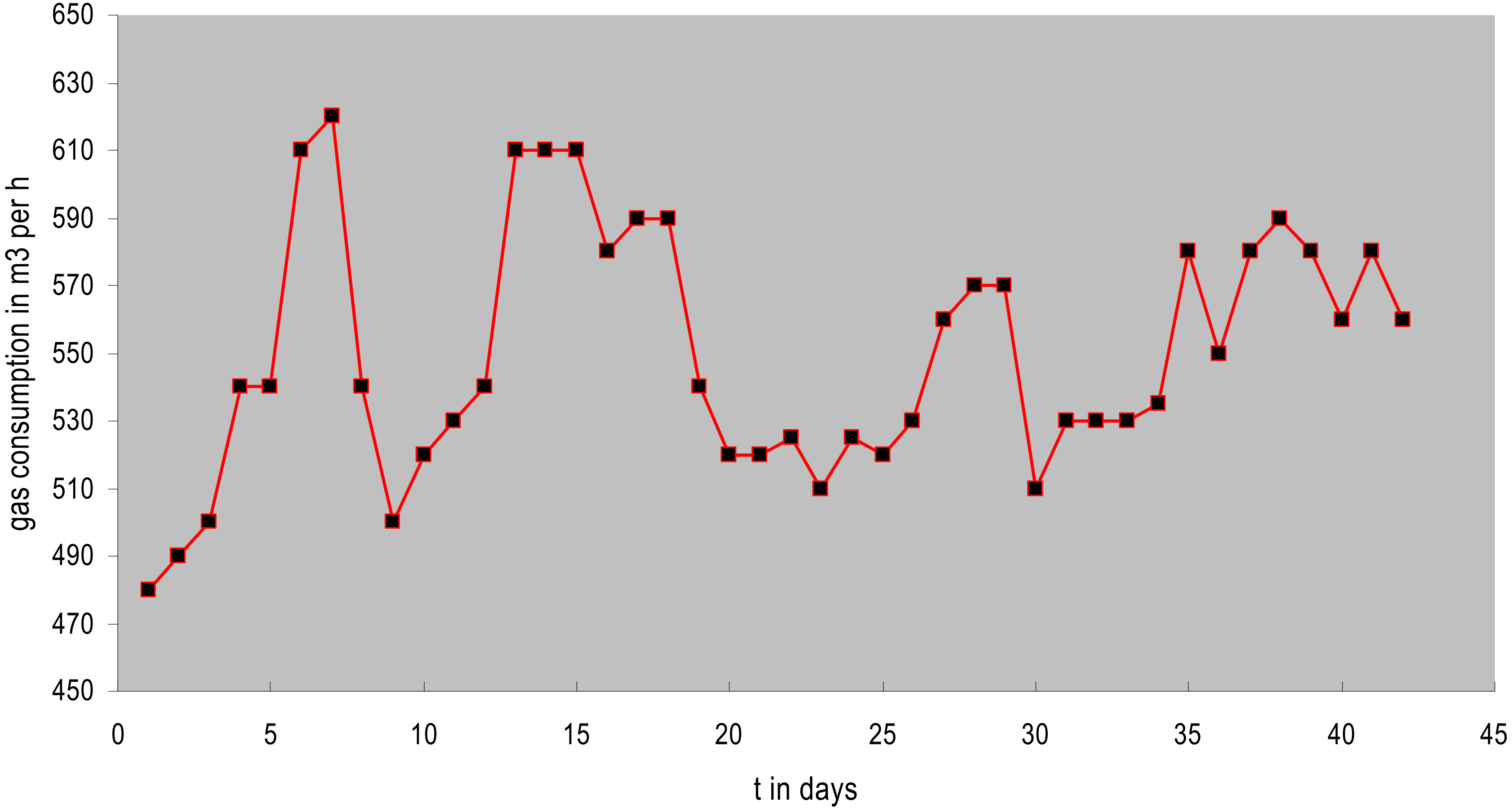
furnace A
furnace B
heat flux in kW/m2
pull rate in t/(m²·d)
140
135
130
125
120
115
110
105
100
95
90
1.3
1.4
1.5
1.6
1.7
1.8
1.9


very simple model:; q_in = q_0 + H_0·r; H_in = q_in / r
q_0 = 51.91 kW/m²
H_0 = 1063.4 kWh/t
q_0 = 22.84 kW/m²
H_0 = 1245.8 kWh/t
q in kW/m2
r in t/(m2*d)
20
40
60
80
100
120
140
160
180
0.0
0.5
1.0
1.5
2.0

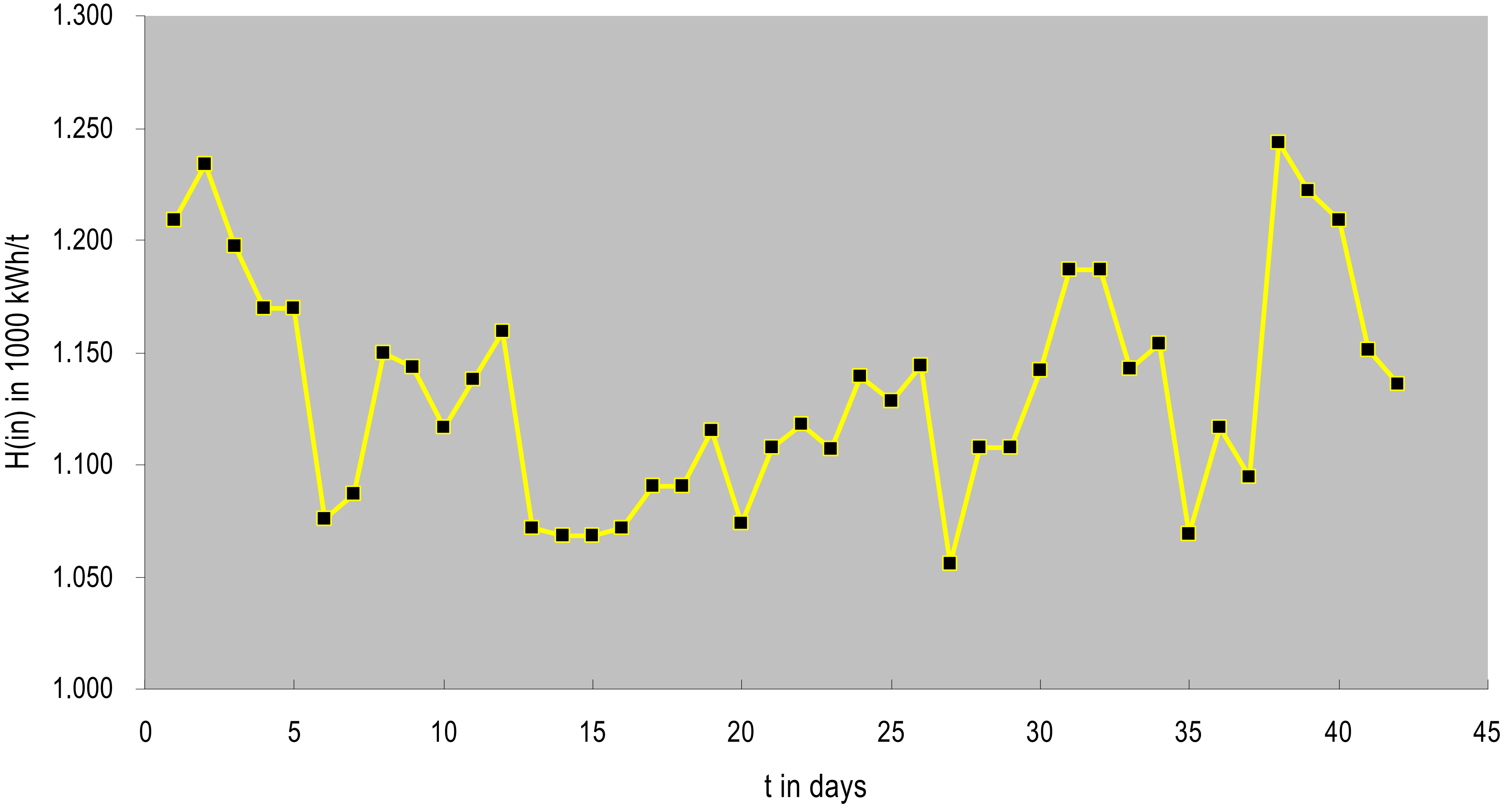

very simple model: $H_{in} = H_0 + q_0 / r$
3000
2500
2000
1500
H in kWh/t
q_0 = 51.91 kW/m²
H_0 = 1063.4 kWh/t
0.5
1.0
1.5
2.0
2.5
r in t/(m2*d)



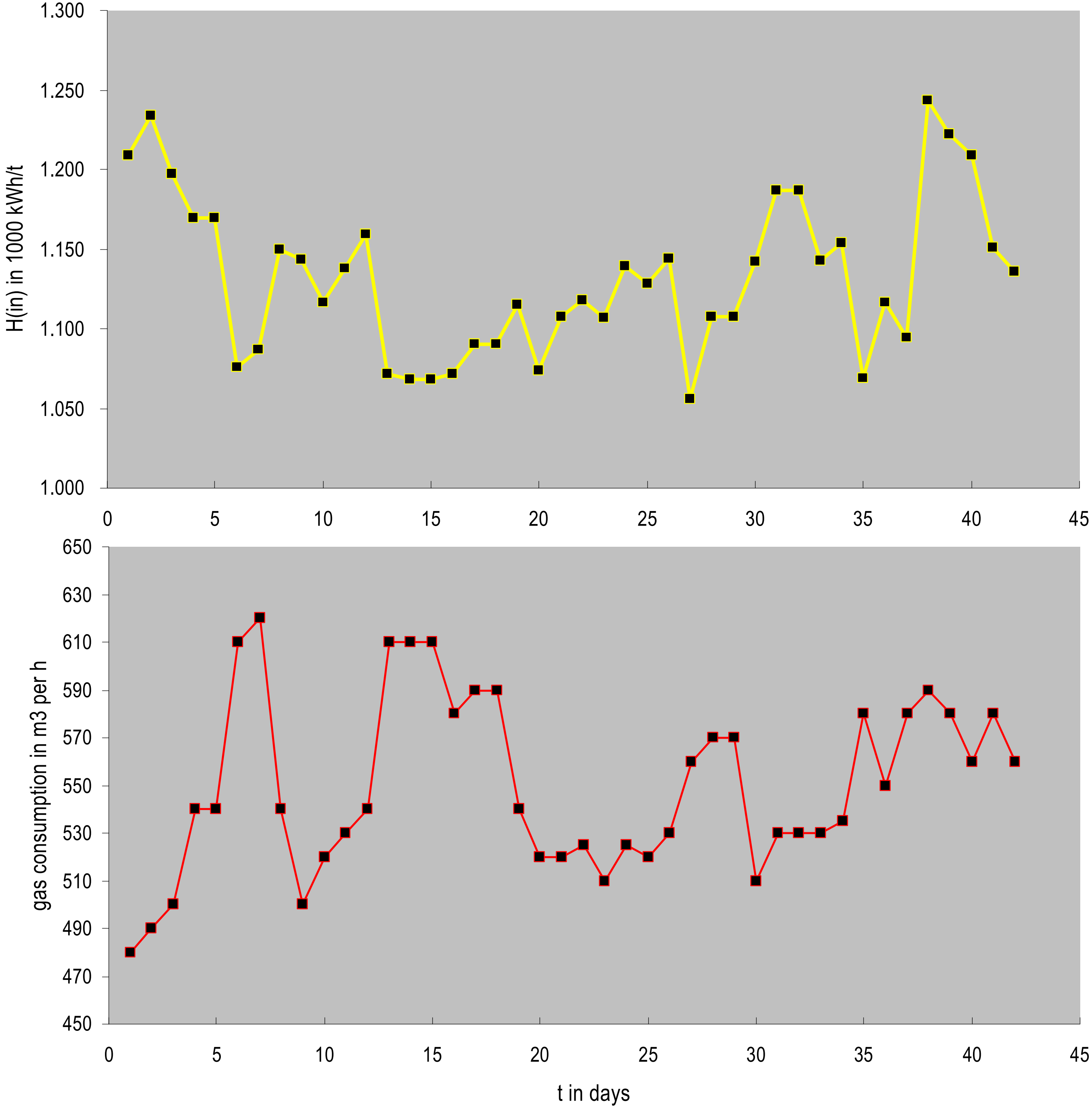
120.0
115.0
110.0
105.0
100.0
95.0
90.0
85.0
80.0
pruduction in t/d
0
5
10
15
20
25
30
35
40
45
t in days



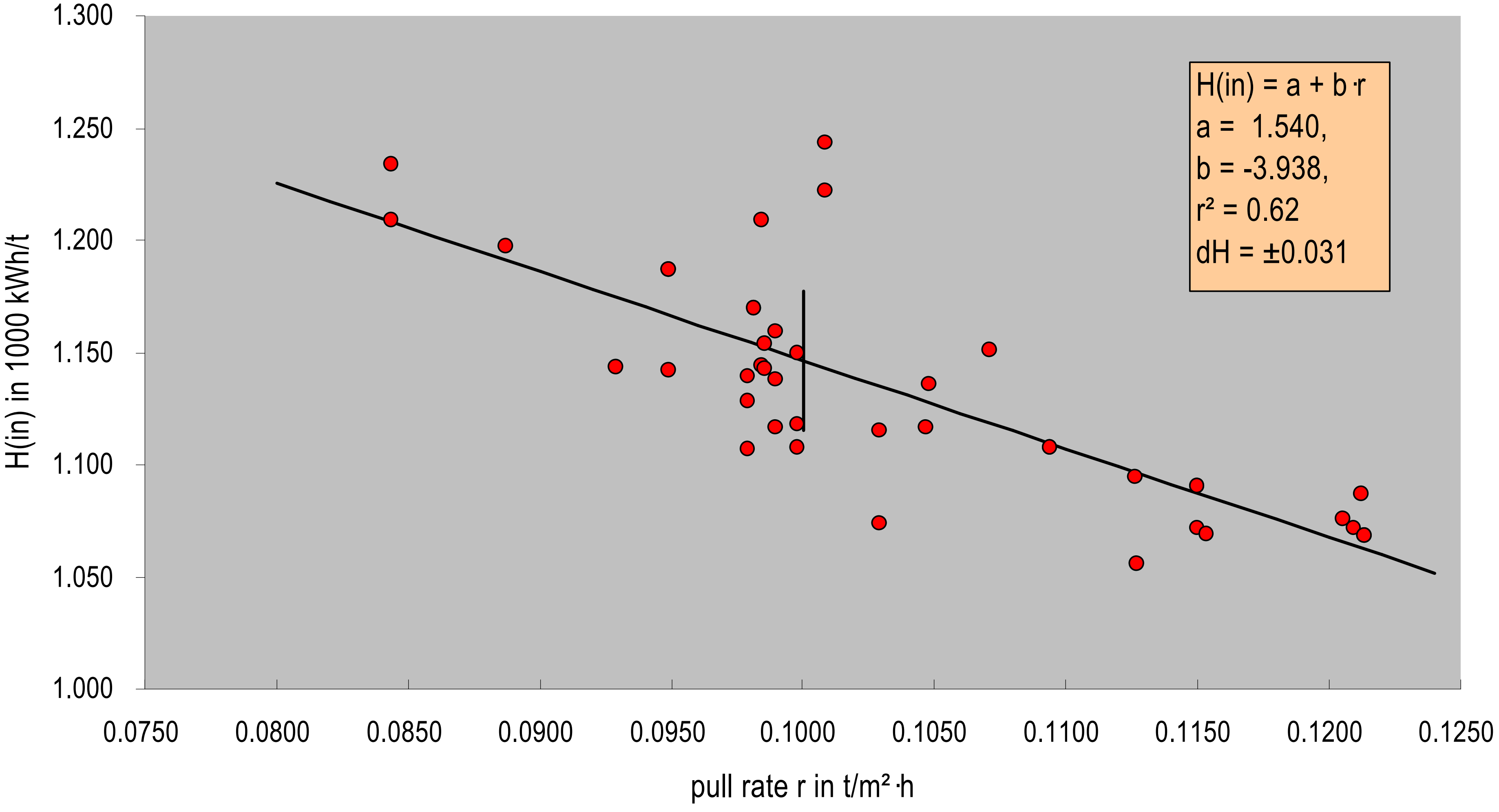
gas consumption in m3 per h
650
630
610
590
570
550
530
510
490
470
450
0
5
10
15
20
25
30
35
40
45
t in days



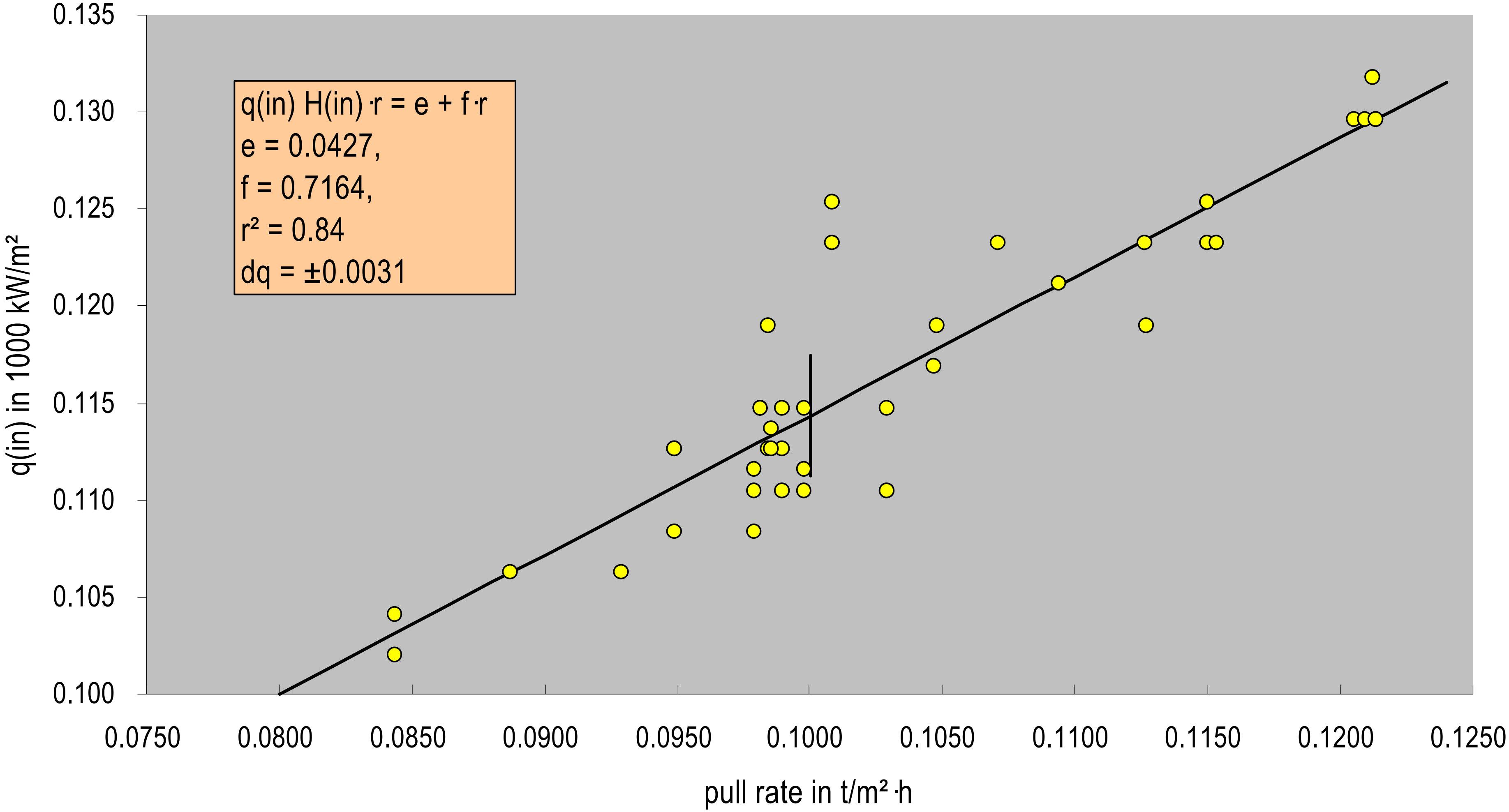
1.300
1.250
1.200
1.150
1.100
1.050
1.000
H(in) in 1000 kWh/t
0
5
10
15
20
25
30
35
40
45
t in days



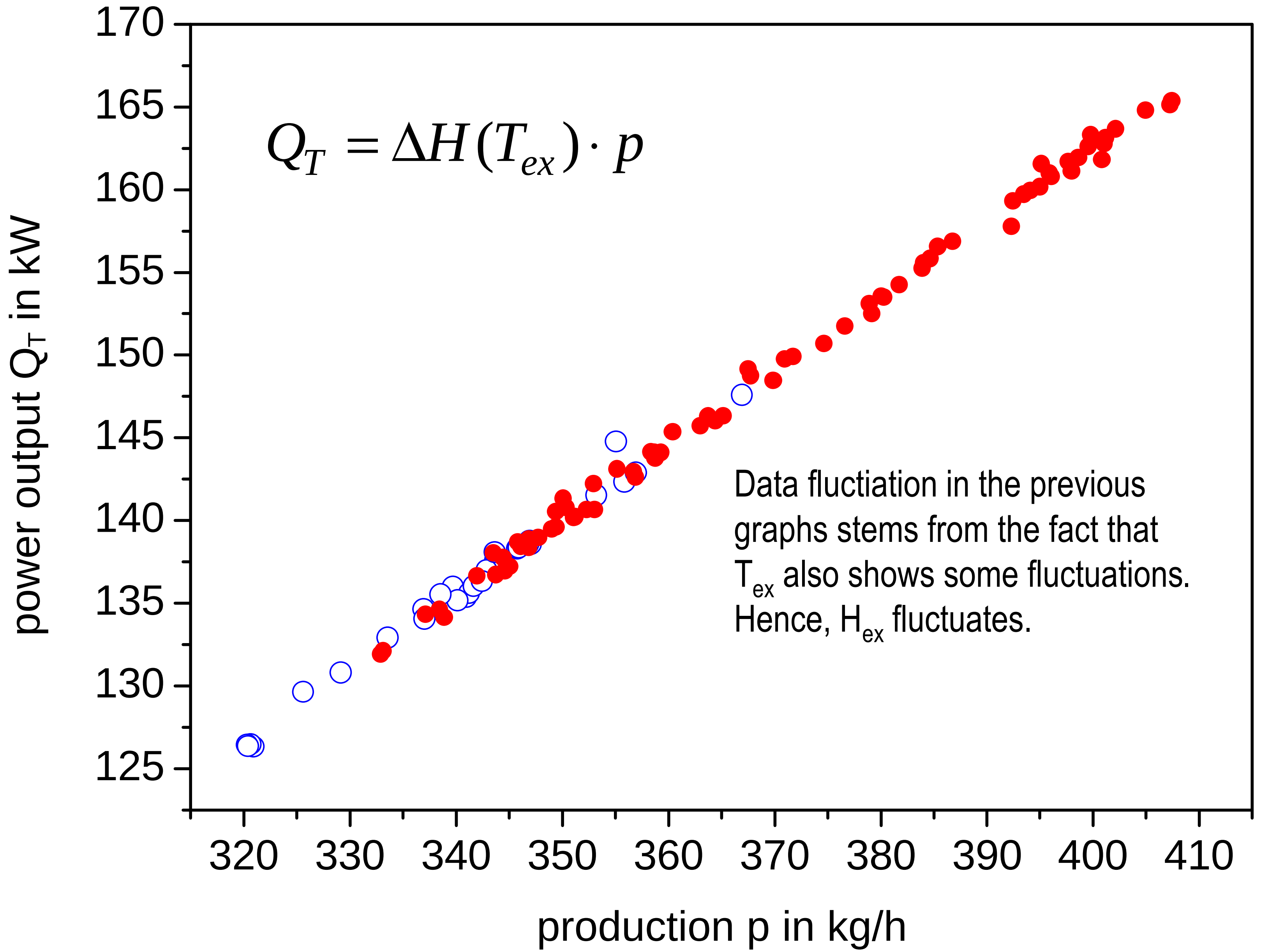
H(in) in 1000 kWh/t
1.300
1.250
1.200
1.150
1.100
1.050
1.000
0
5
10
15
20
25
30
35
40
45
gas consumption in m3 per h
650
630
610
590
570
550
530
510
490
470
450
0
5
10
15
20
25
30
35
40
45
t in days



1.300
1.250
1.200
1.150
1.100
1.050
1.000
H(in) in 1000 kWh/t
0.0750
0.0800
0.0850
0.0900
0.0950
0.1000
0.1050
0.1100
0.1150
0.1200
0.1250
pull rate r in t/m² ·h
H(in) = a + b ·r
a = 1.540,
b = -3.938,
r² = 0.62
dH = ±0.031


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

The best way of evaluation is the assessment of the true ouptput power.



practice

#furnace data.XLS

#heat balance.xls

examples

melting behavior

=

heat demand

$\oplus$

quartz dissolution rate

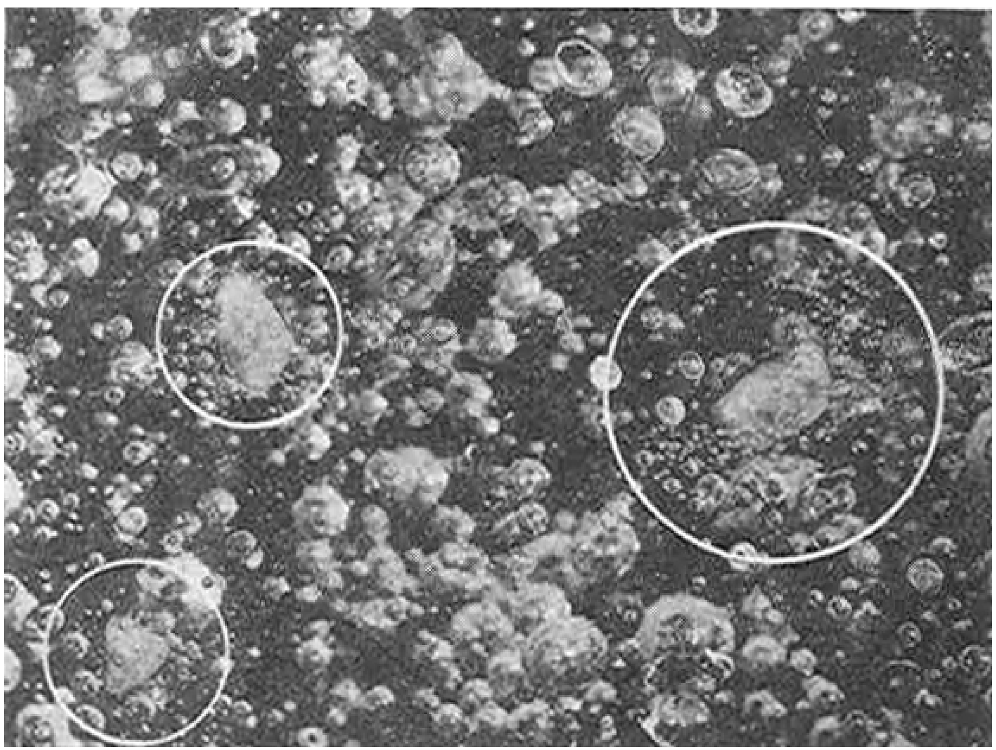
$\oplus$

gas release rate

DH_{chem} does not tell the whole story!

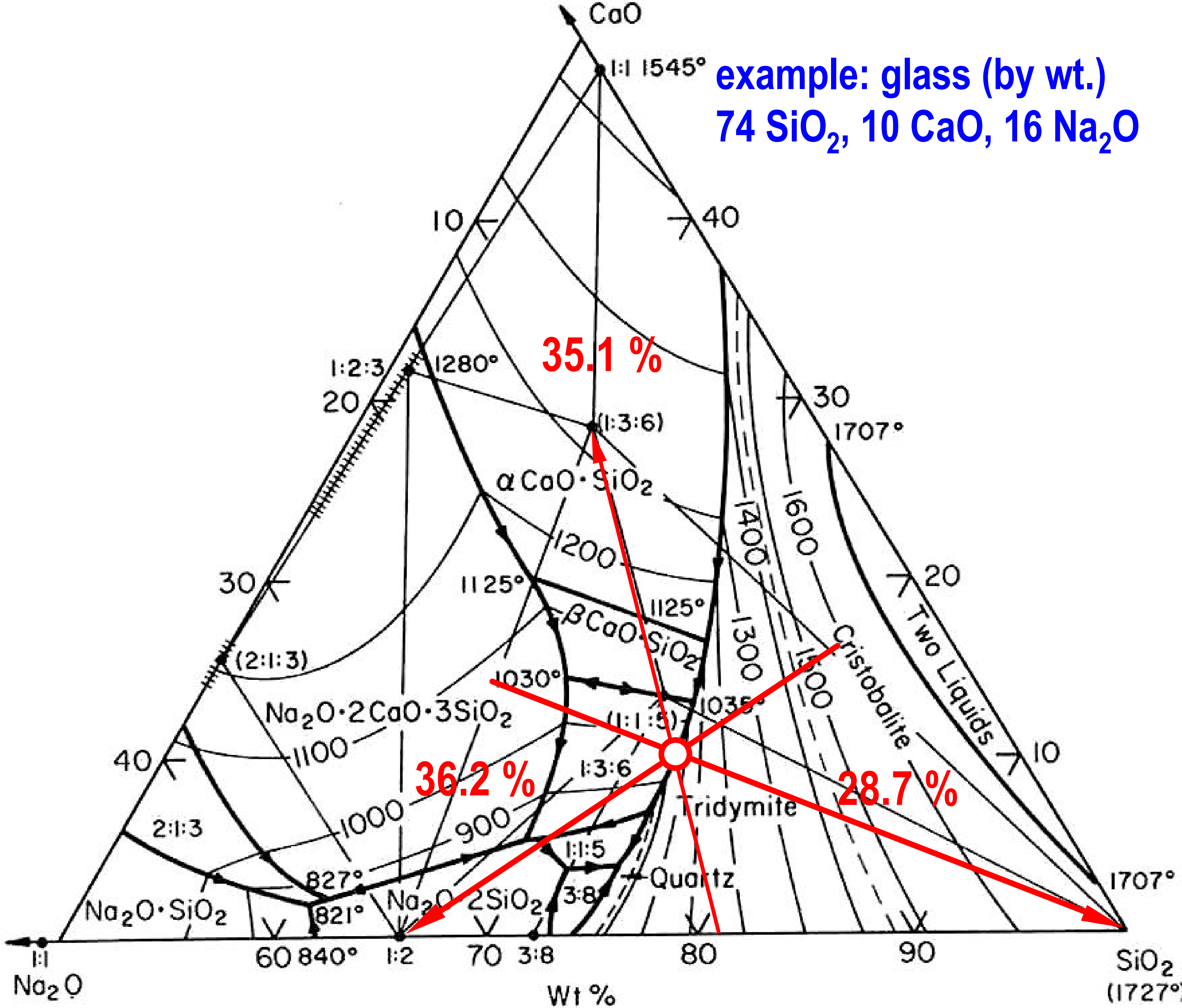
quartz:	H°	= 910.9 kJ/mol
silica glass:	H°	= 901.4 kJ/mol
	DH_{chem}	= 9.5 kJ/mol
		= 43.9 kWh/t

As DH_{chem} for a conventional batch is approx. 140 kWh/t, is adding quartz sand a good way to save energy? OF COURSE NOT! Slow quartz dissolution is a main reason for late fining, long dwell times, high energy consumption.



DESIGN LOW RESIDAL SILICA BATCHES!

example: glass (by wt.)
74 SiO_2, 10 CaO, 16 Na_2O



raw material i	kg/t		oxide j	kg/t		phase k	kg/t
sand	666.96		SiO_2	720.00		SiO_2	227.05
feldspar	77.15		Al_2O_3	15.00		$Na_2O\cdot Al_2O_3\cdot 6SiO_2$	77.15
dolomite	182.98		MgO	40.00		$MgO\cdot SiO_2$	99.62
limestone	34.54		CaO	75.00		$Na_2O\cdot 3CaO\cdot 6SiO_2$	263.34
soda ash	240.91		Na_2O	150.00		$Na_2O\cdot 2SiO_2$	332.84
			CO_2	202.54			
sum	1202.54			1202.54			1000.00

H°(batch) = 4589.5 kWh

H°(gl) = 3942.3 kWh

H°(gas) = 503.0 kWh;

ΔH°_{chem} = 144.2 kWh

ΔH_T(gl) = 404.1 kWh, T = 25 to 1200 °C

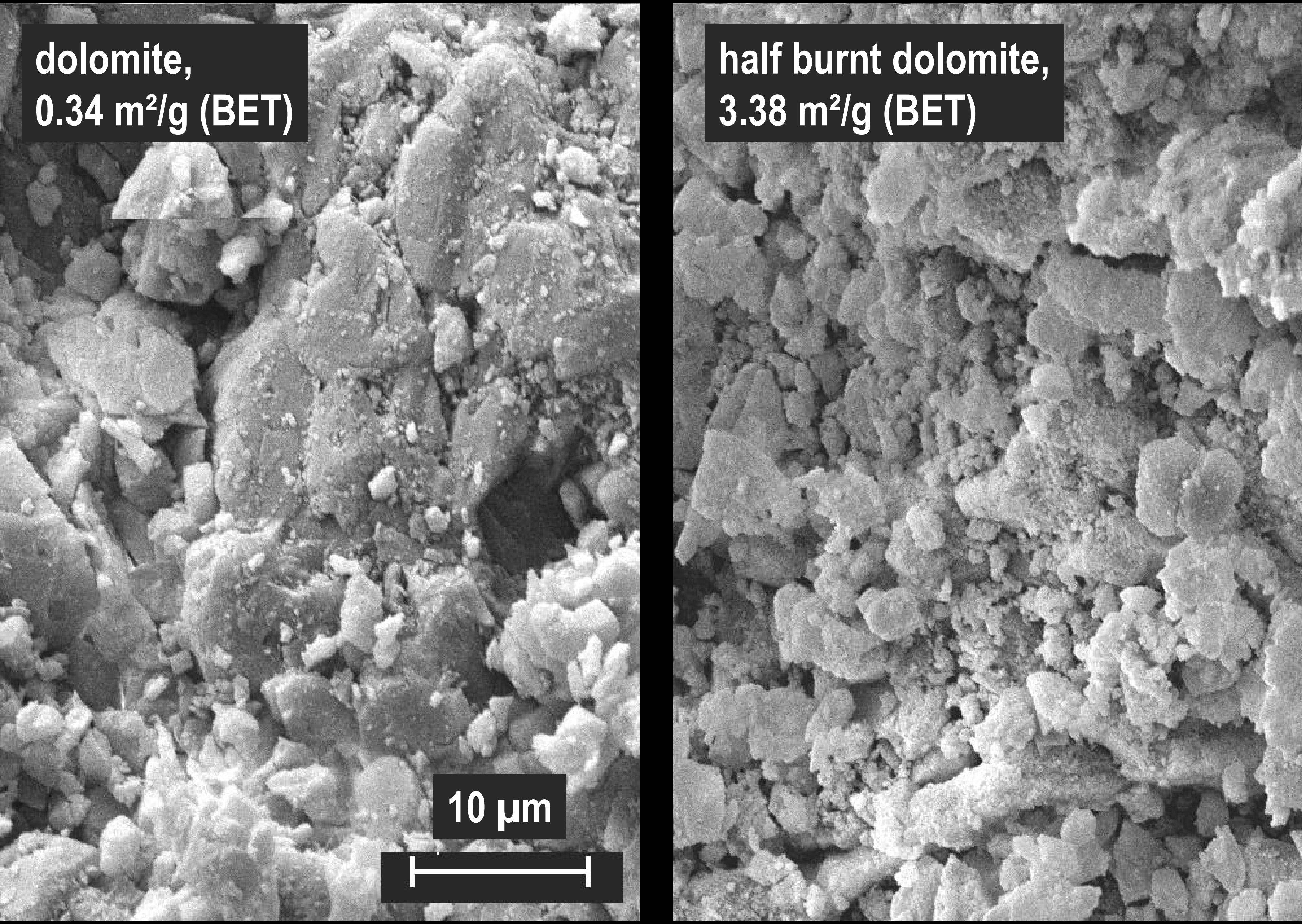
ΔH_T(gas) = 90.2 kWh, T = 25 to 1400 °C

raw material i	kg/t		oxide j	kg/t		phase k	kg/t
sand	666.96		SiO_2	720.00		SiO_2	227.05
feldspar	77.15		Al_2O_3	15.00		$Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	77.15
dolomite	182.98		MgO	40.00		$MgO{\cdot}SiO_2$	99.62
limestone	34.54		CaO	75.00		$Na_2O{\cdot}3CaO{\cdot}6SiO_2$	263.34
soda ash	240.91		Na_2O	150.00		$Na_2O{\cdot}2SiO_2$	332.84
			CO_2	202.54			
sum	1202.54			1202.54			1000.00

H°(batch) = 4589.5 kWh
H°(gl) = 3942.3 kWh
H°(gas) = 503.0 kWh;
D$H°_{chem}$ = 144.2 kWh
DH_T(gl) = 404.1 kWh, T = 25 to 1200 °C
DH_T(gas) = 90.2 kWh, T = 25 to 1400 °C

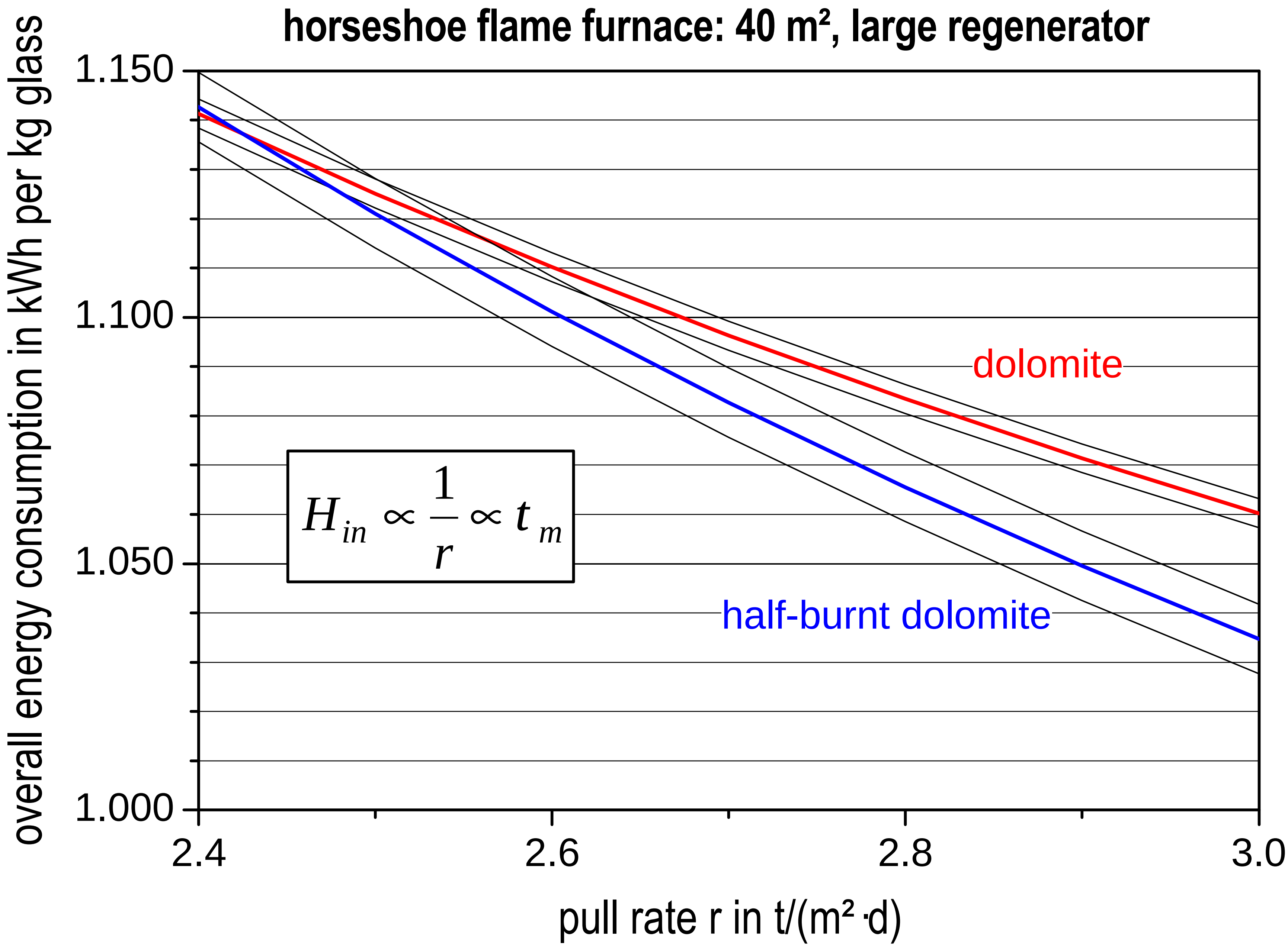
residual amount of crystalline SiO_2: >23 %, dissolved by diffusion, not by chem reaction

NOTE: Each raw material by itself is a multioxide mineral system.


dolomite,
0.34 m²/g (BET)
10 µm
half burnt dolomite,
3.38 m²/g (BET)

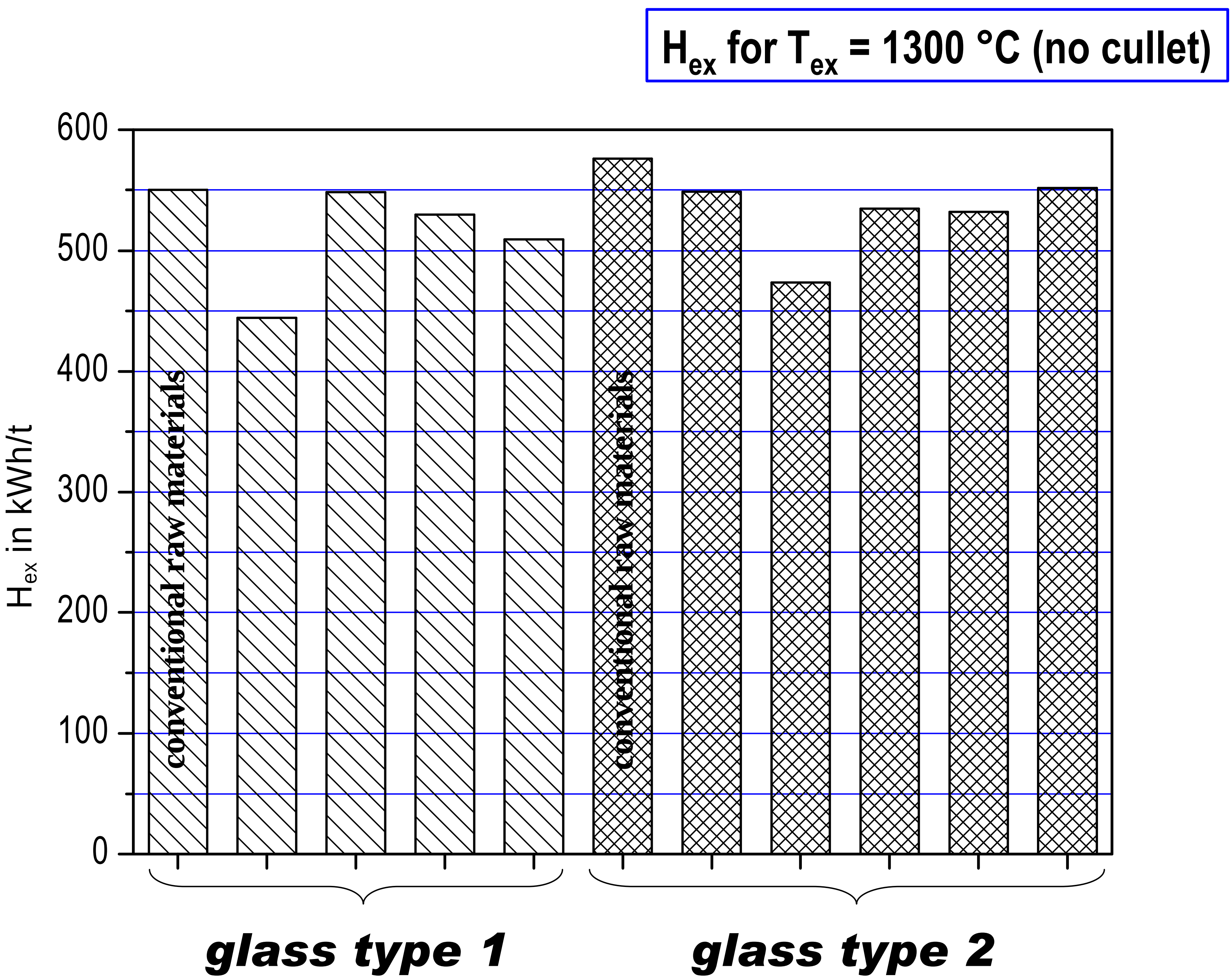
	$H°$	$\Delta_r H°$	$\Delta_r H°$ per [MgO]		4 % MgO
	kJ/mol	kJ/mol	MJ/kg	kWh/kg	kWh/t glass
dolomite	2314.2	290.7	7.21	2.00	80
half-burnt	1808.5	178.5	4.43	1.23	49
difference		112.2	2.78	0.77	31

depending on η_{ex} (30 – 55 %) $\Rightarrow$ 60 – 105 kWh (0 % cullet)
43 – 80 kWh (25 %)


horseshoe flame furnace: 40 m², large regenerator
overall energy consumption in kWh per kg glass
1.150
1.100
1.050
1.000
2.4
2.6
2.8
3.0
pull rate r in t/(m²·d)
dolomite
half-burnt dolomite
$H_{in} \propto \frac{1}{r} \propto t_m$

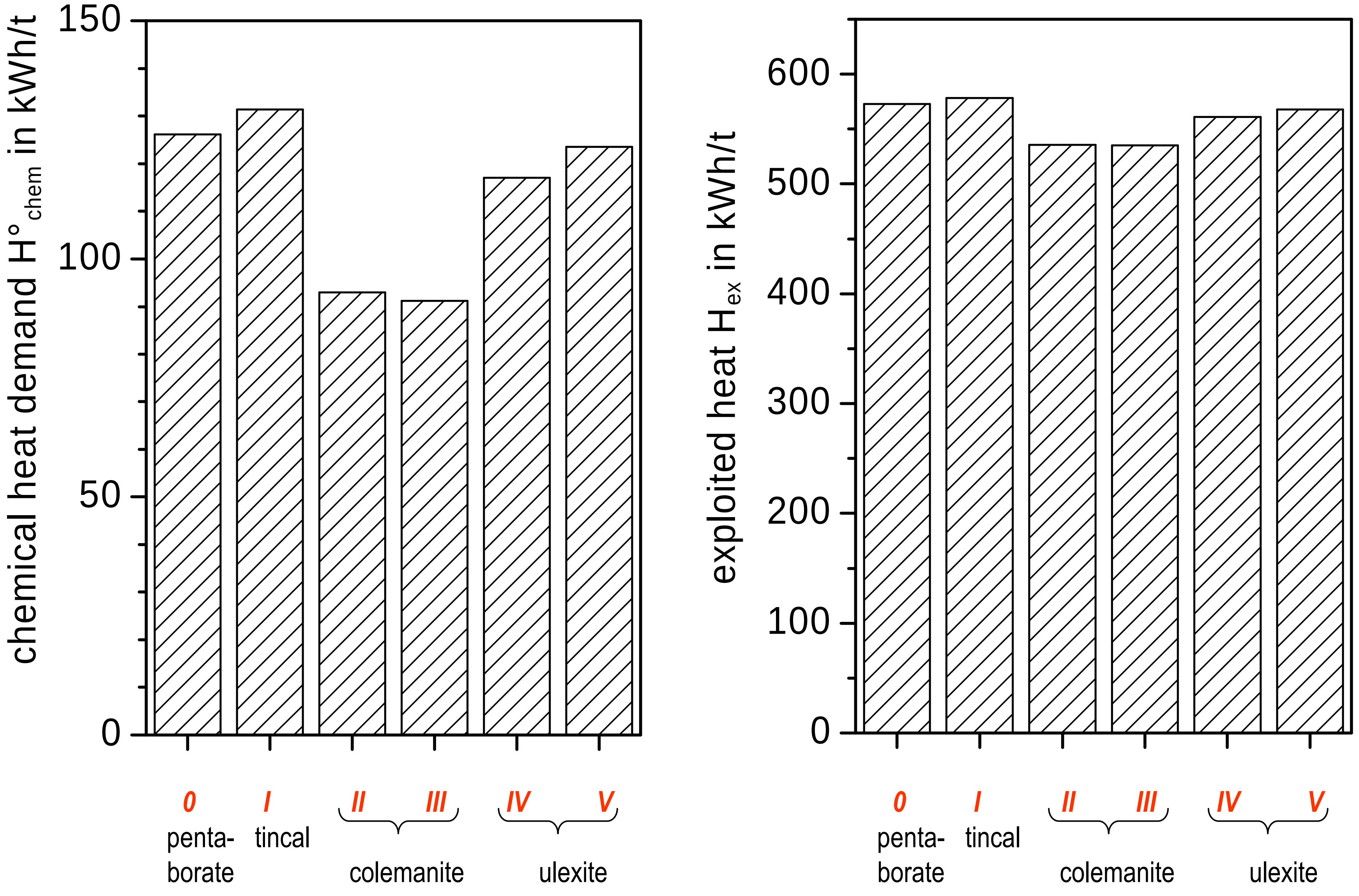
Normalized composition of theoretical and real raw materials

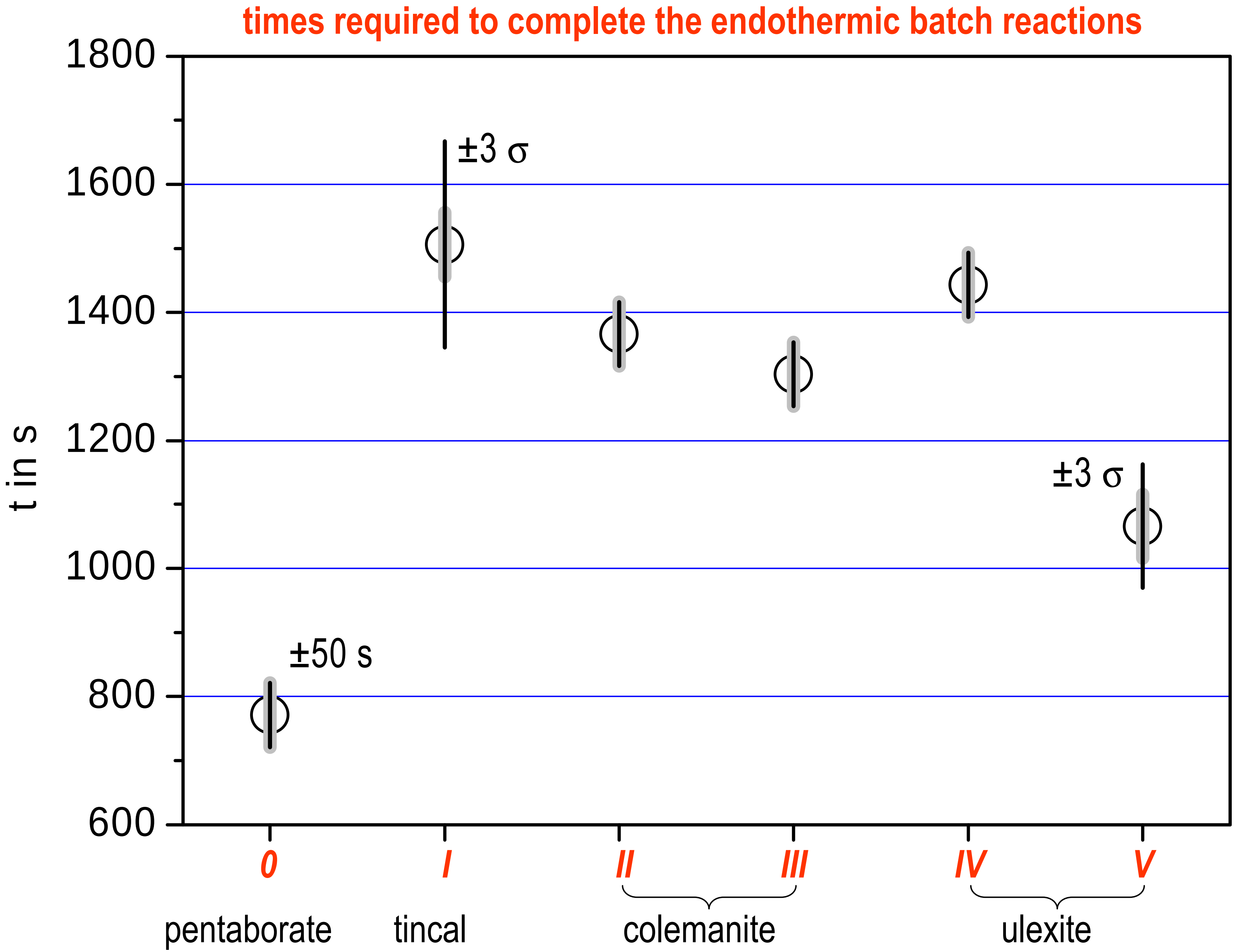
	NB_2H_5	NB_2H_{10}	tincal	$C_2B_3H_5$	colemanite	$NC_2B_5H_{16}$	ulexite
	penta	deca	real		real		real
oxide content in kg per kg of raw material							
SiO_2			0.0220		0.0370		0.0290
TiO_2			0.0001		0.0001		
Al_2O_3			0.0016		0.0014		0.0008
B_2O_3	0.4780	0.3651	0.4830	0.5081	0.4310	0.4295	0.3770
Fe_2O_3			0.0006		0.0006		0.0030
MgO			0.0242		0.0161		0.0142
CaO			0.0289	0.2728	0.2670	0.1384	0.1670
SrO			0.0027		0.0095		0.0061
Na_2O	0.2128	0.1625	0.2220		0.0008	0.0765	0.0636
K_2O			0.0011		0.0005		0.0003
released gases in kg per kg of raw material							
$CO_2(g)$					0.0455		0.0340
$H_2O(g)$	0.3092	0.4724	0.2126	0.2191	0.1859	0.3556	0.3043
$SO_2(g)$			0.0010		0.0026		0.0006
$O_2(g)$			0.0002		0.0021		0.0001
balance in kg per kg raw material							
sum	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
glass	0.6908	0.5276	0.7862	0.7809	0.7640	0.6444	0.6610
gases	0.3092	0.4724	0.2138	0.2191	0.2360	0.3556	0.3390
heat of formation in kWh per kg of raw material							
$H°_{raw\ mat}$	4.5676	4.5625	4.4834	4.6891	4.5453	4.6353	4.5145



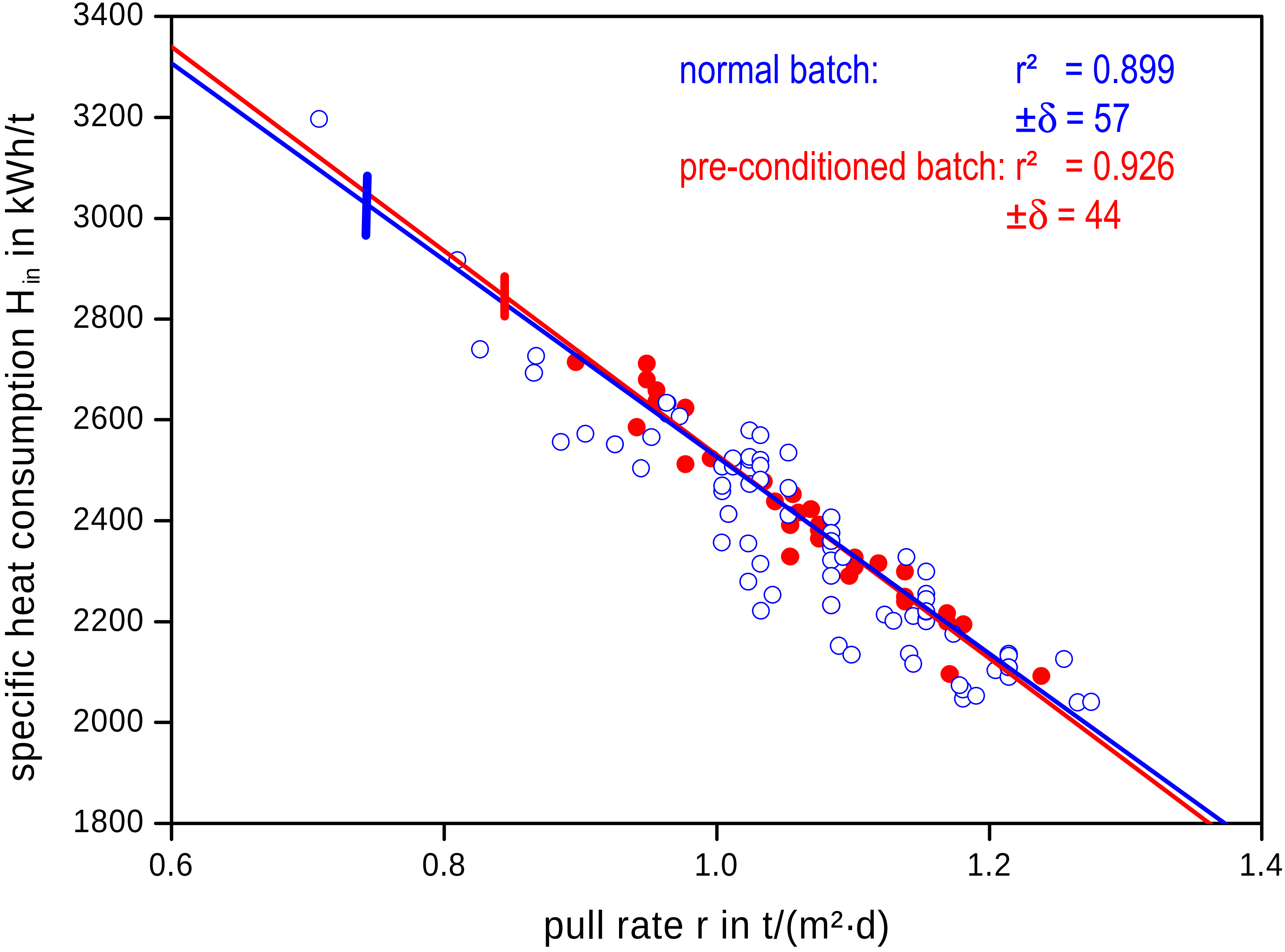
H_{ex} for T_{ex} = 1300 °C (no cullet)
H_{ex} in kWh/t
0
100
200
300
400
500
600
conventional raw materials
conventional raw materials
glass type 1
glass type 2

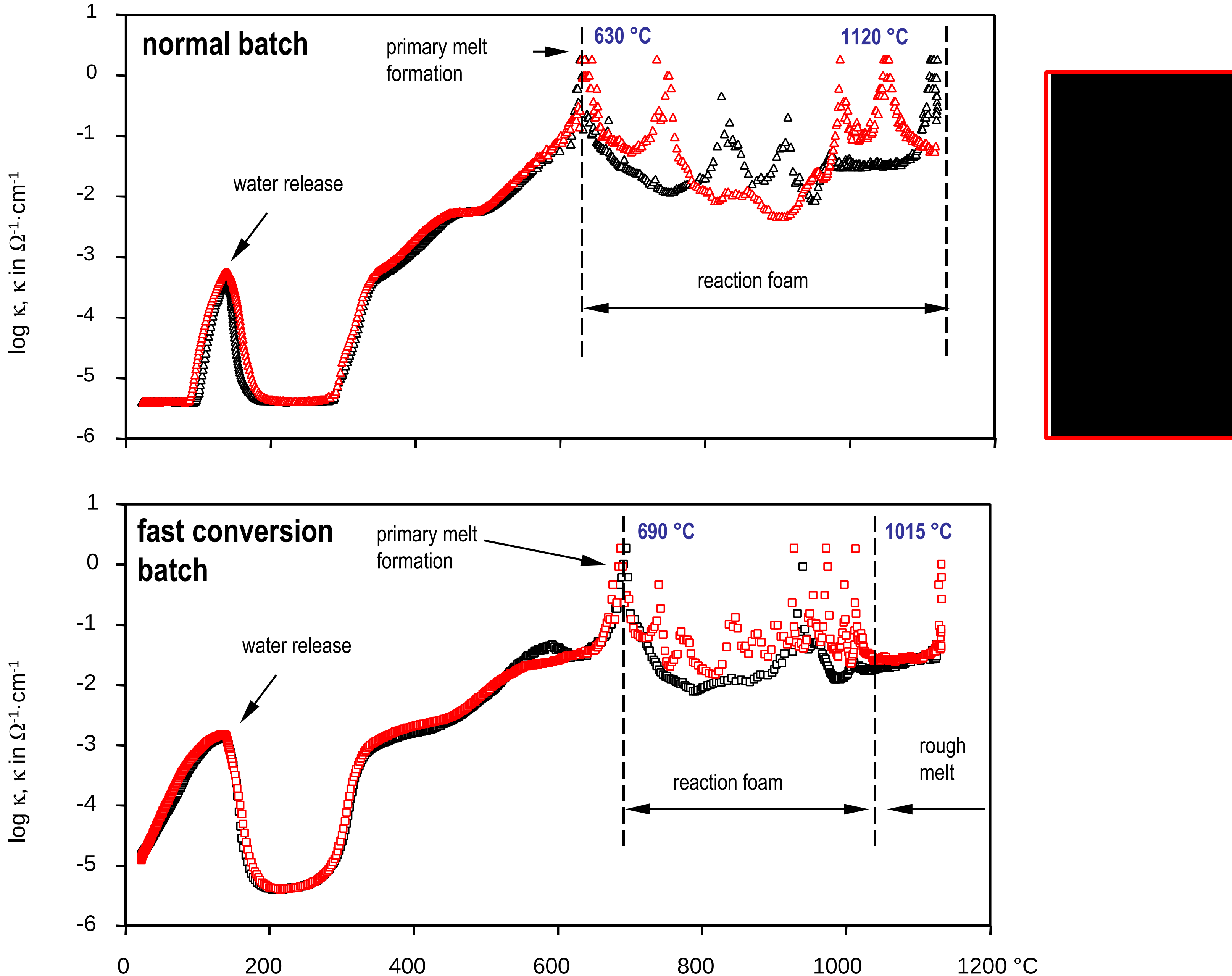
energy demand, calculated from real raw material composition

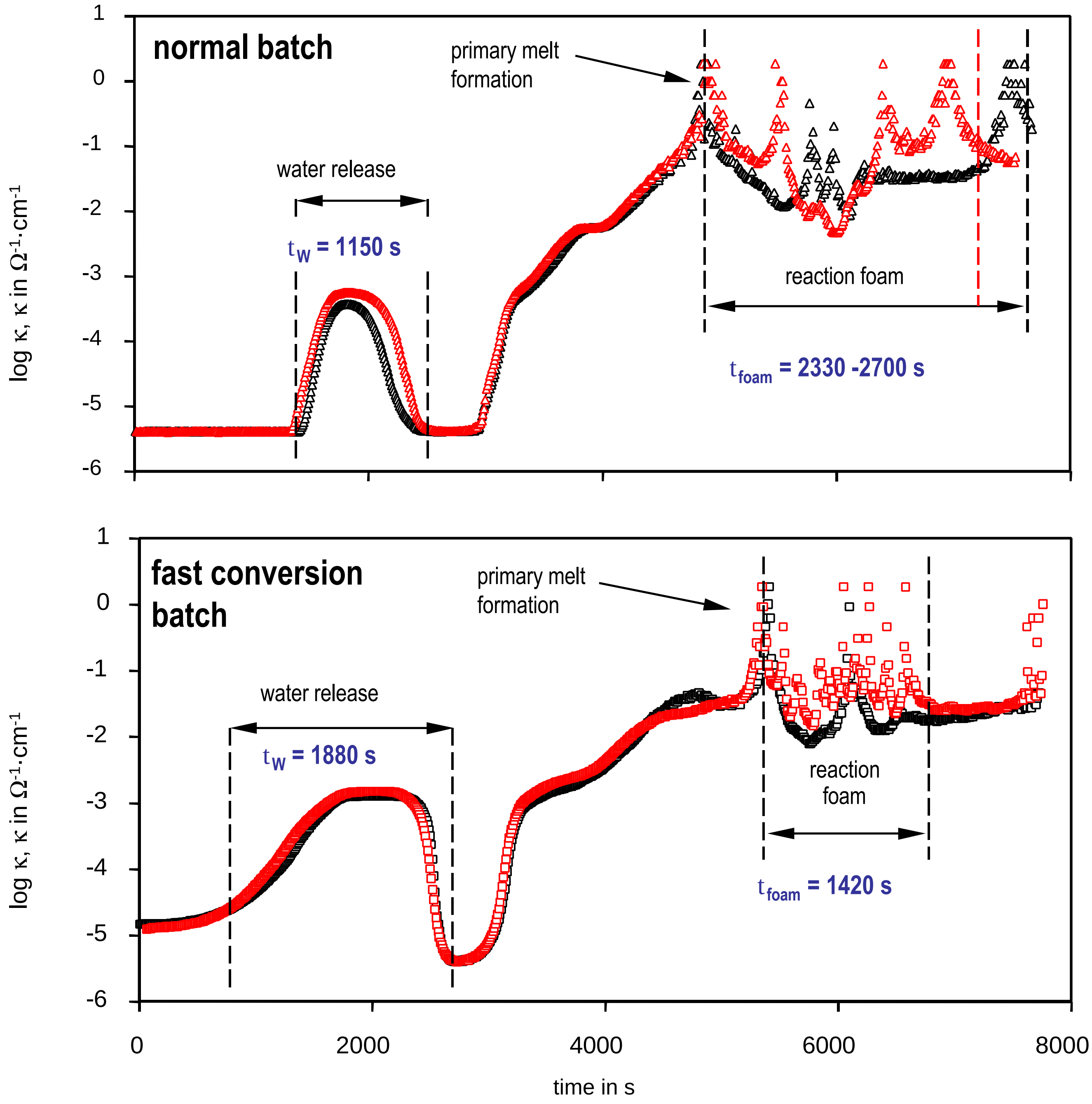



times required to complete the endothermic batch reactions
1800
1600
1400
1200
1000
800
600
t in s
±3 σ
±3 σ
±50 s
0
I
II
III
IV
V
pentaborate
tincal
colemanite
ulexite

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

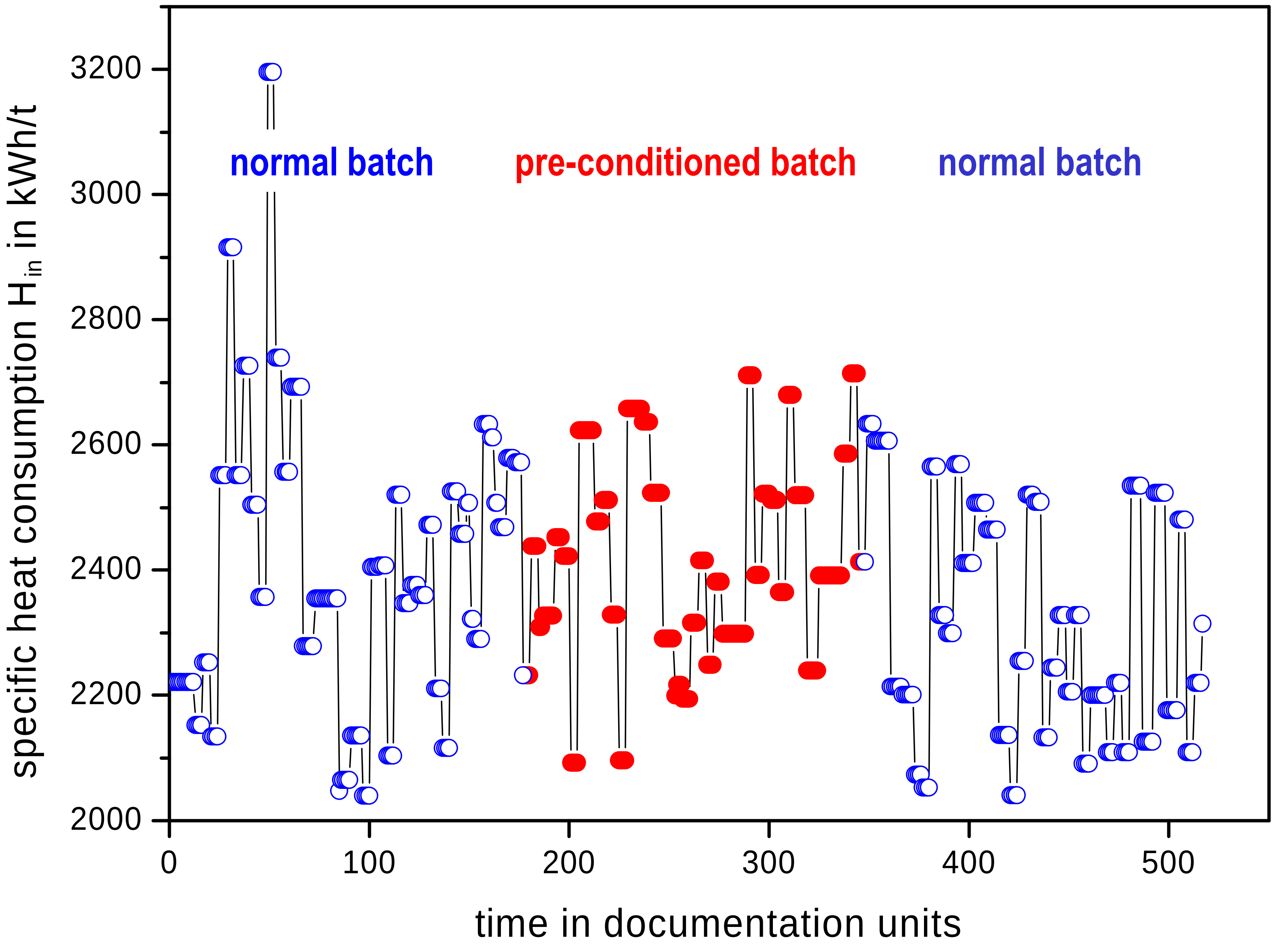



normal batch
primary melt formation
630 °C
1120 °C
water release
reaction foam
log κ, κ in Ω-1·cm-1
1
0
-1
-2
-3
-4
-5
-6
fast conversion batch
primary melt formation
690 °C
1015 °C
water release
reaction foam
rough melt
log κ, κ in Ω-1·cm-1
0
200
400
600
800
1000
1200 °C

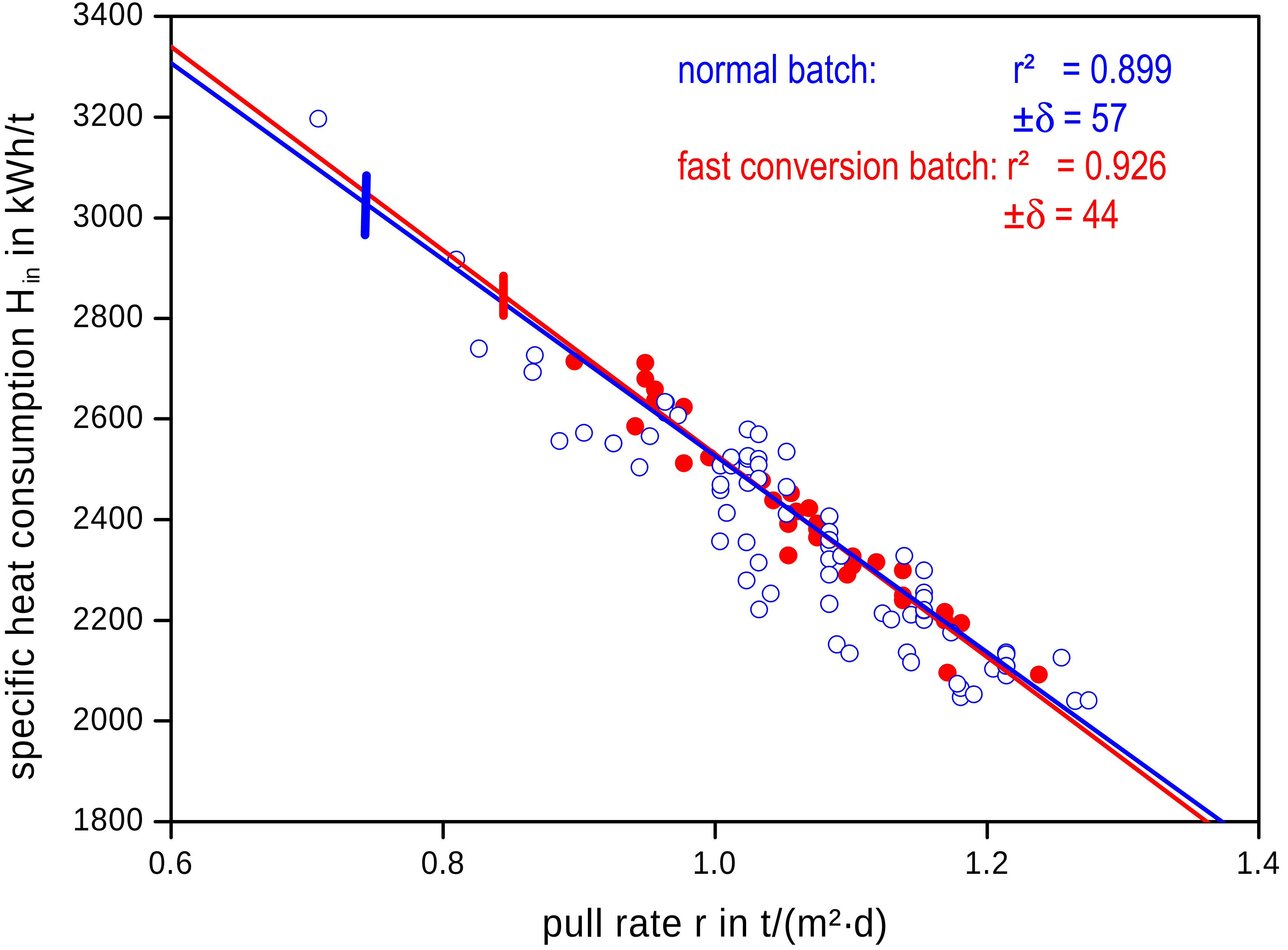


normal batch
primary melt formation
water release
t_W = 1150 s
reaction foam
t_{foam} = 2330 -2700 s
fast conversion batch
primary melt formation
water release
t_W = 1880 s
reaction foam
t_{foam} = 1420 s
log κ, κ in $\Omega^{-1}\cdot cm^{-1}$
log κ, κ in $\Omega^{-1}\cdot cm^{-1}$
1
0
-1
-2
-3
-4
-5
-6
0
2000
4000
6000
8000
time in s

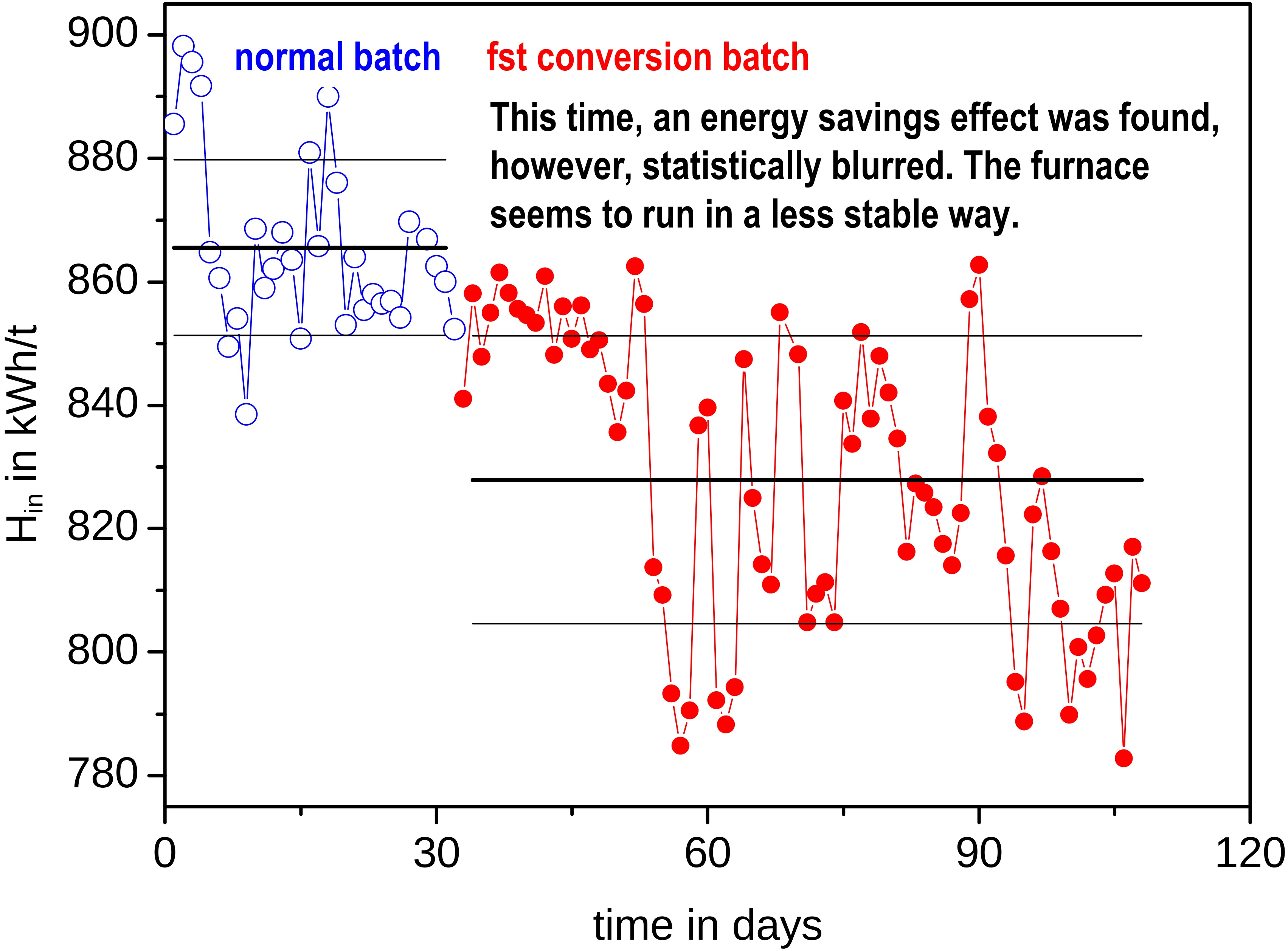
Due to the manager's impatience, no significant difference was found ...



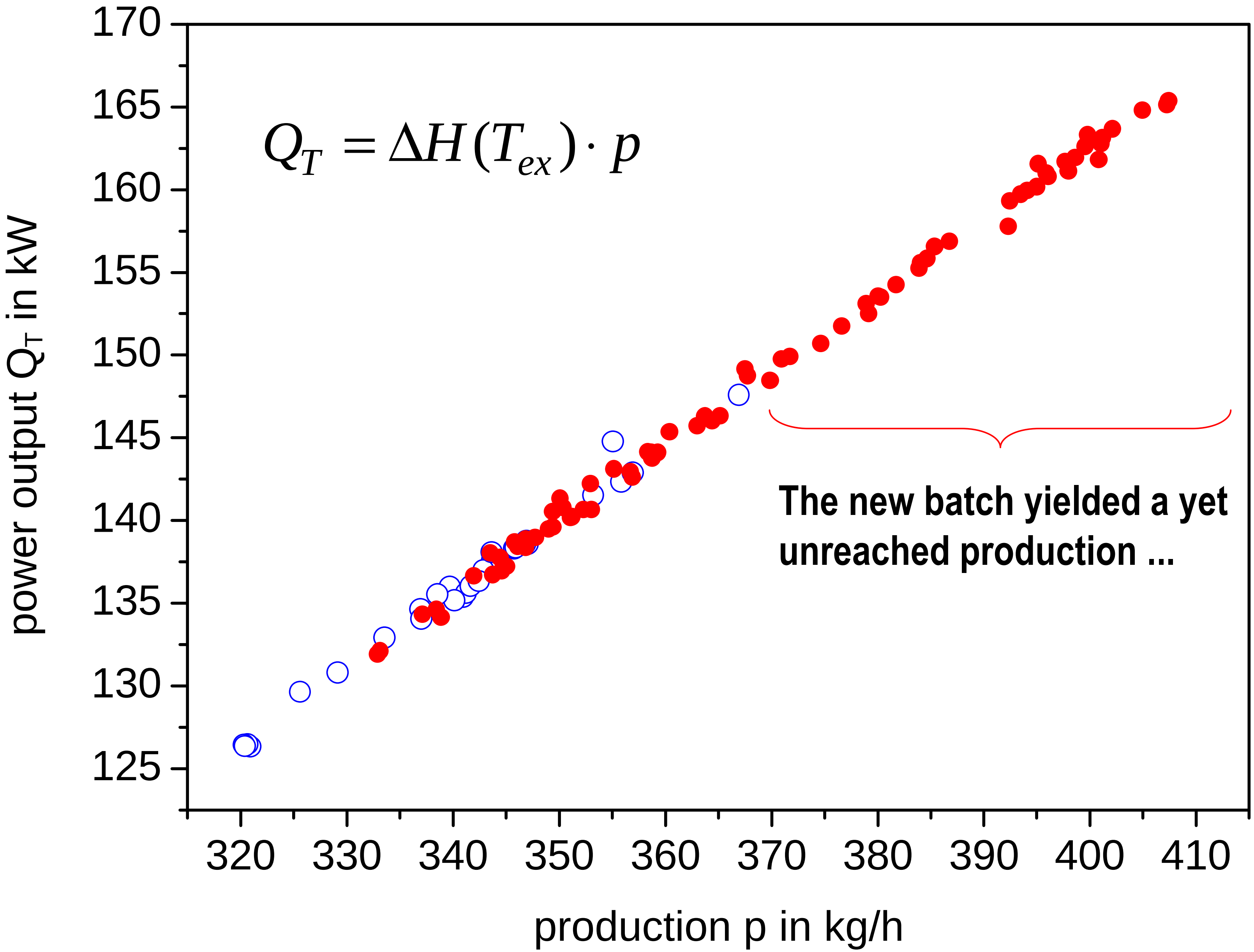
... although the new batch quickly makes the furnace more stable.

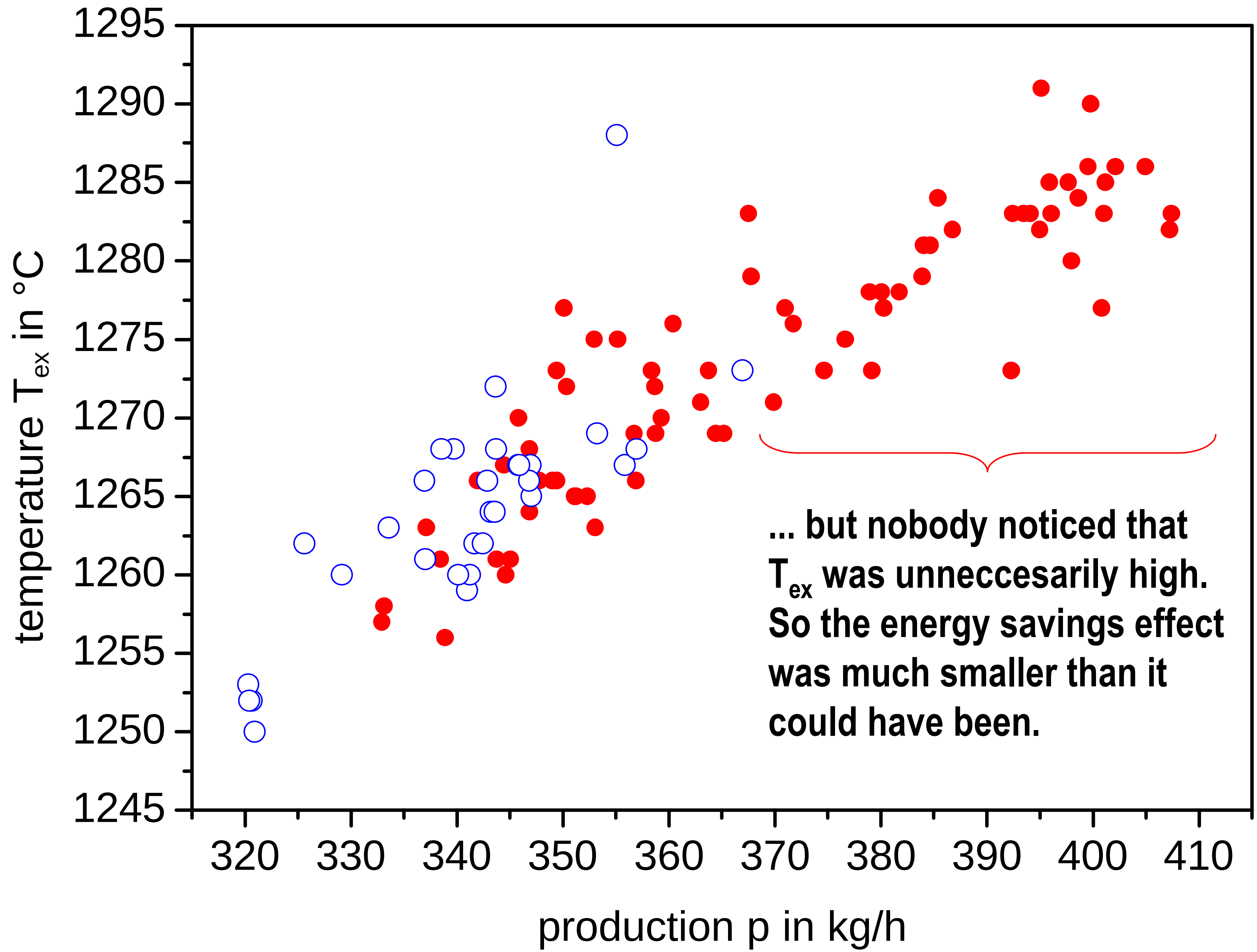


Same type of batches in a different factory.



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

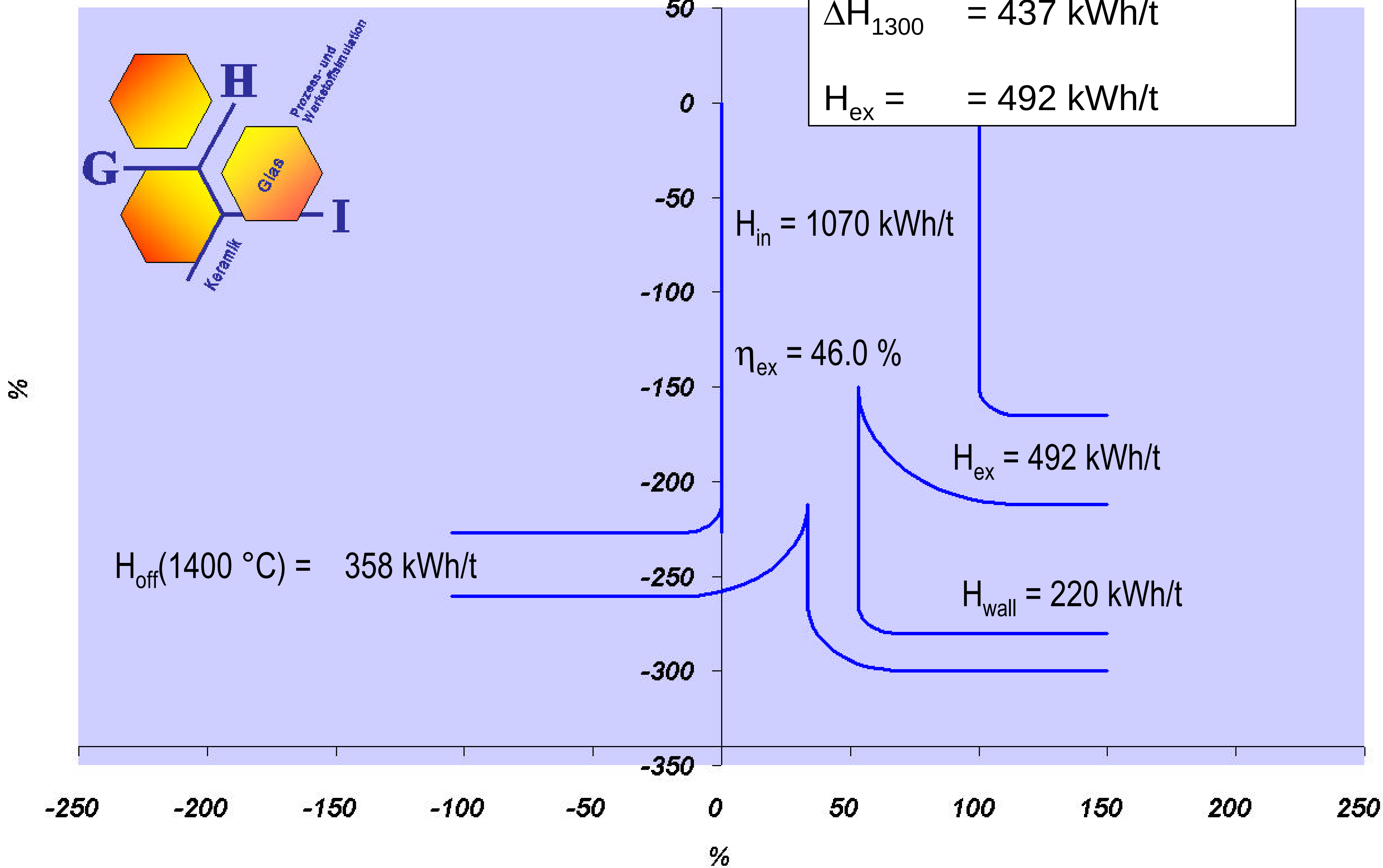


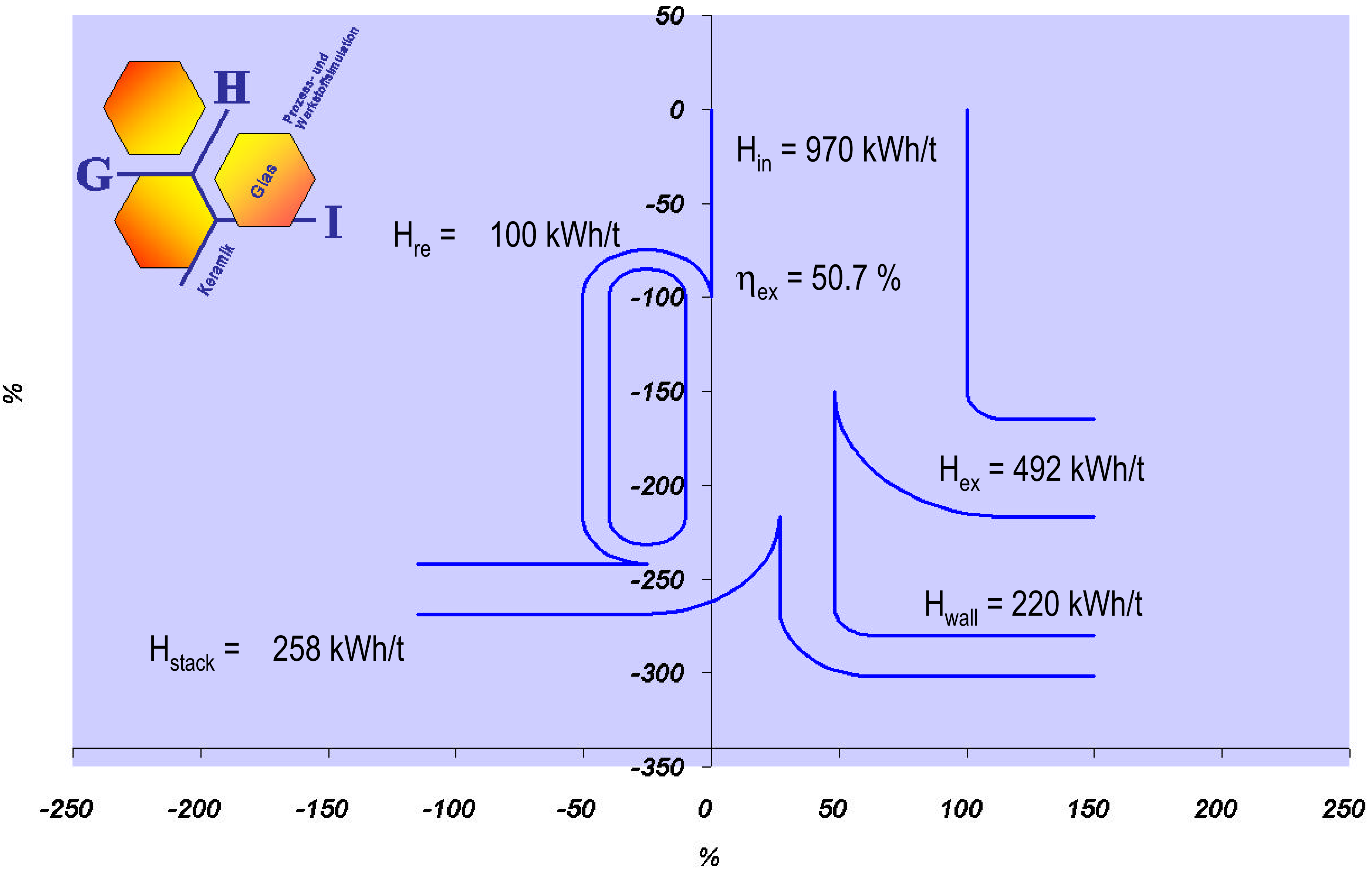


1295
1290
1285
1280
1275
1270
1265
1260
1255
1250
1245
temperature T_{ex} in °C
320
330
340
350
360
370
380
390
400
410
production p in kg/h
... but nobody noticed that T_{ex} was unneccesarily high. So the energy savings effect was much smaller than it could have been.

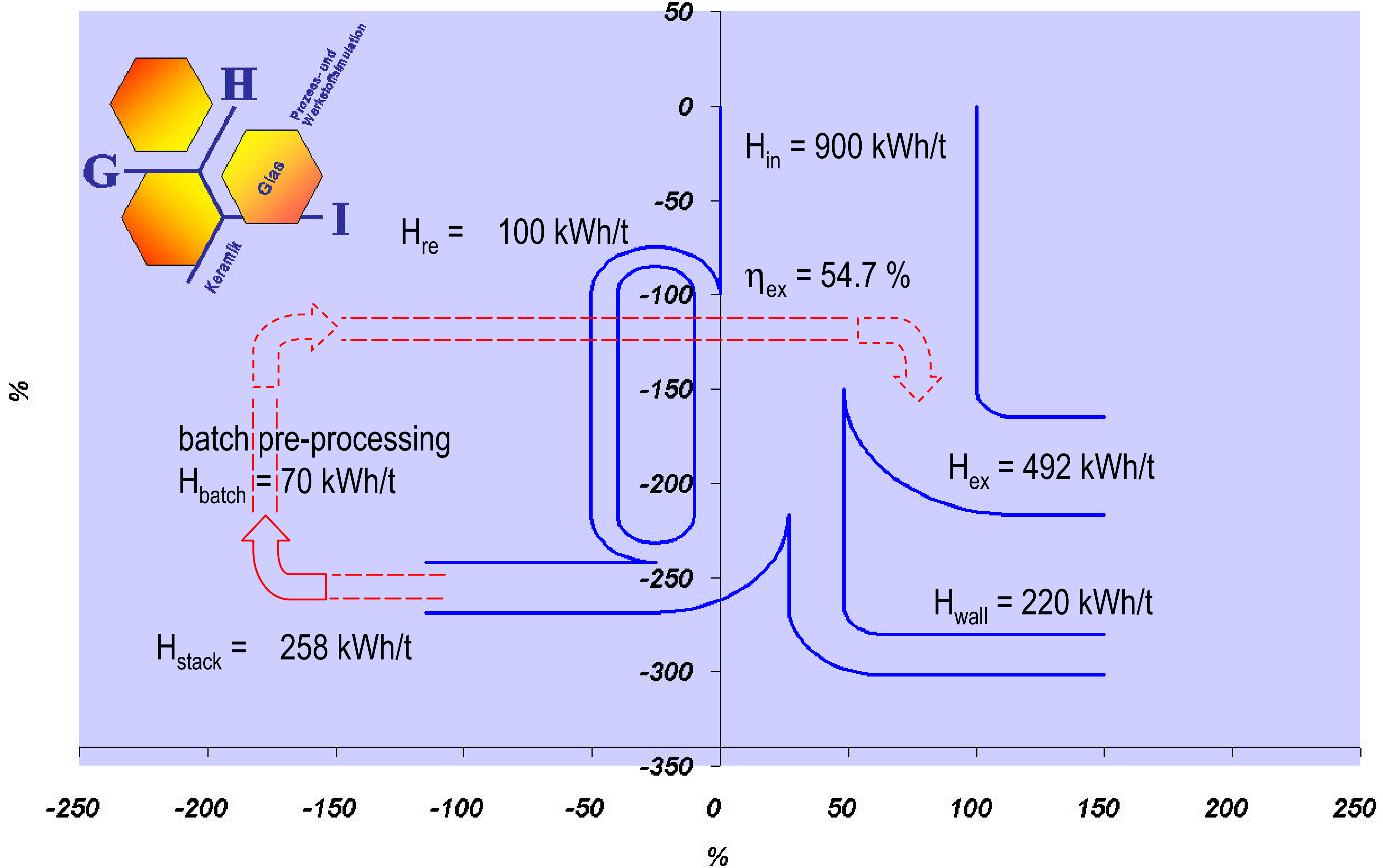
$$H_{ex} = (1 - y_C) \cdot \Delta H°_{chem} + \Delta H_{1300}$$

y_C	= 62 %
$\Delta H°_{chem}$	= 129 kWh/t
	+ 16 kWh/t (water)
ΔH_{1300}	= 437 kWh/t
H_{ex} =	= 492 kWh/t





H = 970 kWh/t (subscript: in)
H = 100 kWh/t (subscript: re)
η = 50.7 % (subscript: ex)
H = 492 kWh/t (subscript: ex)
H = 220 kWh/t (subscript: wall)
H = 258 kWh/t (subscript: stack)
50
0
-50
-100
-150
-200
-250
-300
-350
-250
-200
-150
-100
-50
0
50
100
150
200
250
%
%
G
H
I
Glas
Keramik
Prozess- und
Werkstoffsimulation



H
G
I
Glas
Keramik
Prozess- und Werkstoffsimulation
H_{in} = 900 kWh/t
H_{re} = 100 kWh/t
η_{ex} = 54.7 %
batch pre-processing
H_{batch} = 70 kWh/t
H_{ex} = 492 kWh/t
H_{wall} = 220 kWh/t
H_{stack} = 258 kWh/t
50
0
-50
-100
-150
-200
-250
-300
-350
-250
-200
-150
-100
-50
0
50
100
150
200
250
%
%

Thank you
for your kind attention!