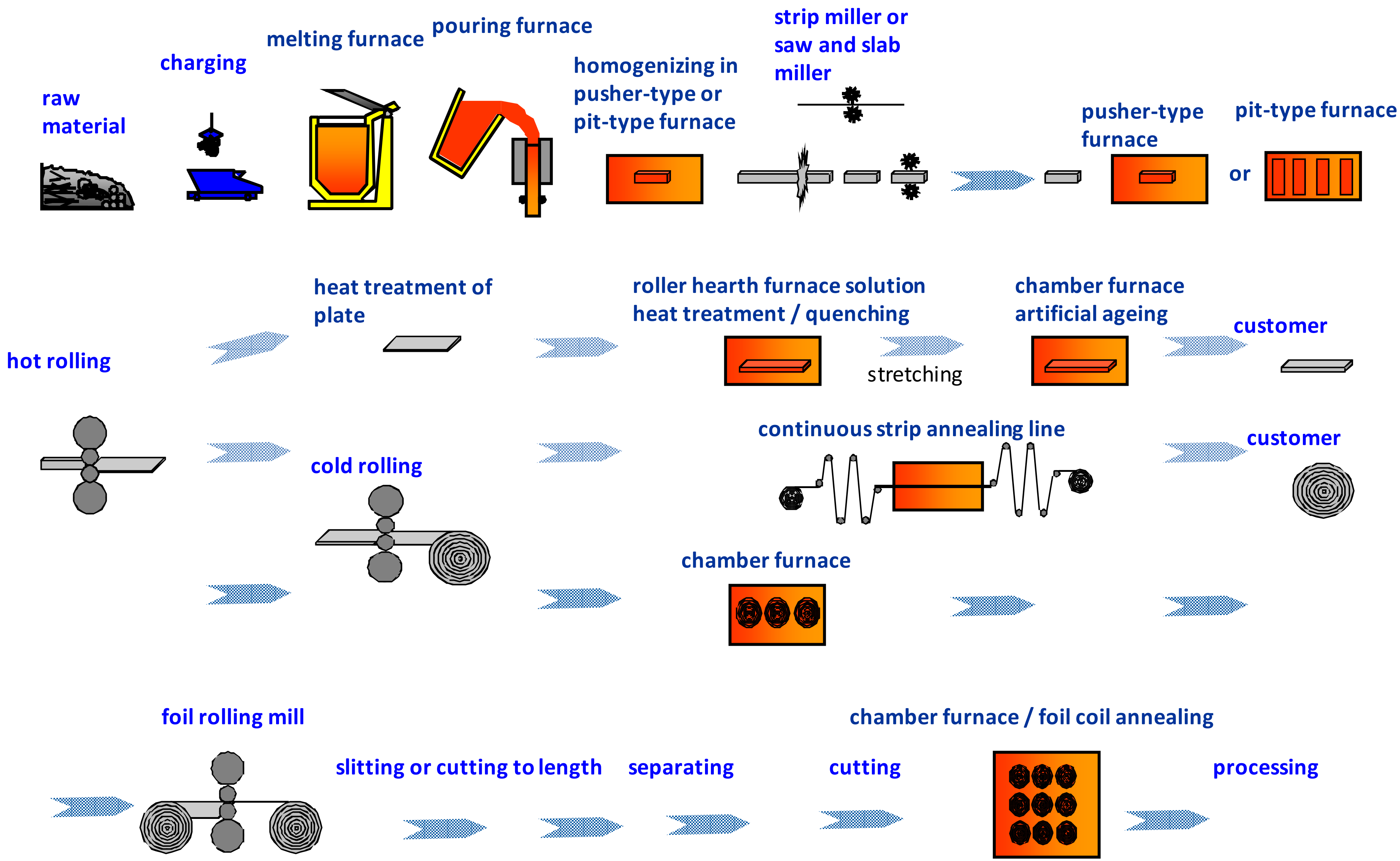
Sebastian März (Otto Junker, Lammersdorf)
Prof. Dr. Herbert Pfeifer (RWTH Aachen University, Department of Industrial Furnaces and Heat Engineering)

„Modern Furnaces for the Aluminium Industry "

Thursday, December 11st 2014



Process routes for the production of aluminium flat products based on secondary raw materials

Table A2.2: Heating- and hot forming temperatures for nonferrous metals [1]

Nonferrous metals	Heating-temperature °C	Hot forming temperature	
		at start °C	at end °C
Al and Al-alloys			
Pure aluminium	500 to 570	480 to 550	340 to 360
Al-Mg-alloys (Al-Mg 3)	420 to 470	400 to 450	300 to 330
Al-Cu-Mg-alloys (AlCu4 Mg2)	500 to 540	480 to 520	340 to 360
Al-Mn-alloys (2 % Mn)	500 to 540	480 to 520	400 to 450
Al-Zn-Mg-Cr-alloys (AlZnMgCu0,5)	440 to 500	420 to 480	330 to 360

Table A2.3: Temperatures for the annealing of steels and nonferrous metals [1]

Annealing process	Temperature °C
Aluminium and Al-alloys	
Homoginizing (Solution annealing)	460 to 580
Stress-relief annealing (Recrystallization annealing)	300 to 440
Recovery annealing	150 to 330
Artificial ageing	120 to 200

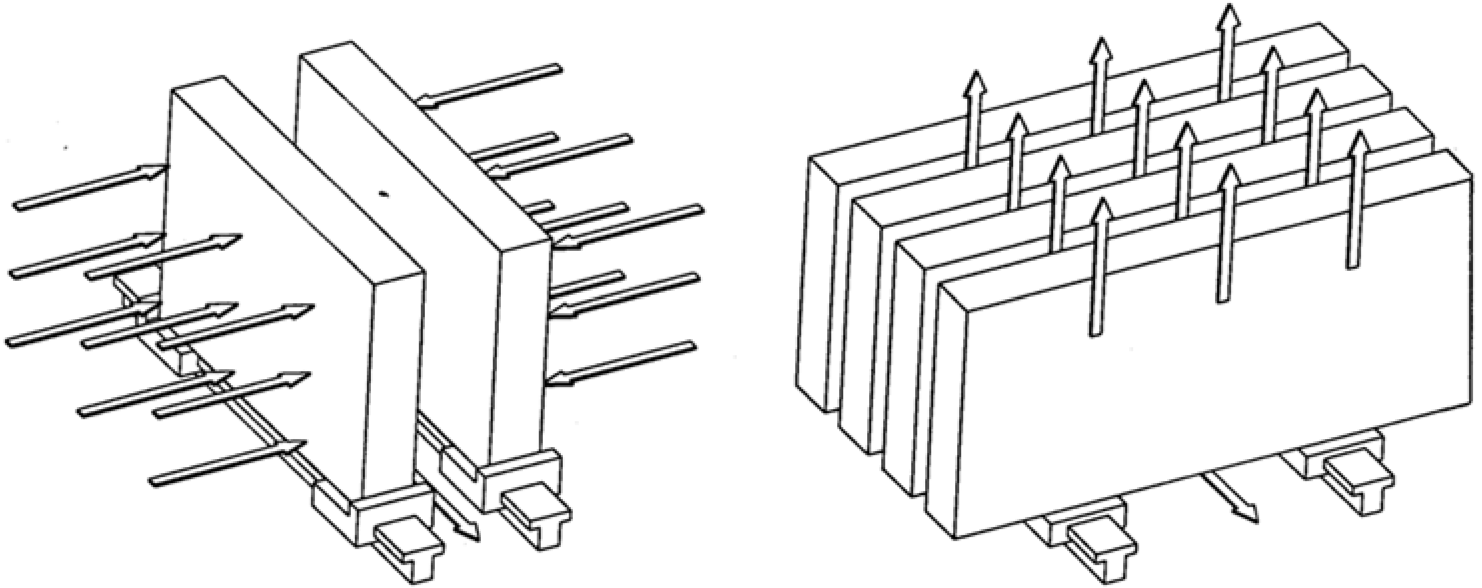
Table A2.5: Homogenizing temperatures for Al-alloys [2]

Alloy	Temperature range °C	Duration h
Al 99.9	560 to 590	16 to 20
Al Mg2	460 to 500	10 to 15
Al Mg5	470 to 530	12 to 18
Al Mn1	590 to 630	6 to 9
Al MgSi0.5	500 to 580	6 to 8
Al Mg1Si	530 to 550	14 to 18
Al CuMg1	480 to 510	8 to 18
Al CuMg2Mn	470 to 490	12 to 20
Al ZnMgCu1.5	460 to 490	up to 13

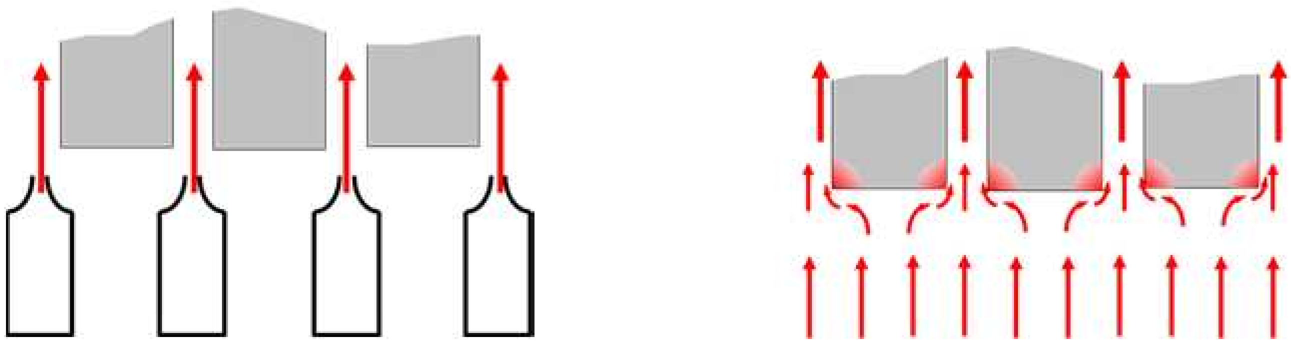
Table A2.8: Quenching times for thermosetting aluminium alloys [2]

Chemical symbol Prefix EN AW-	Solution annealing temperature °C	Cooling time to <200 °C s	Specific quenching fluid
Al Cu4MgSi(A)	500	5 to 10	Water
Al Cu2.5Mg0.5	475 to 505	40 to 60	Water; alternatively for plates with d < 1.5 mm a high convection air flow
Al SiMgMn	540	20 to 30	Water for d > 3 mm; high convection air flow for d < 3 mm
EAl MgSi(B)	530	40 to 60	Water d > 5 mm Air for d < 5 mm
Al Zn4.5Mg1	450	5 to 20 min	Air
Al Zn5.5MgCu(A)	530	30 to 40	Water or water spray

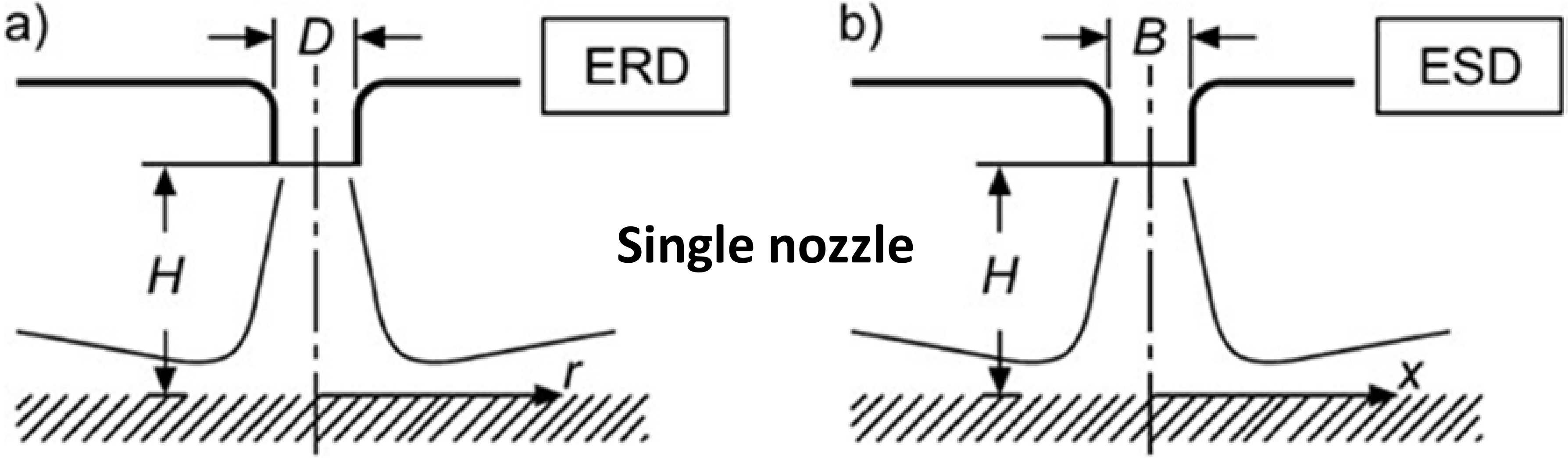
Furnaces for the heat treatment of Al are dominated by convective heat transfer



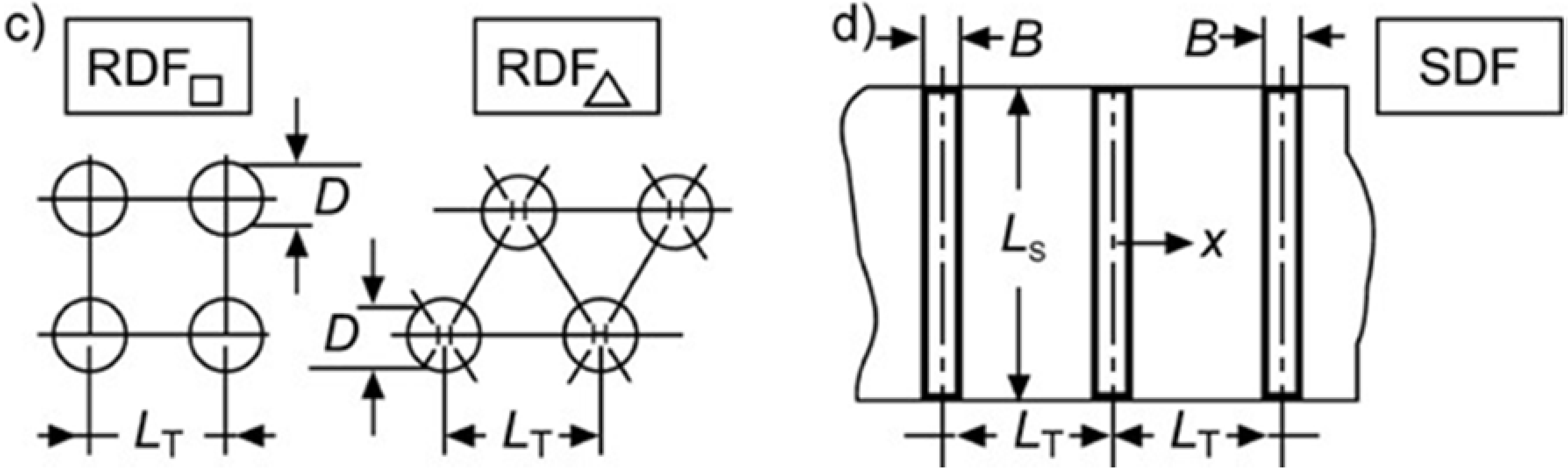
Convective heat transfer to rolling slabs, (a) impingement flow, (b) gap flow



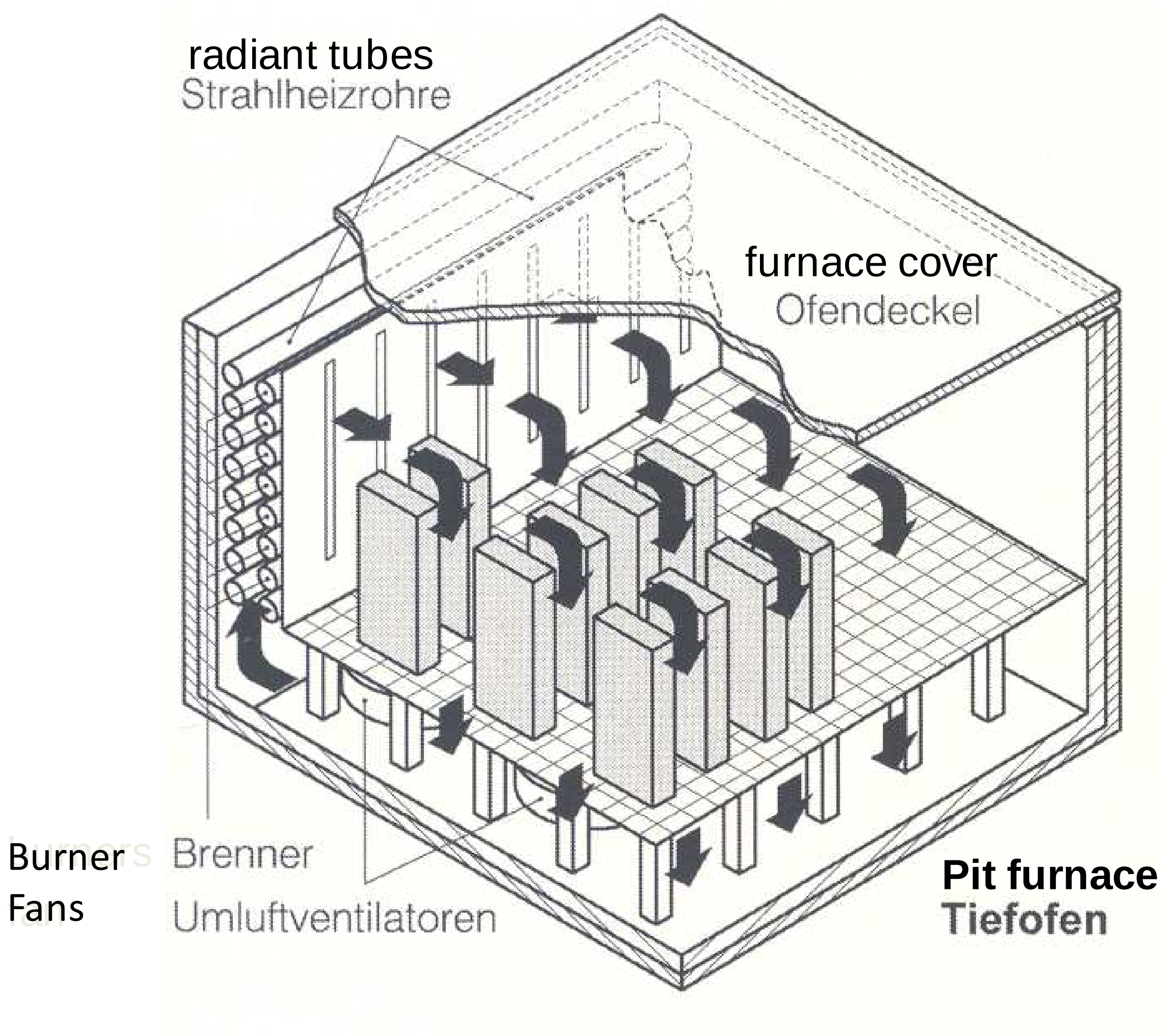
Flow principles in reheating furnaces for Al slabs, (a) gap flow, (b) mass flow



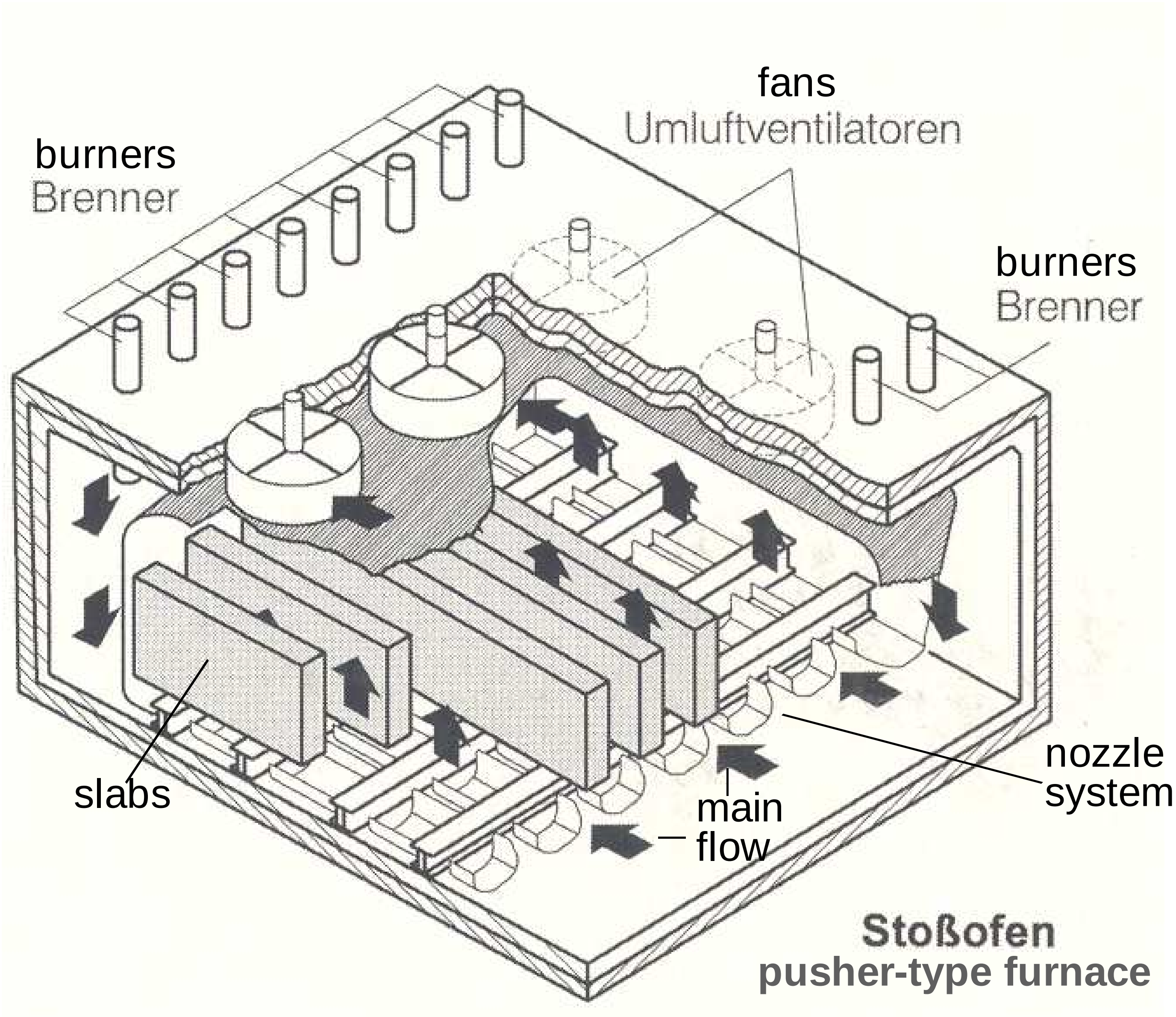
Single nozzle



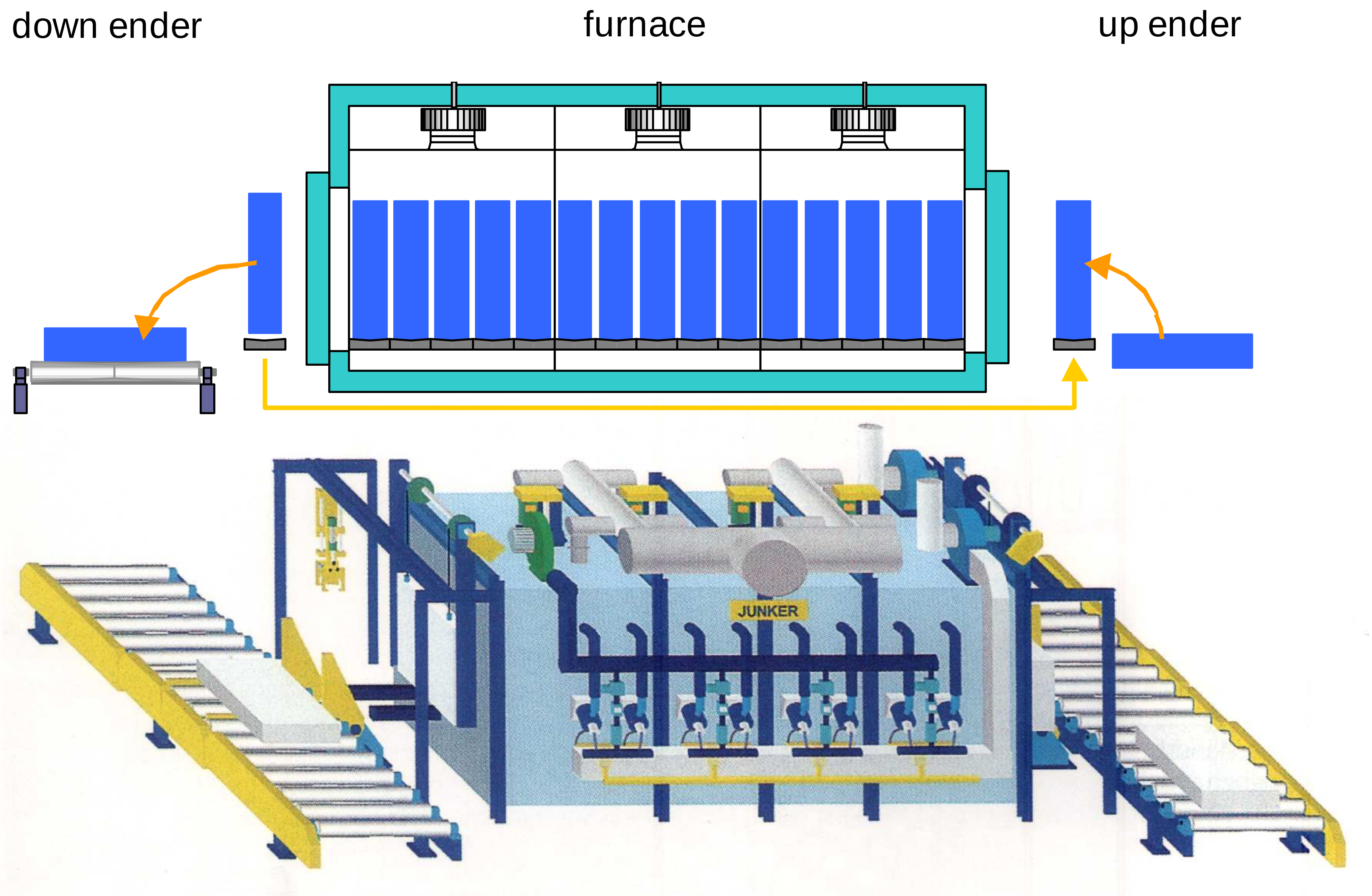
Round and flat nozzle fields



Al-Pit furnace



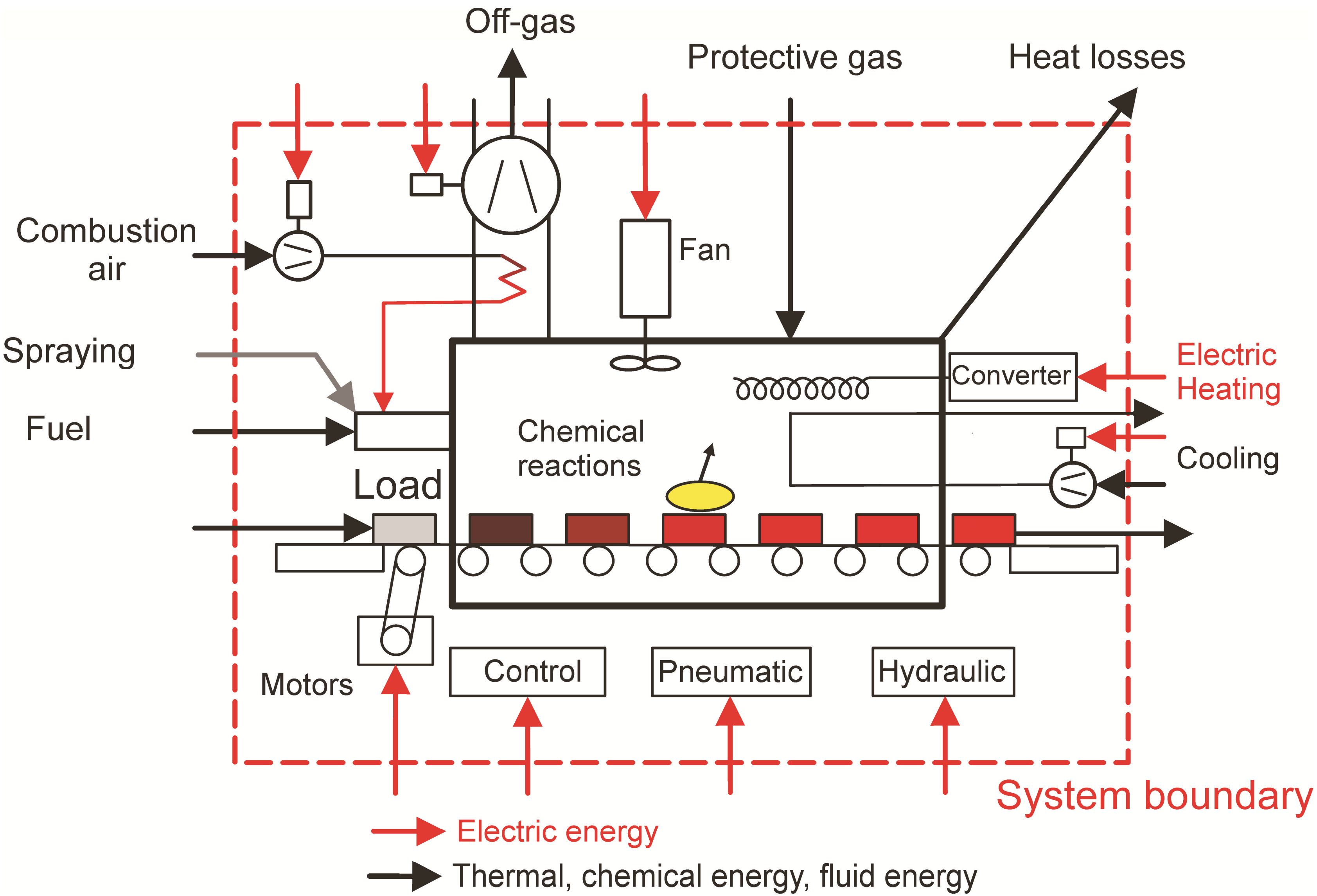
Al-pusher type furnace



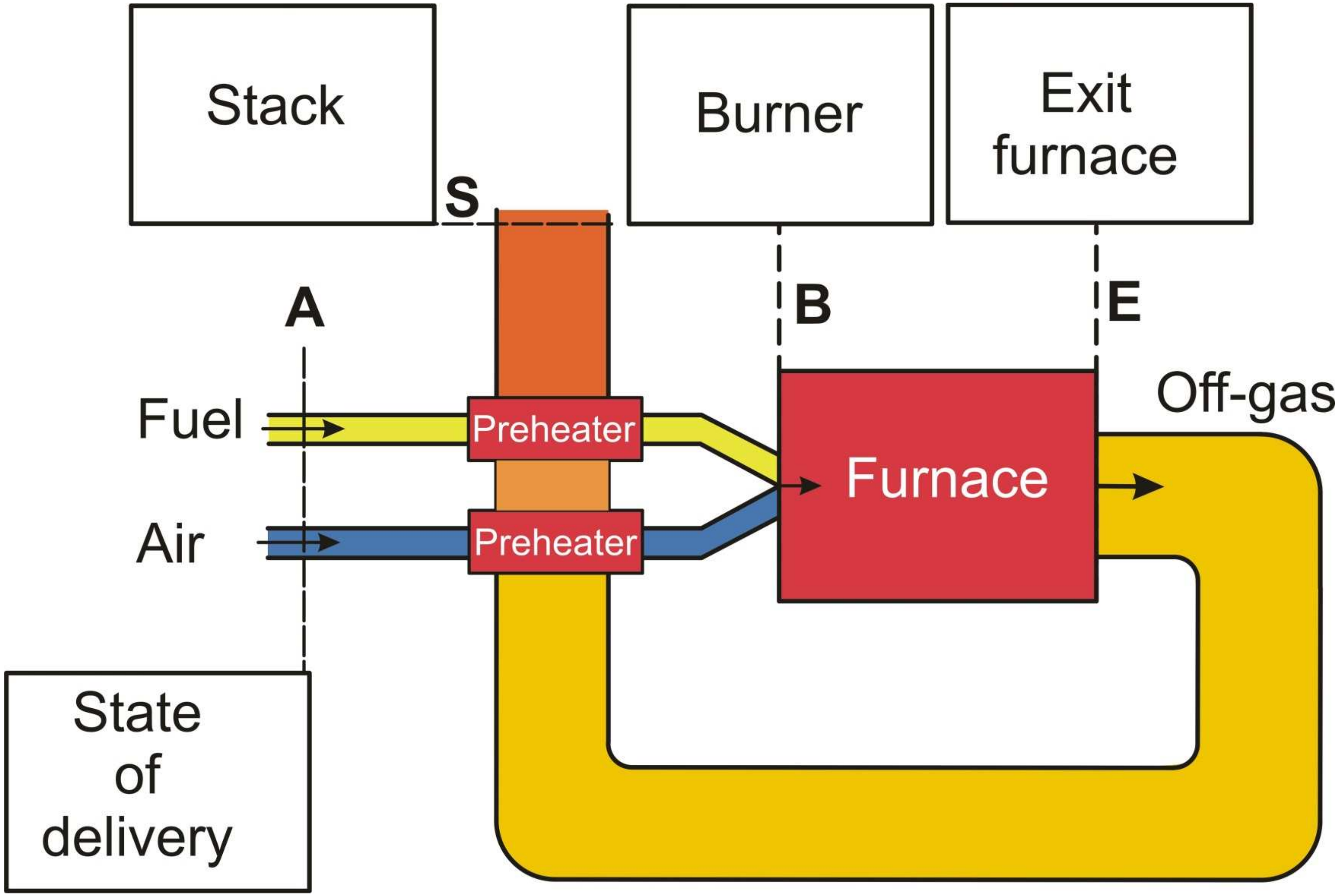
Direct gas heated pusher-type furnace for pre-heating and homogenisation of Al-slabs

Table 2.12: Balance of the energy demand of a fuel-fired batch-type homogenizing furnace

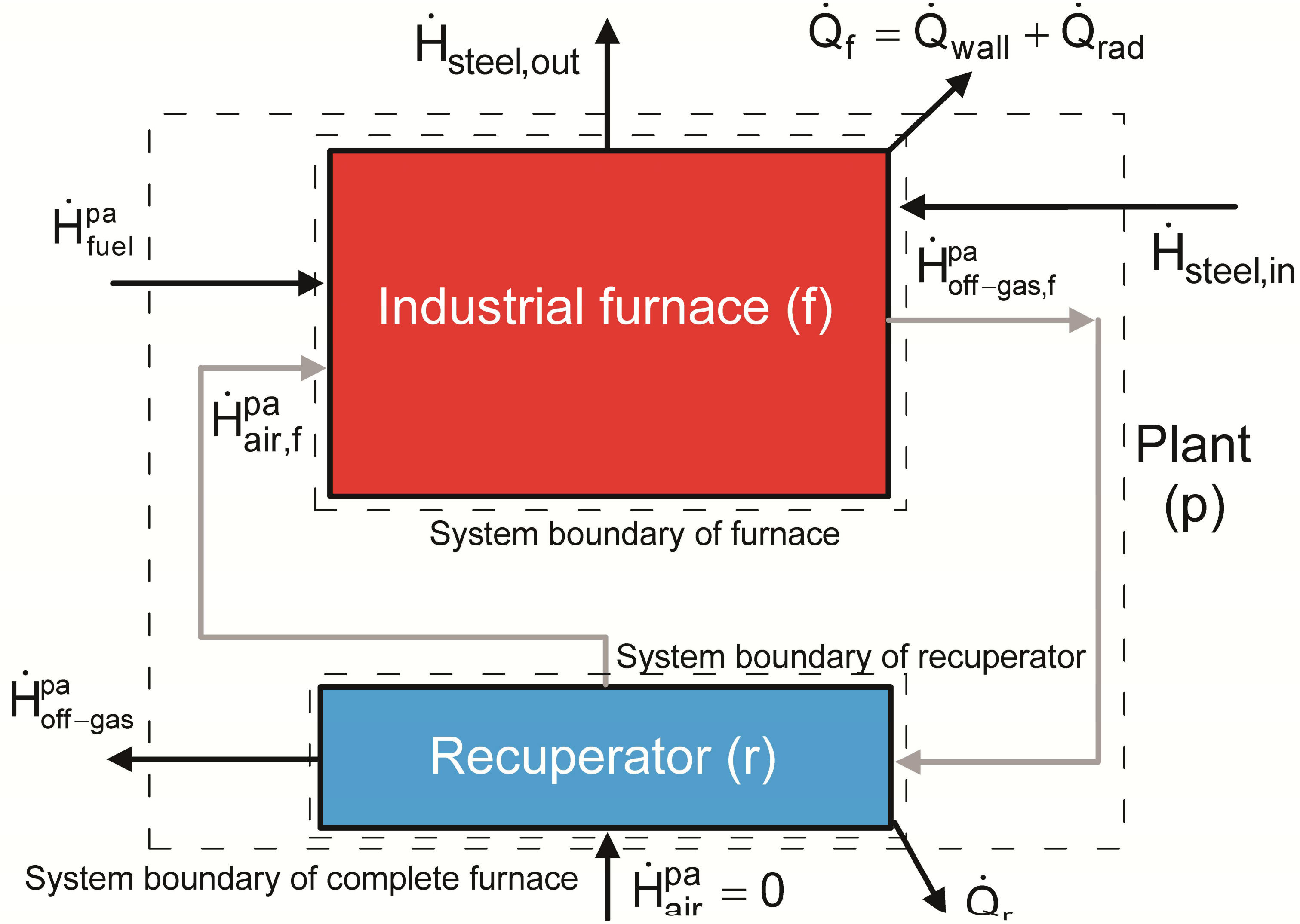
Consumption		Fuel consumption		Electrical energy consumption	
Process step	**User**	**Cold air burner**	**Recuperative burner**	**Cold air burner**	**Recuperative burner**
Holding	Heat flow to load	7,825 kWh	7,825 kWh	–	–
	Recirculating fan	-239 kWh	-239 kWh	266 kWh	266 kWh
Holding	Recirculating fan	-36 kWh	-36 kWh	40 kWh	40 kWh
Heating + holding	Heat flow to load	556 kWh	556 kWh	–	–
	Combustion air fan	-124 kWh	-103 kWh	138 kWh	115 kWh
Cooling	Recirculating fan	–	–	620 kWh	620 kWh
Heating + holding + cooling	Control unit	–	–	45 kWh	45 kWh
Net consumption		7,981 kWh	8,002 kWh	1,108 kWh	1,086 kWh
Gross consumption		11,241 kWh	9,414 kWh	–	–
Spec. consumption related on load mass		**245 kWh/t**	**205 kWh/t**	**24 kWh/t**	**24 kWh/t**



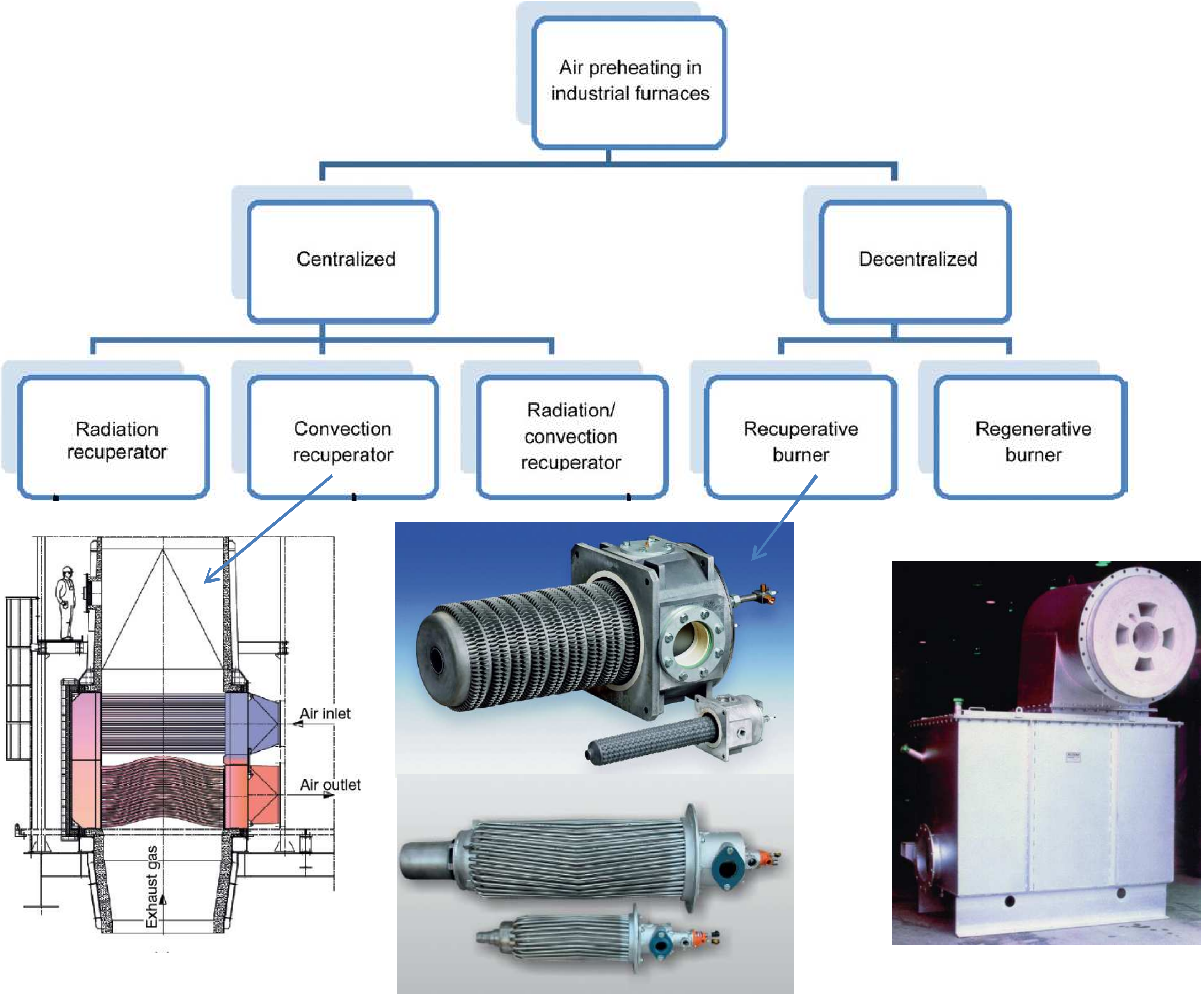
Energy and material flows for the determination of the total energy input

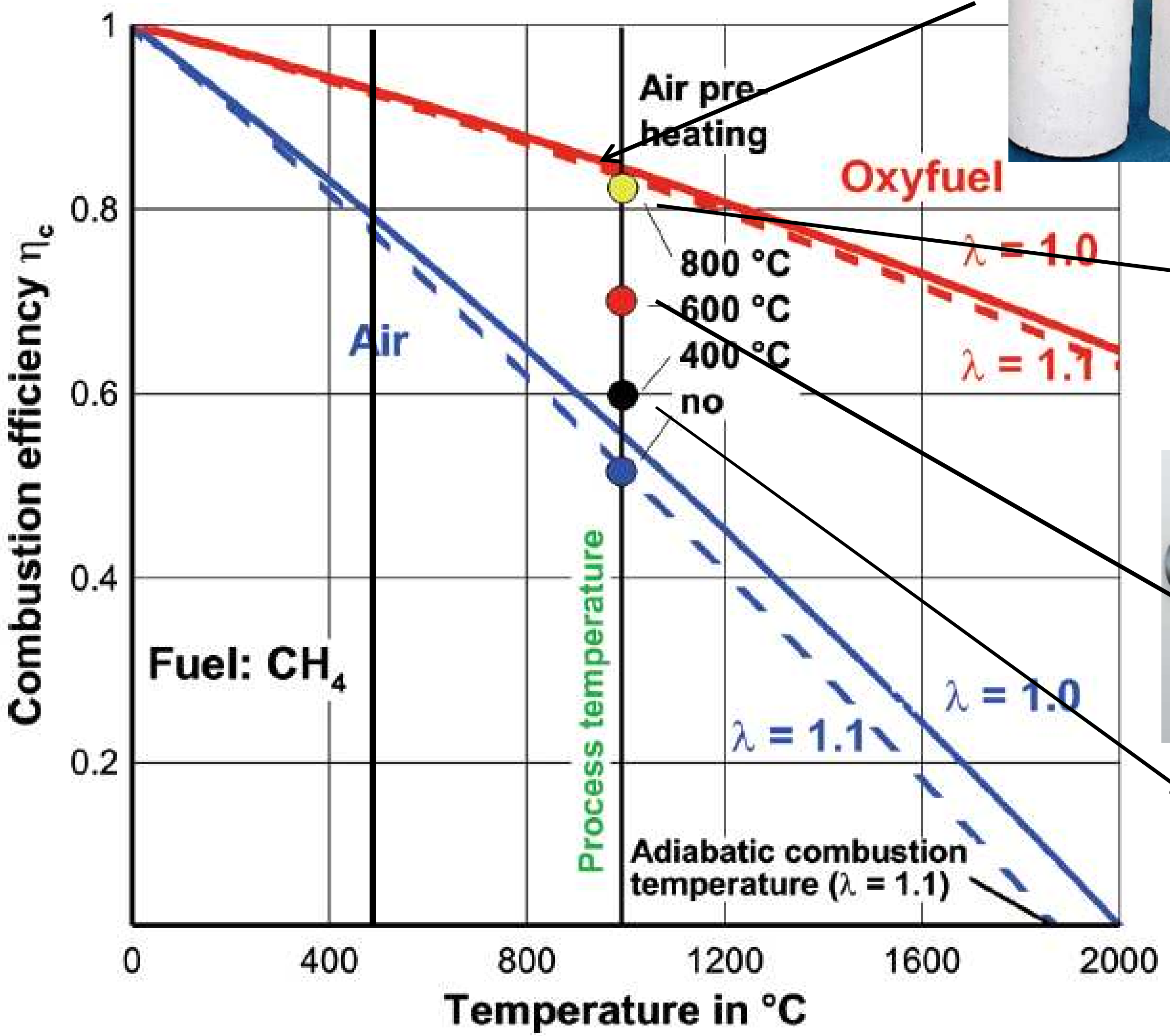


Characteristic mass flows of combustion

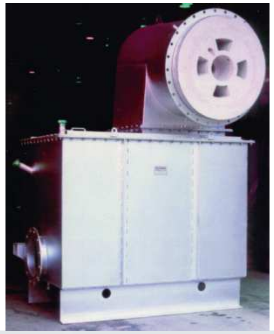


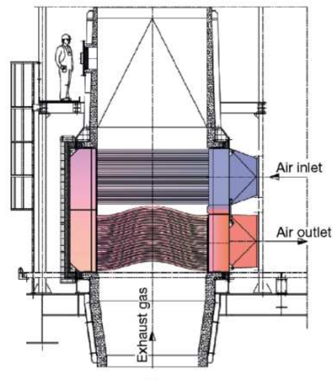
Energy balances and system boundaries for an industrial furnace with air preheating


Air preheating in industrial furnaces
Centralized
Decentralized
Radiation recuperator
Convection recuperator
Radiation/ convection recuperator
Recuperative burner
Regenerative burner
Air inlet
Air outlet
Exhaust gas



Combustion efficiency



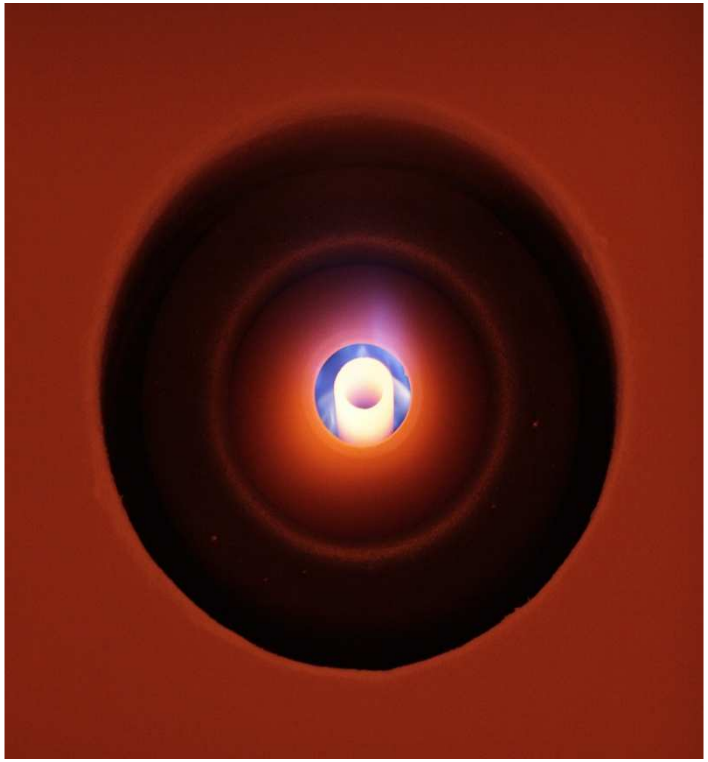


Advantage and characteristics of flameless oxidation

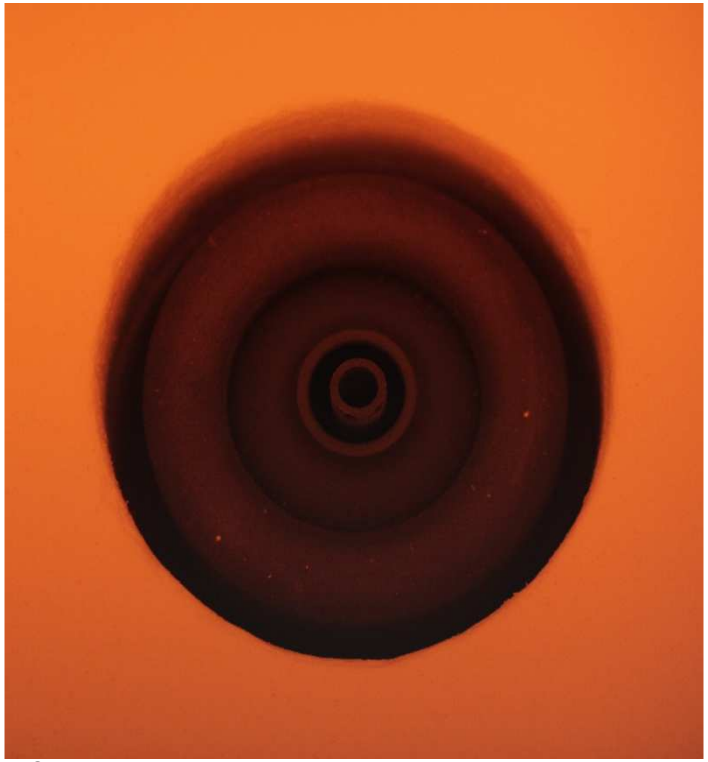
- Development and enhancement of fuel fired burners
  - main goal: increase of efficiency
  - use of high off-gas enthalpy for air preheating
  - challenge: Reduction of high NO_x-emission

- FLOX® - Combustionreaction without flame
  - high inlet velocity (> flame velocity)
  - recirculation of off-gas
  - increase of reacting volume
  - homogenization of temperature in reaction zone
  - no temperature maxima as in flame-front
  - significant dedrease of NO_x-emission

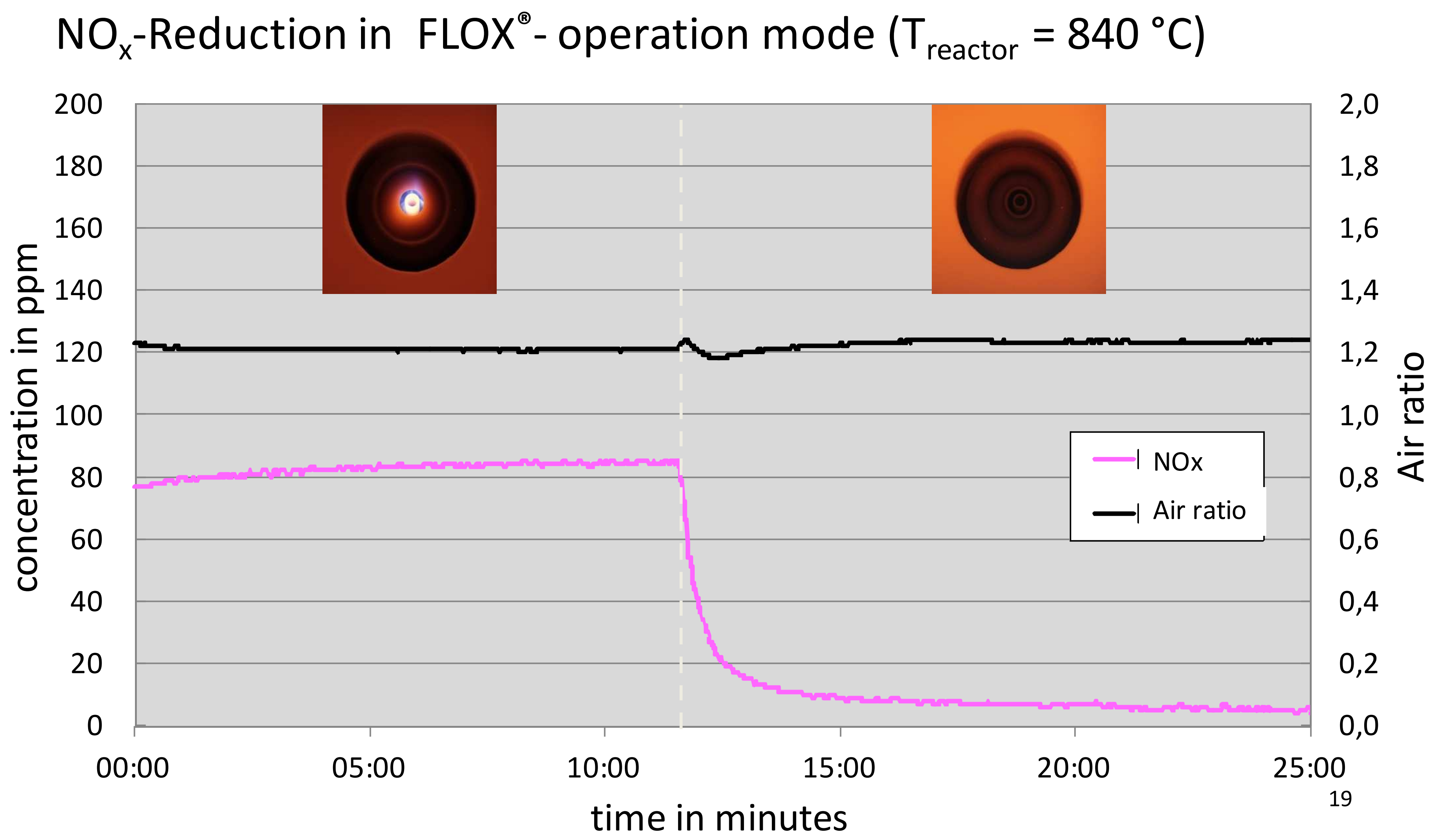
- flame operation mode for heat-up process
- (blue) stoiciometric gas flame
- power: 8 kW



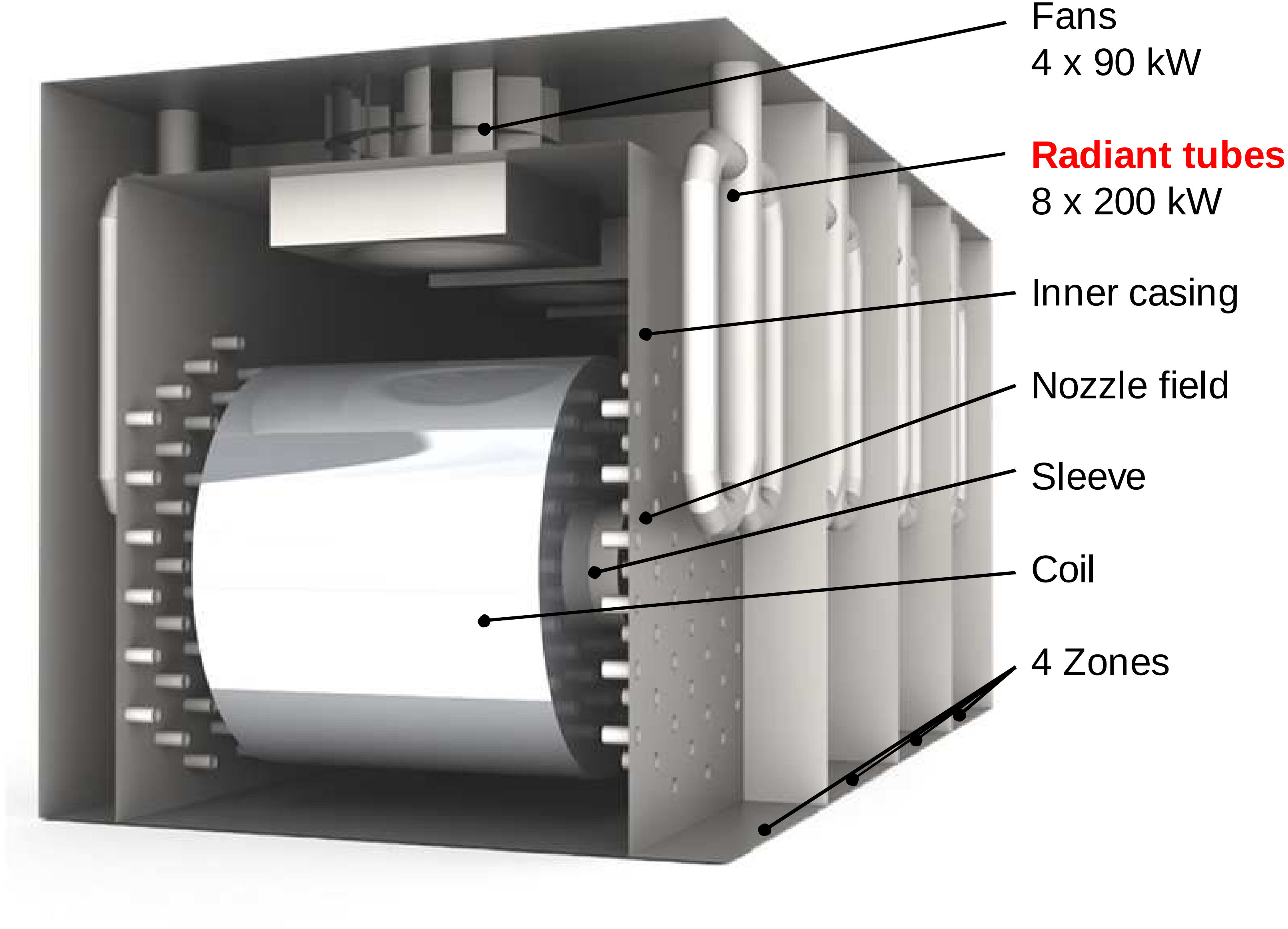
flame operation mode



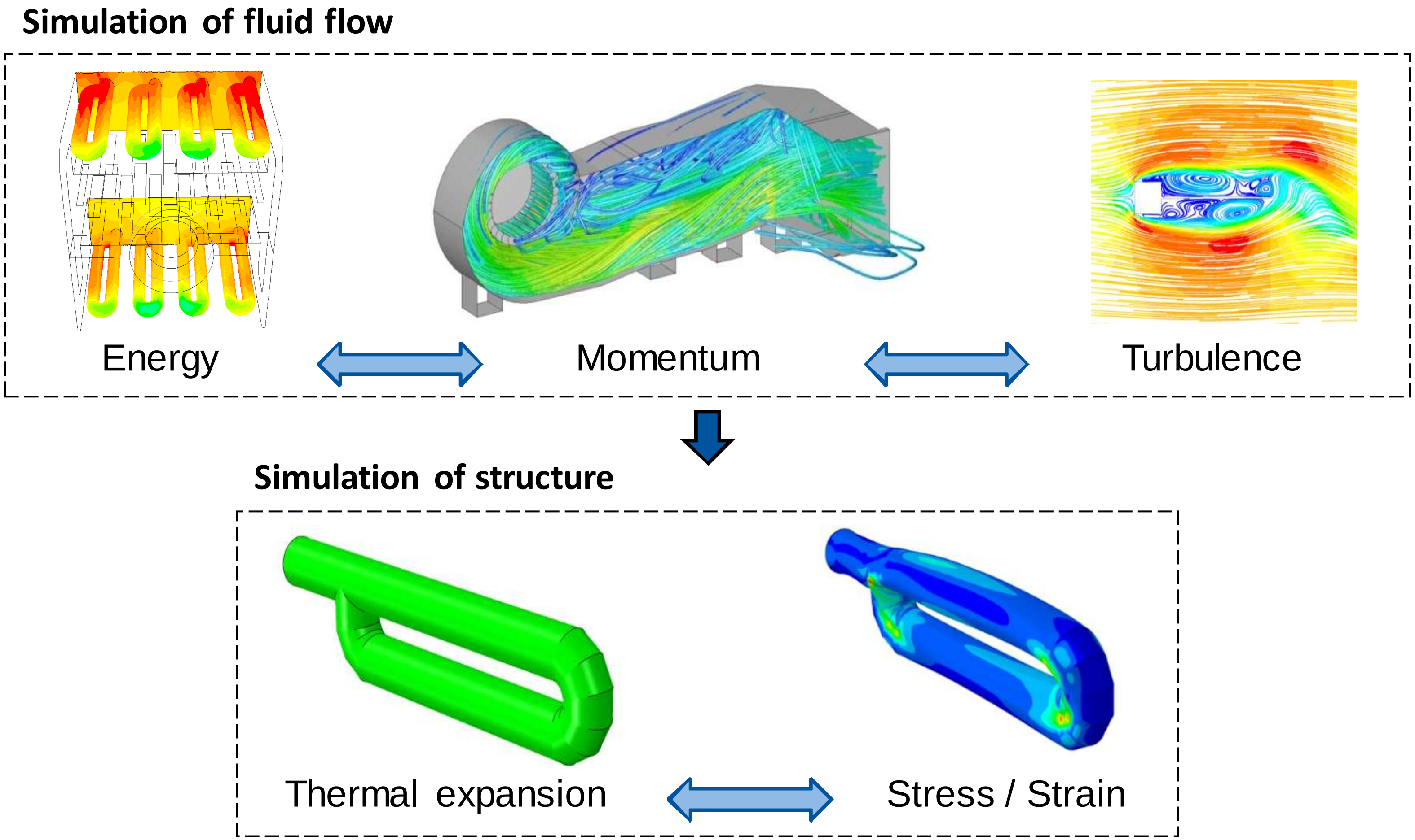
FLOX® - operation



NOx-Reduction in FLOX®- operation mode (T reactor = 840 °C)
concentration in ppm
200
180
160
140
120
100
80
60
40
20
0
2,0
1,8
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Air ratio
NOx
Air ratio
00:00
05:00
10:00
15:00
20:00
25:00
time in minutes

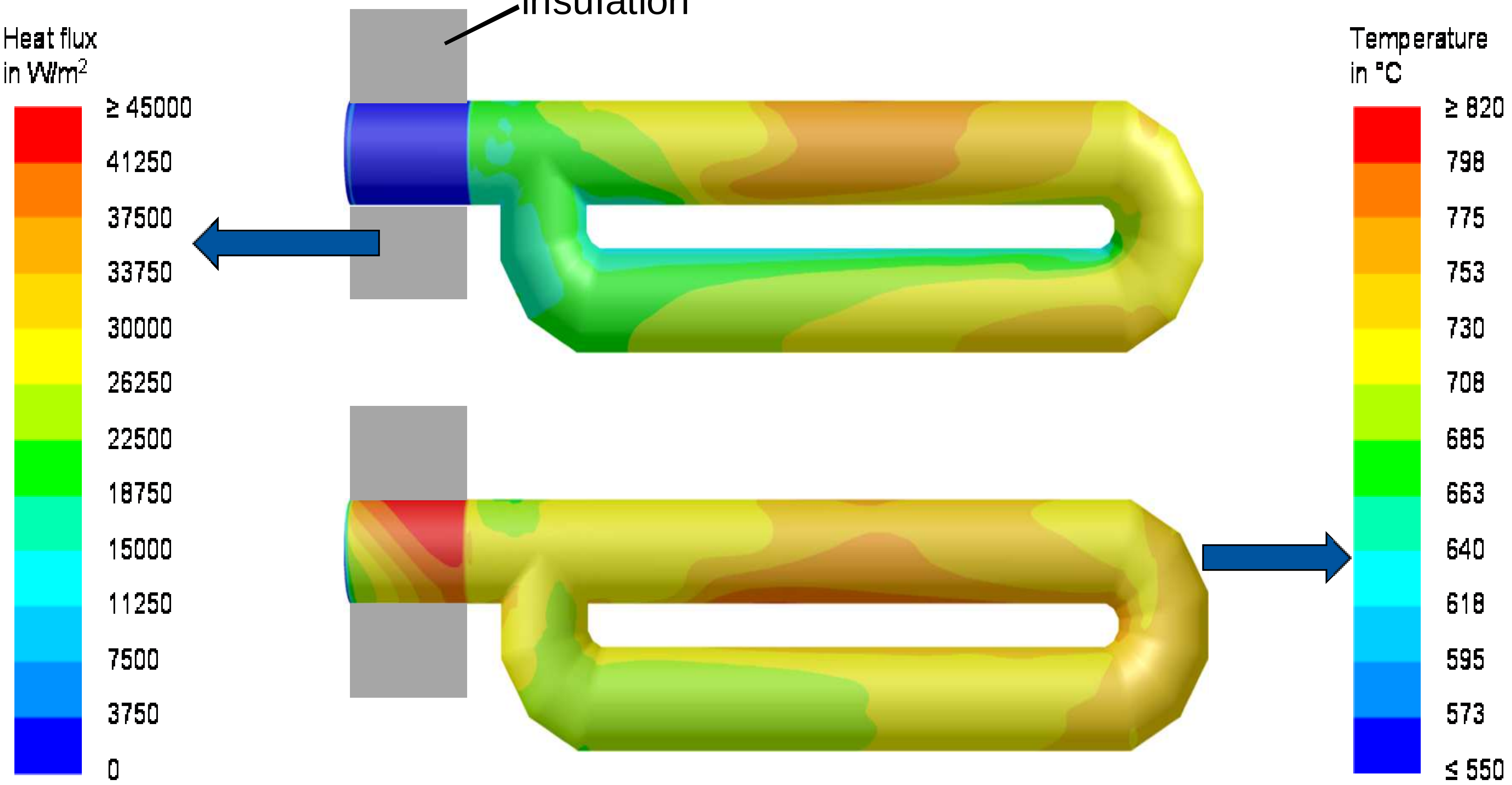

Fans
4 x 90 kW
Radiant tubes
8 x 200 kW
Inner casing
Nozzle field
Sleeve
Coil
4 Zones

Fluid-Structure-Interaction (FSI) in the field of industrial furnace engineering:

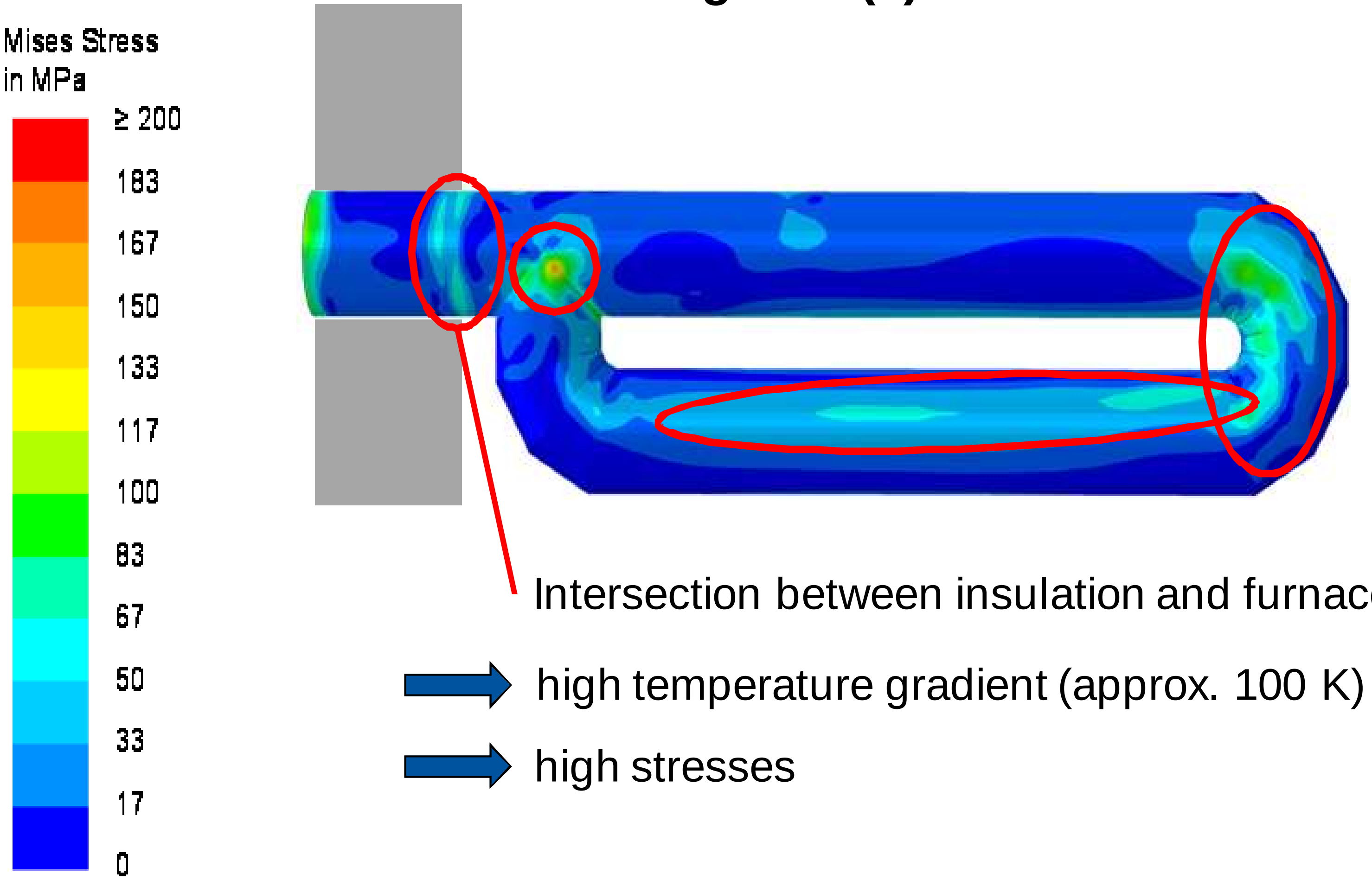


1-Way Coupling: → small deformations fluid flow → structure

Total heat flux and temperature distribution



Stresses on the radiant heating tube (1)

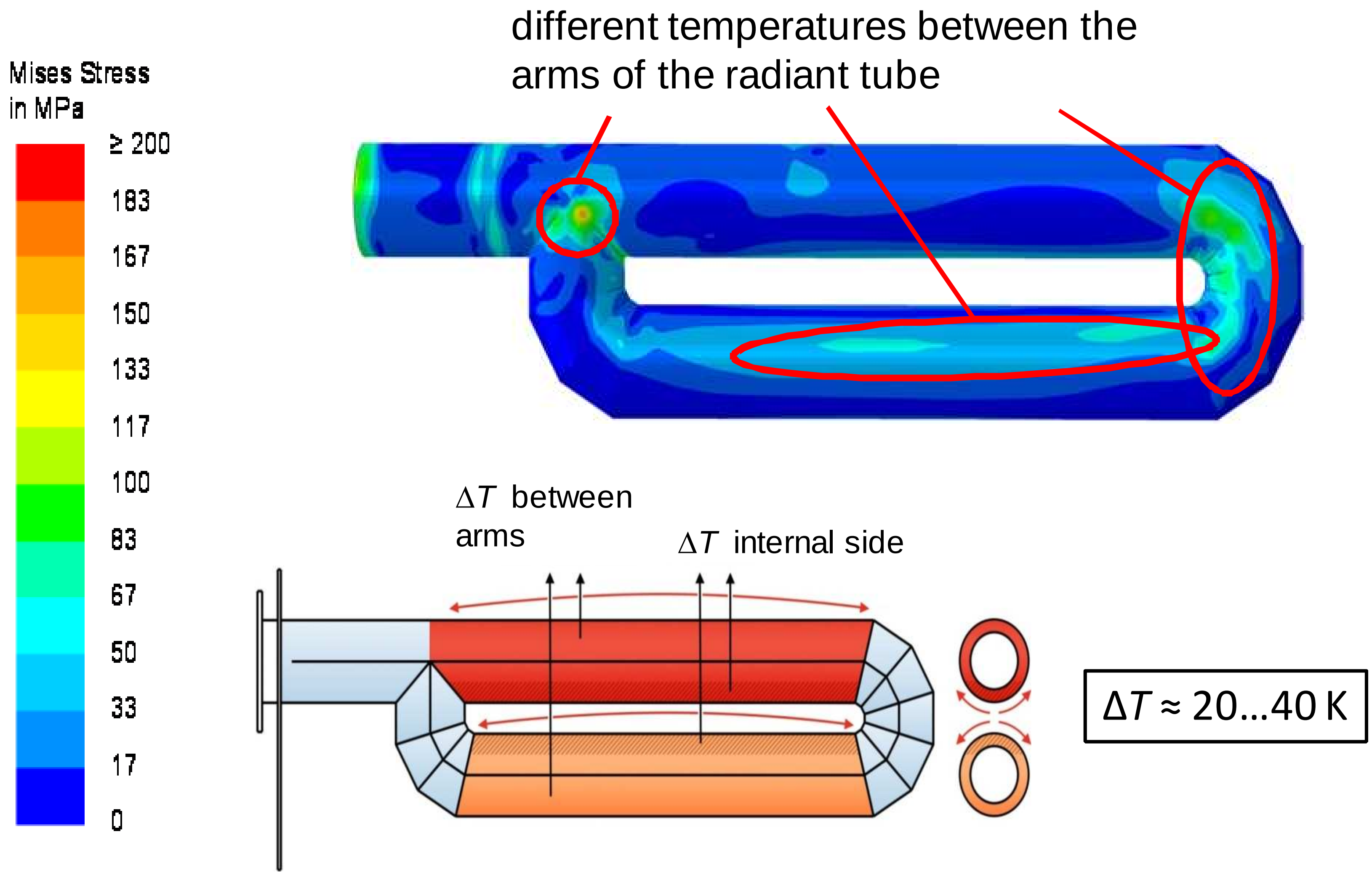


Intersection between insulation and furnace chamber

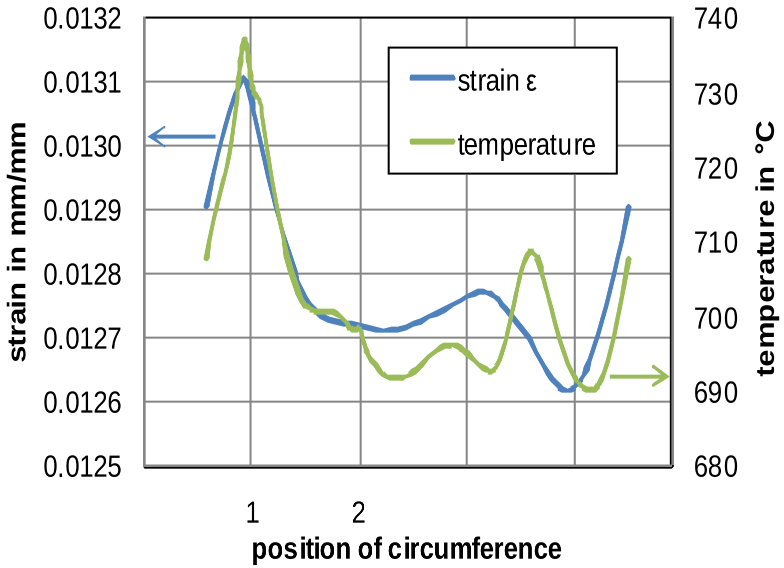
→ high temperature gradient (approx. 100 K)

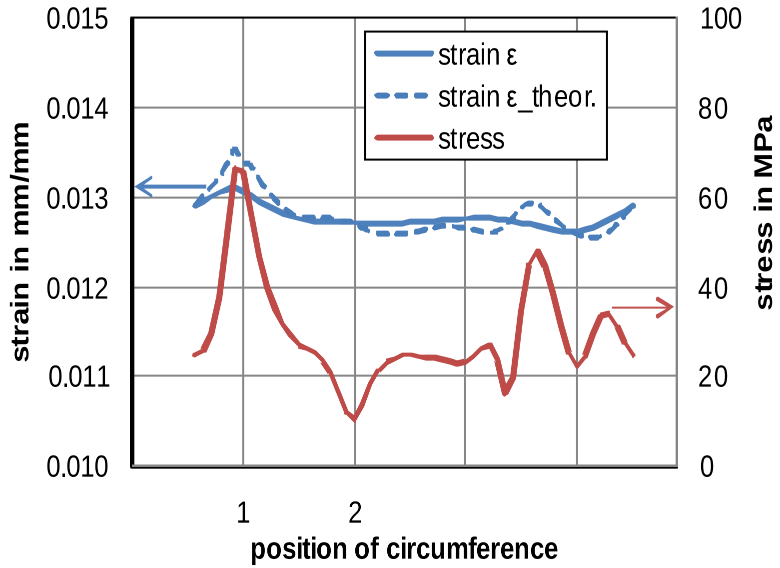
→ high stresses

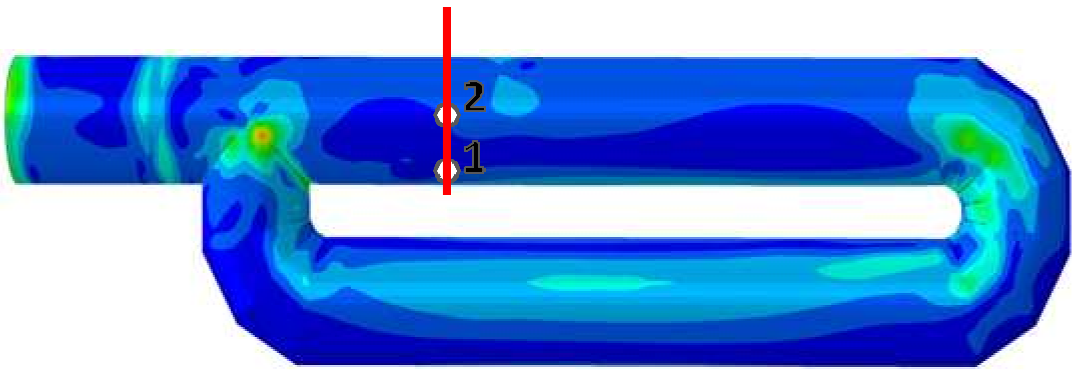
Stresses on the radiant heating tube (2)

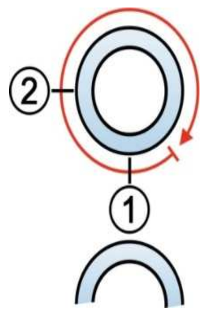


Stress and strain as a function of circumference

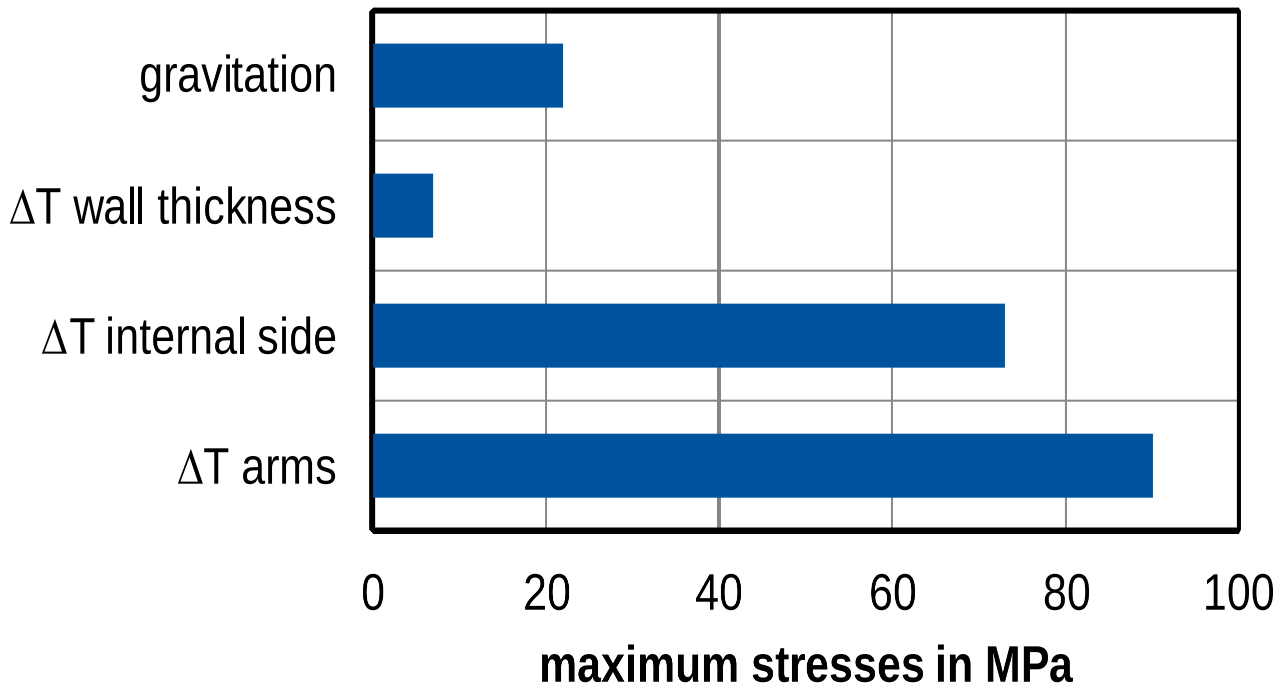


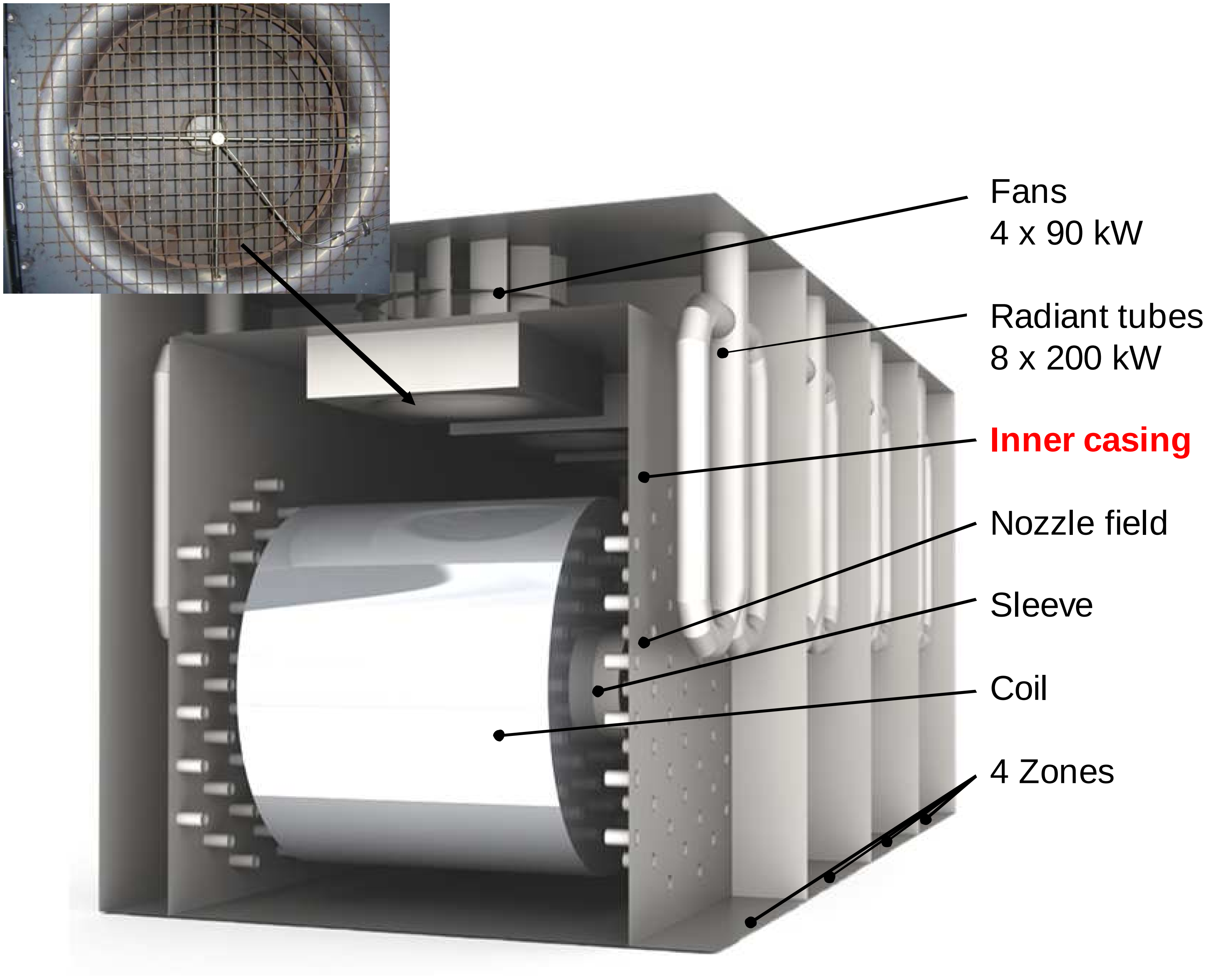


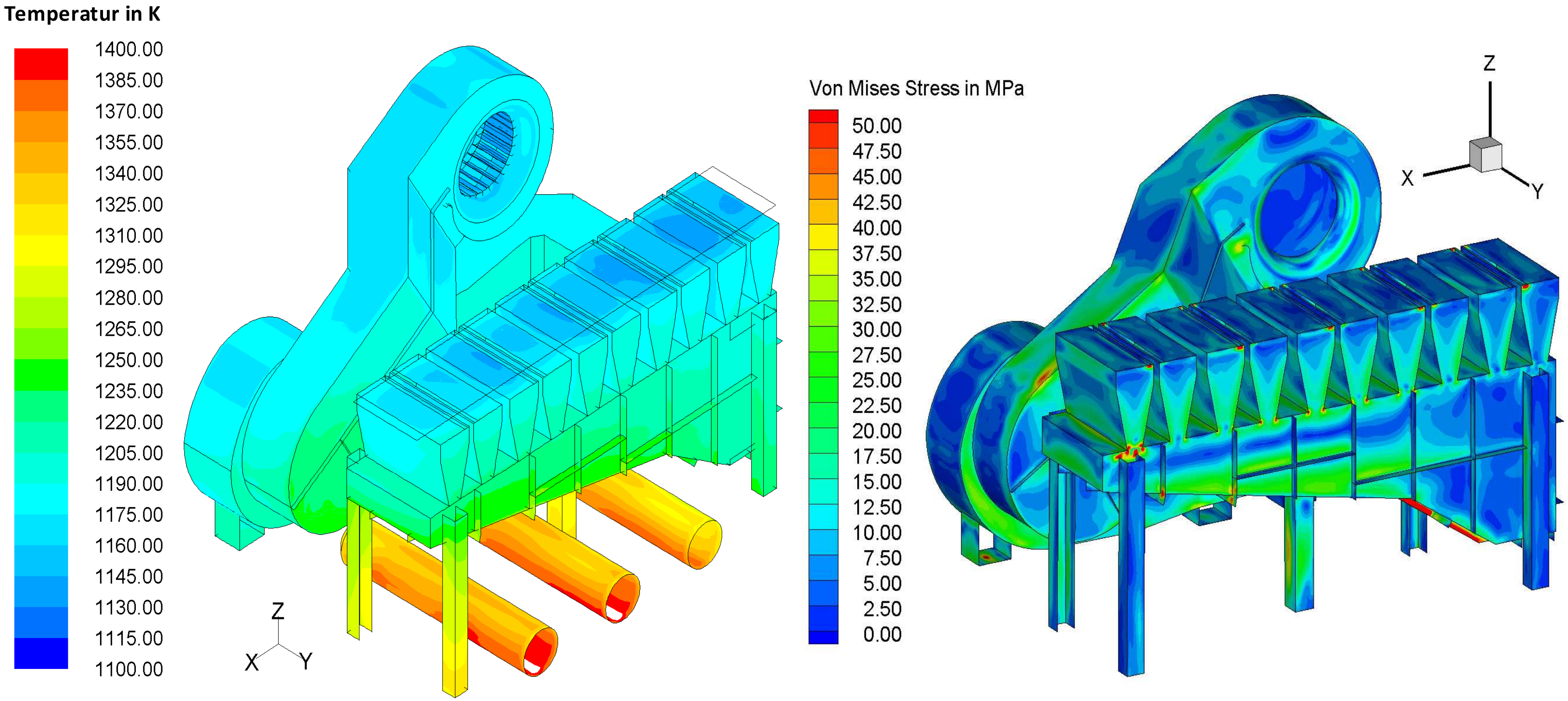


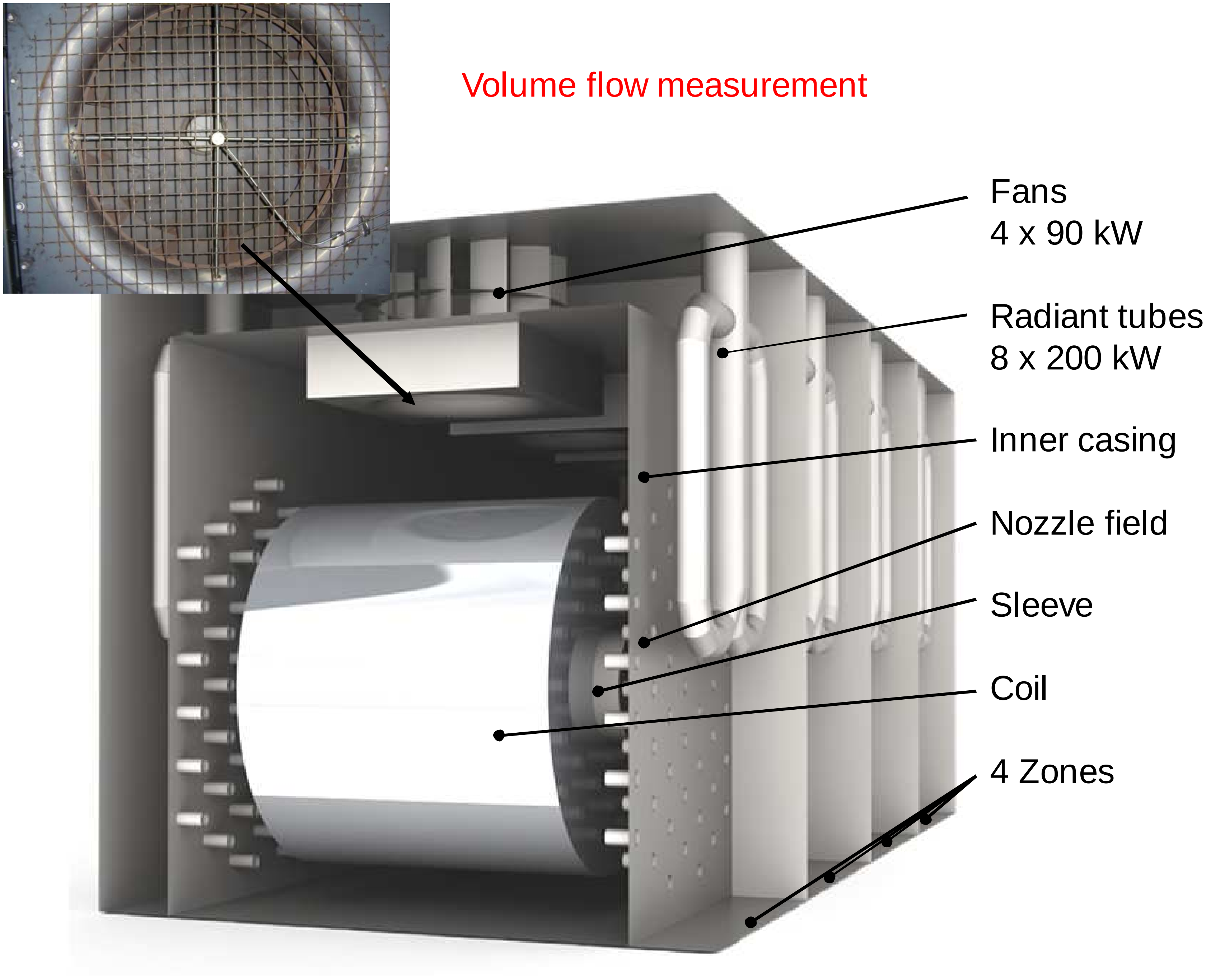


Contribution of stresses on the radiant heating tube

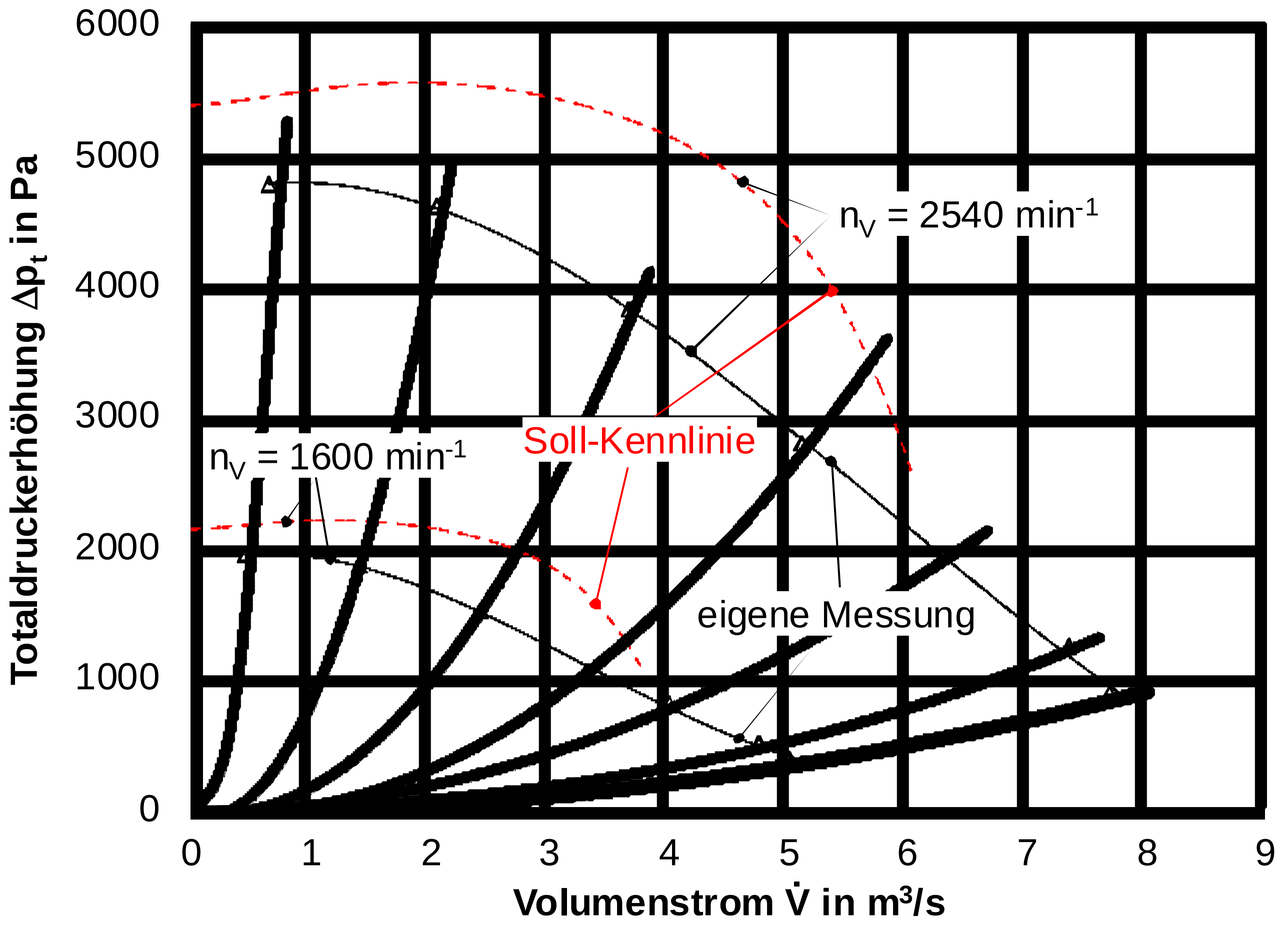



Fans
4 x 90 kW
Radiant tubes
8 x 200 kW
Inner casing
Nozzle field
Sleeve
Coil
4 Zones


Temperatur in K
1400.00
1385.00
1370.00
1355.00
1340.00
1325.00
1310.00
1295.00
1280.00
1265.00
1250.00
1235.00
1220.00
1205.00
1190.00
1175.00
1160.00
1145.00
1130.00
1115.00
1100.00
Z
X
Y
Von Mises Stress in MPa
50.00
47.50
45.00
42.50
40.00
37.50
35.00
32.50
30.00
27.50
25.00
22.50
20.00
17.50
15.00
12.50
10.00
7.50
5.00
2.50
0.00
Z
X
Y


Volume flow measurement
Fans
4 x 90 kW
Radiant tubes
8 x 200 kW
Inner casing
Nozzle field
Sleeve
Coil
4 Zones

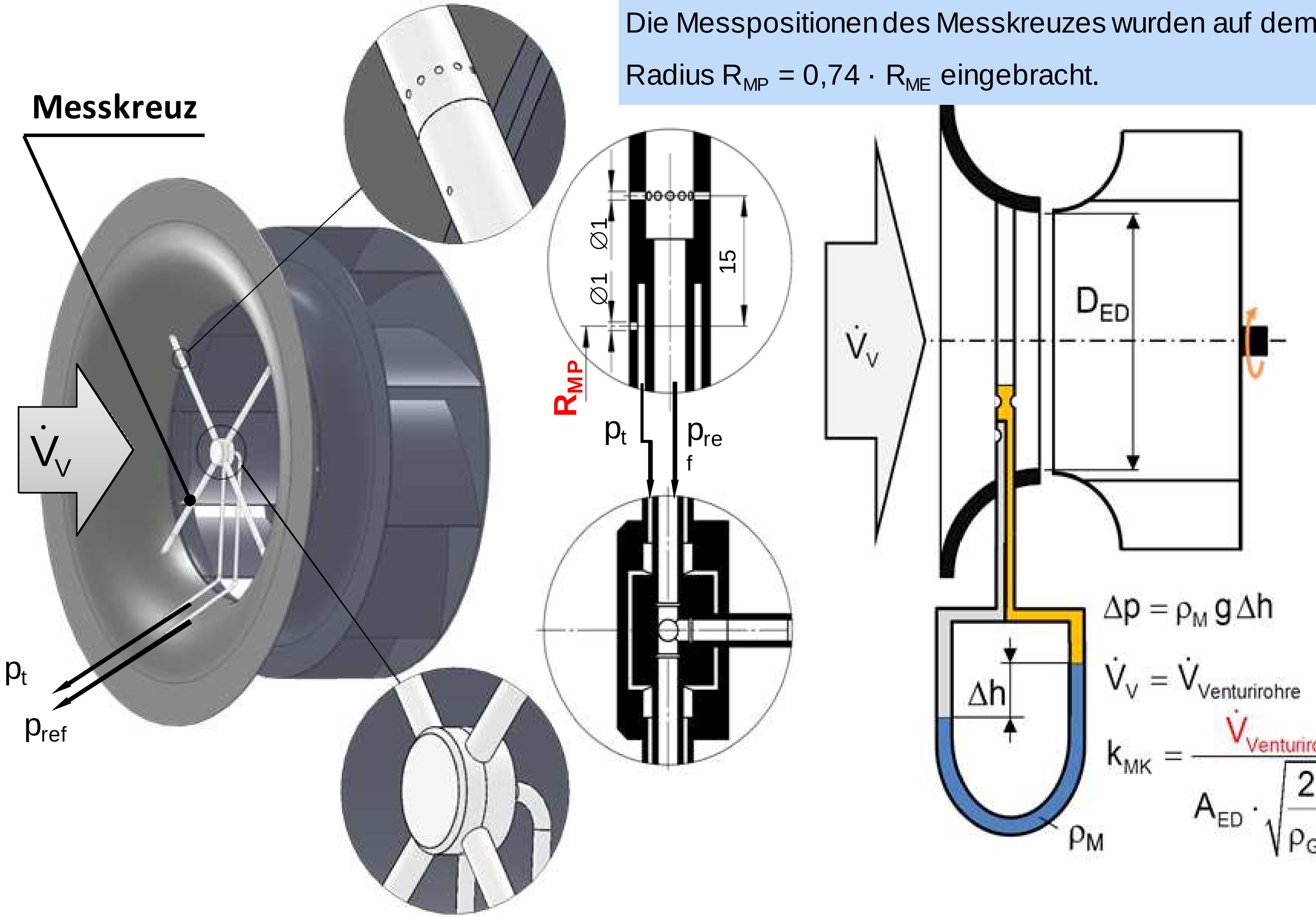
$$\alpha_{Gut} \sim \dot{V}_V^{2/3}$$



Deutliche Abweichungen zwischen Herstellerangaben (Normprüfstand) und Ofen/Versuchsstand

Ziel dieses Projektes: kontinuierliche Volumenstromerfassung als Standardmessung in Wärmebehandlungsöfen

Die Messpositionen des Messkreuzes wurden auf dem Radius $R_{MP} = 0{,}74 \cdot R_{ME}$ eingebracht.

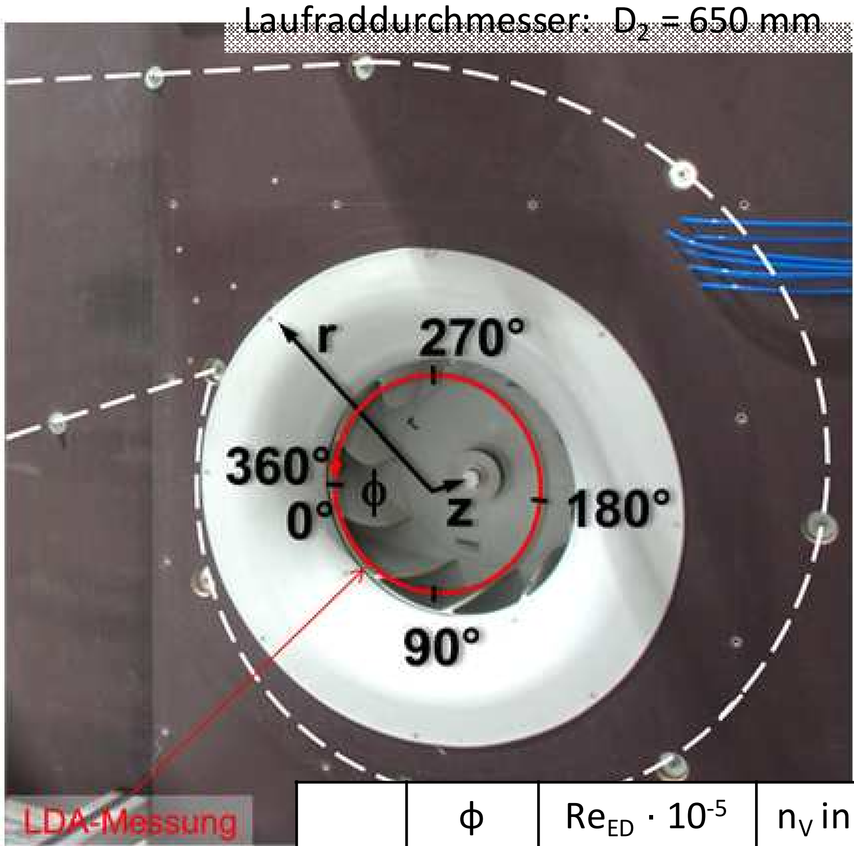


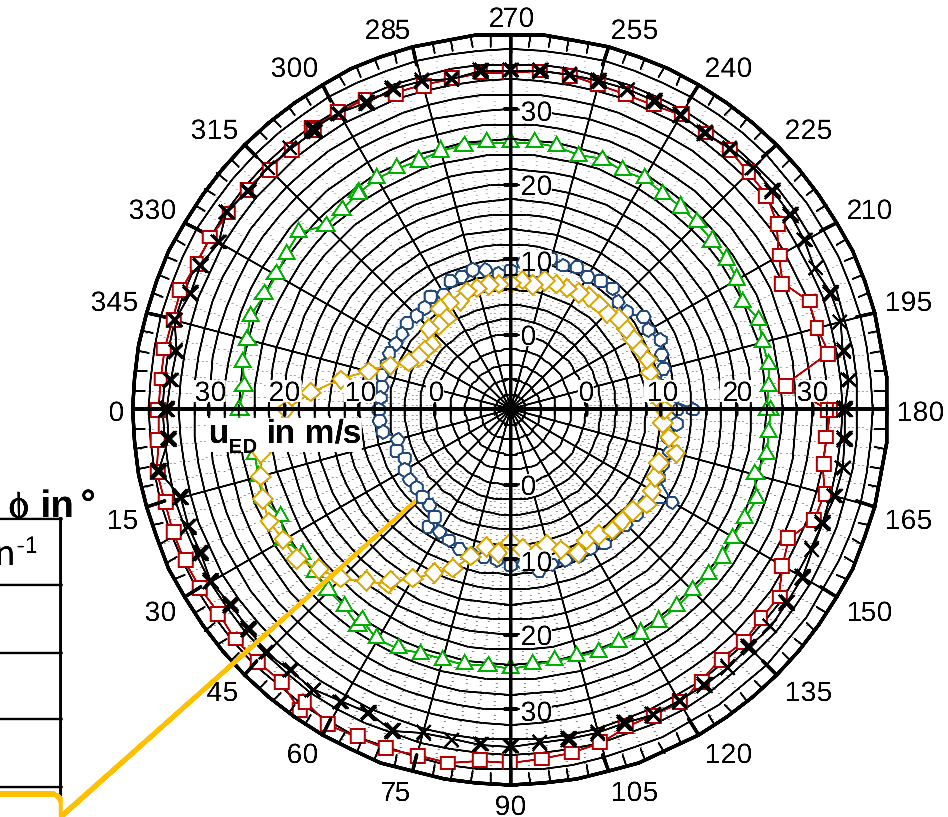
$$\Delta p = \rho_M \, g \, \Delta h$$

$$\dot{V}_V = \dot{V}_{Venturirohre}$$

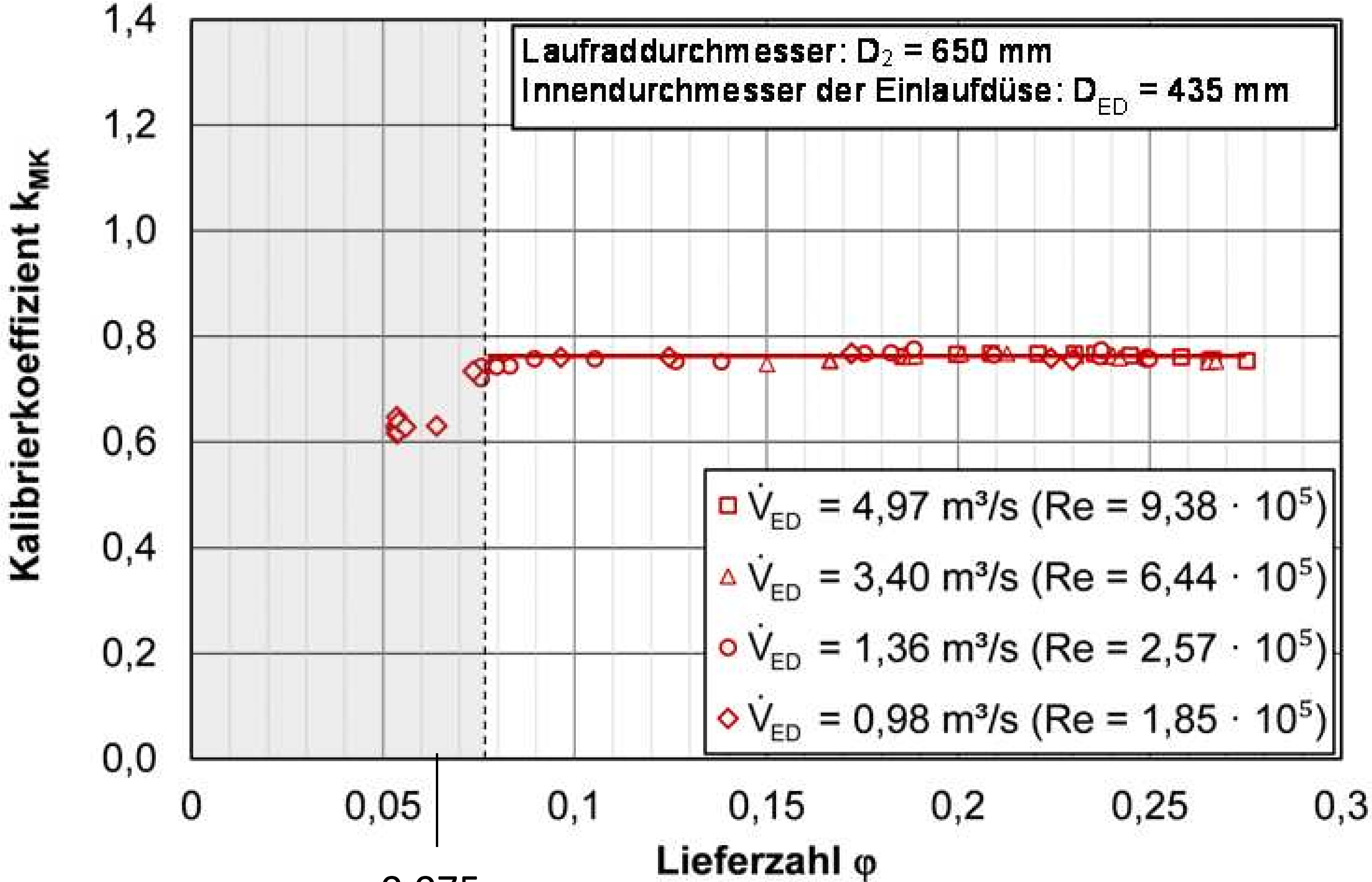
$$k_{MK} = \frac{\dot{V}_{Venturirohre}}{A_{ED} \cdot \sqrt{\frac{2}{\rho_G} \cdot \Delta p}}$$

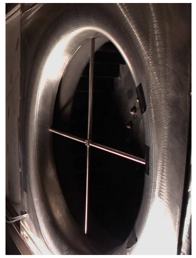
Strömungsgeschwindigkeit in der Einlaufdüse als Funktion des Azimuts ϕ (Polarkoordinaten, z = 80, r = 190 mm)





	ϕ	$Re_{ED} \cdot 10^{-5}$	n_V in min^{-1}
□ 1	0,274	9,38	1600
△ 2	0,188	6,44	1600
○ 3	0,075	2,65	1600
◇ 4	0,054	1,85	1600
× 5	0,188	9,38	2330





$$\varphi = k_V \cdot \frac{\dot{V}_V}{n_V}$$

$R_{MP} = 0{,}74 \cdot R_{ME}$

$k_{MK} = const = 0{,}76$

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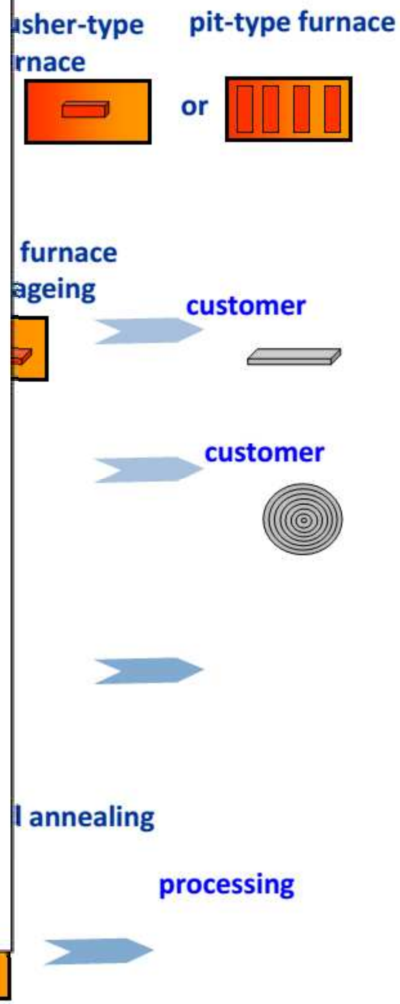
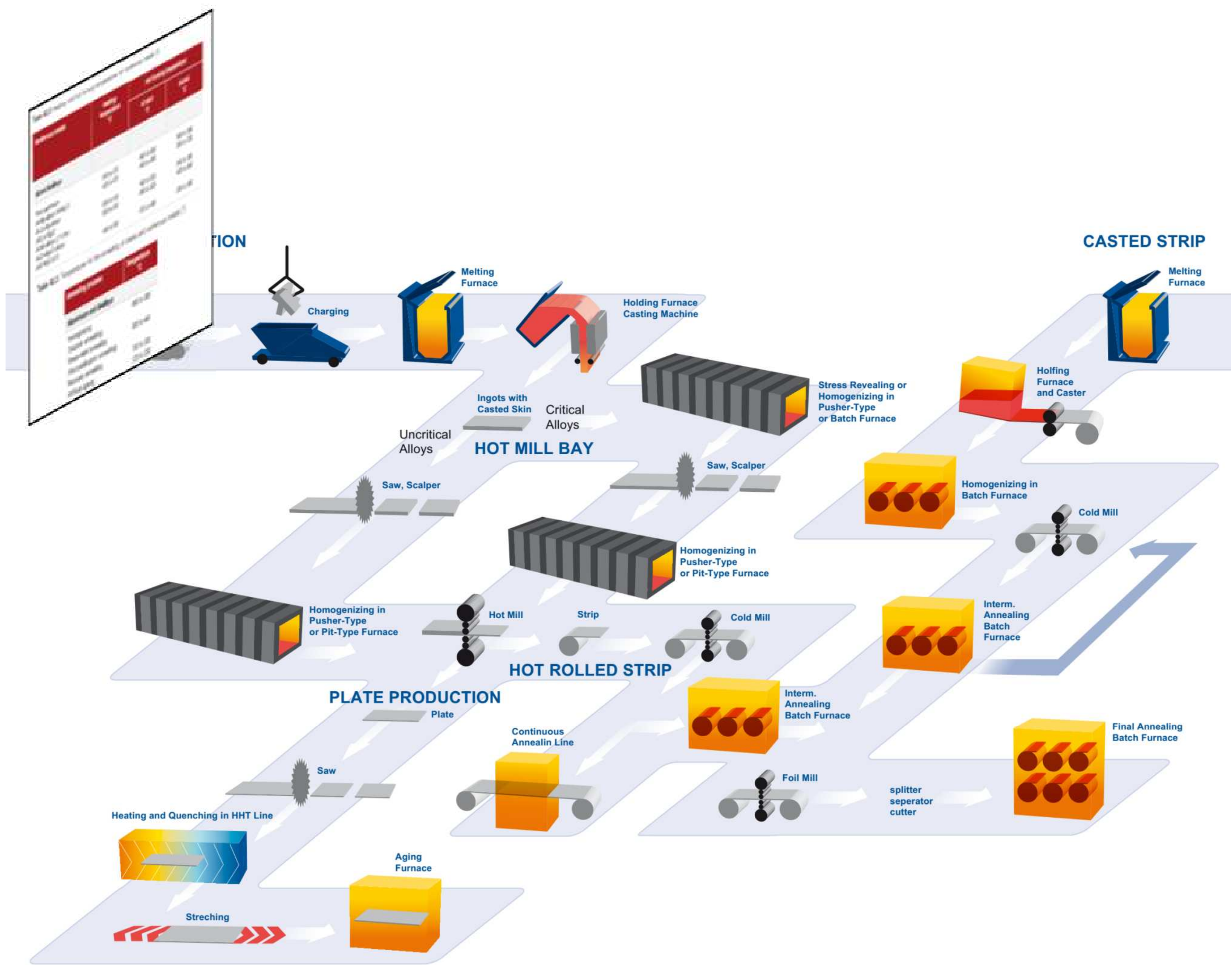
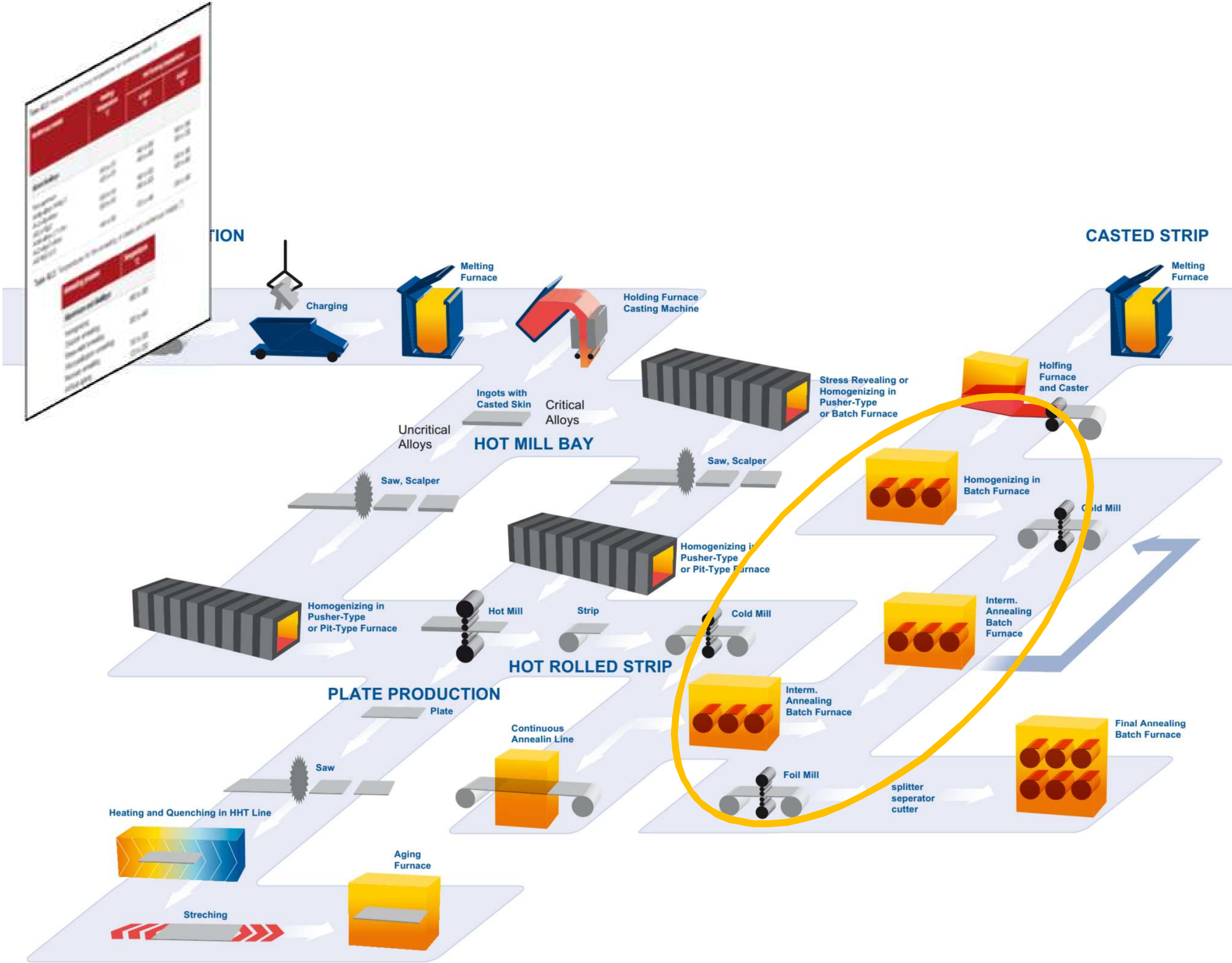



TION
CASTED STRIP
Charging
Melting Furnace
Holding Furnace Casting Machine
Melting Furnace
Holfing Furnace and Caster
Stress Revealing or Homogenizing in Pusher-Type or Batch Furnace
Ingots with Casted Skin
Critical Alloys
Uncritical Alloys
HOT MILL BAY
Saw, Scalper
Saw, Scalper
Homogenizing in Batch Furnace
Cold Mill
Homogenizing in Pusher-Type or Pit-Type Furnace
Homogenizing in Pusher-Type or Pit-Type Furnace
Hot Mill
Strip
Cold Mill
Interm. Annealing Batch Furnace
HOT ROLLED STRIP
PLATE PRODUCTION
Plate
Interm. Annealing Batch Furnace
Continuous Annealin Line
Final Annealing Batch Furnace
Saw
Foil Mill
splitter seperator cutter
Heating and Quenching in HHT Line
Aging Furnace
Streching

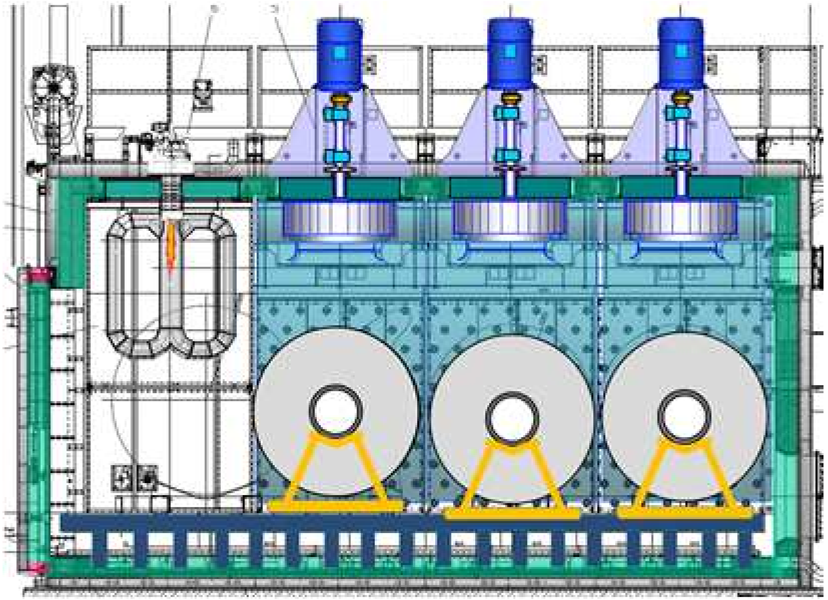

Casting up to 700 °C
Furnace
Charging
Stress Relief up to 550°C
Casting up to 700 °C
Holfing Furnace
Ingots with Casted Skin
Critical Alloys
Uncritical Alloys
Homogenization up to 550 °C
PreHeat / Homogenization up to 550 °C
Saw, Scalper
Cold Mill
Homogenizing in Pusher-Type or Pit-Type Furnace
PreHeat / Homogenization up to 550 °C
Interm. Anneal up to 550 °C
Pusher-Type or Pit-Type Furnace
Hot Mill
Strip
Cold Mill
HOT ROLLED STRIP
PLATE PRODUCTION
Interm. Annealing
Strip Solutionizing up to 550°C
Final. Anneal up to 550 °C
Final Annealing Batch Furnace
Saw
Plate Solutionizing up to 550 °C
splitter seperator cutter
Final. Anneal up to 550 °C



TION
CASTED STRIP
Charging
Melting Furnace
Holding Furnace Casting Machine
Ingots with Casted Skin
Critical Alloys
Uncritical Alloys
HOT MILL BAY
Stress Revealing or Homogenizing in Pusher-Type or Batch Furnace
Melting Furnace
Holfing Furnace and Caster
Saw, Scalper
Saw, Scalper
Homogenizing in Batch Furnace
ld Mill
Homogenizing i
Pusher-Type
or Pit-Type Furnace
Homogenizing in Pusher-Type or Pit-Type Furnace
Hot Mill
Strip
Cold Mill
HOT ROLLED STRIP
Interm. Annealing Batch Furnace
PLATE PRODUCTION
Plate
Interm. Annealing Batch Furnace
Continuous Annealin Line
Saw
Foil Mill
splitter seperator cutter
Final Annealing Batch Furnace
Heating and Quenching in HHT Line
Aging Furnace
Streching

Technology Today

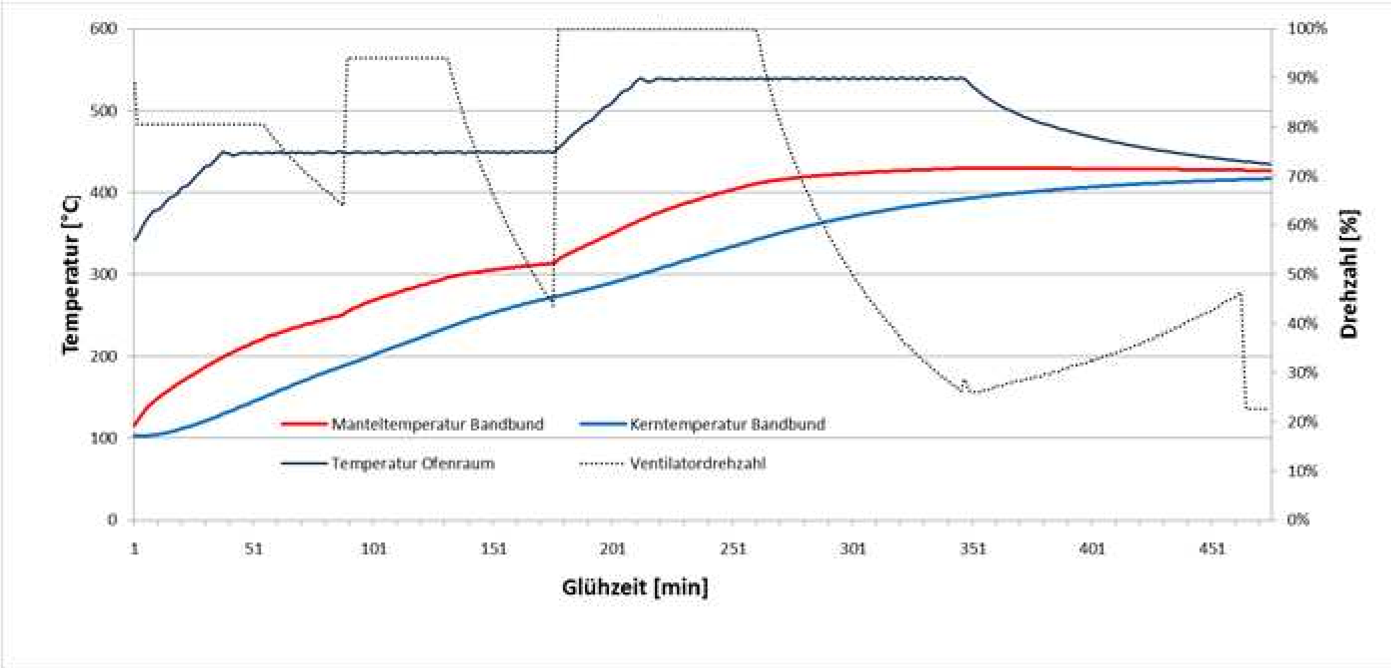
- Coil Annealing Furnaces for Intermediate or Temper Annealing of rolled aluminium coils



- Discontinous process:
    - Compiling the batch
    - Feeding the Furnace, Start of Heat Treatment
    - Heat Treatment
    - End of Heat Treatment – Remove the Batch

Stand der Technik - Prozessführung

Heat Treatment Process



- …either according to pre determined receipe (Temperature/Time/Fanspeed)
- Or according to measured metal temperature

•Energy demand and CO_2 emission of coil annealing furnaces

- Reference: aluminium, 20-420°C, energy demand: 185 kWh_{th}/t and 28 kWh_{el}/t, respectively

- At an annual output of 1.8 million tonnes of flat products, at
- least 100,000 tonnes of CO_2 are released for intermediate
- and final annealing purposes in Germany alone.

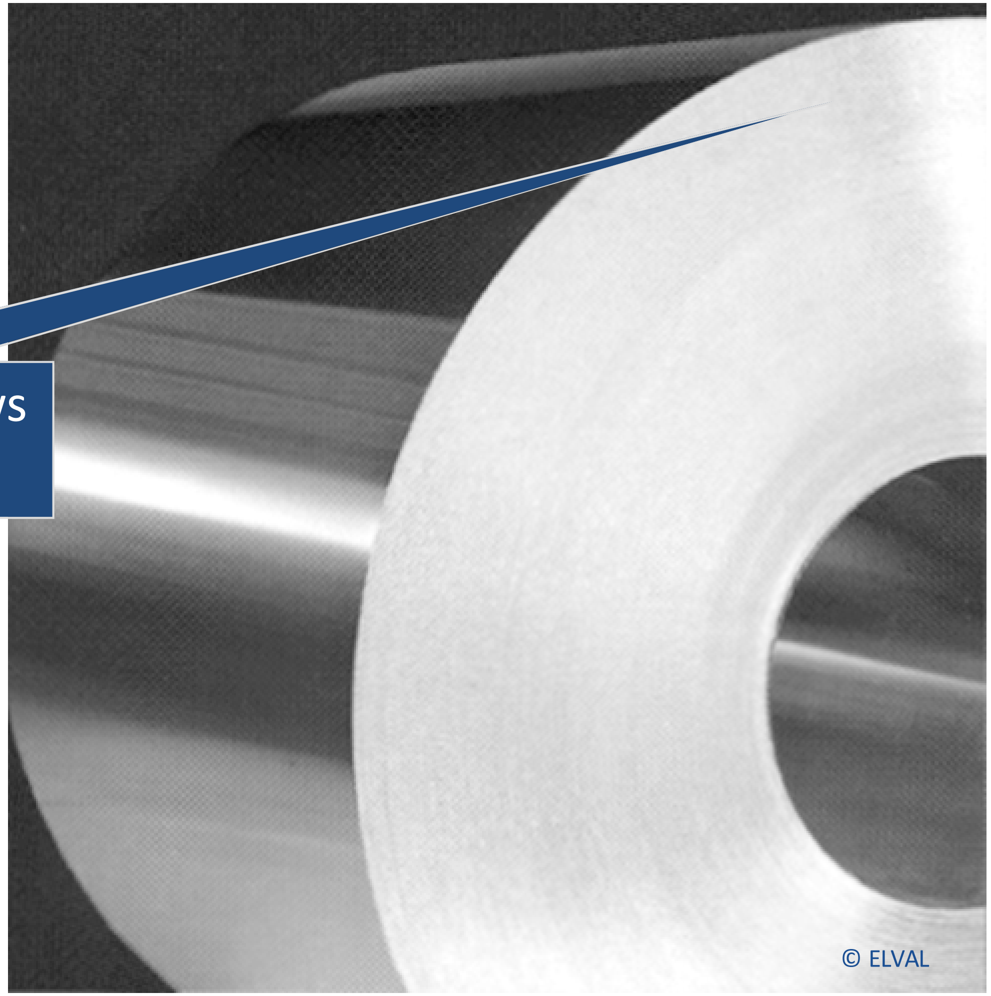
- The need to purchase CO_2 emission rights is to be anticipated as of 2013

Reason enough to start examining the use of saving potentials as early as today!

An Aluminium Coil ....

...looks like a big solid block

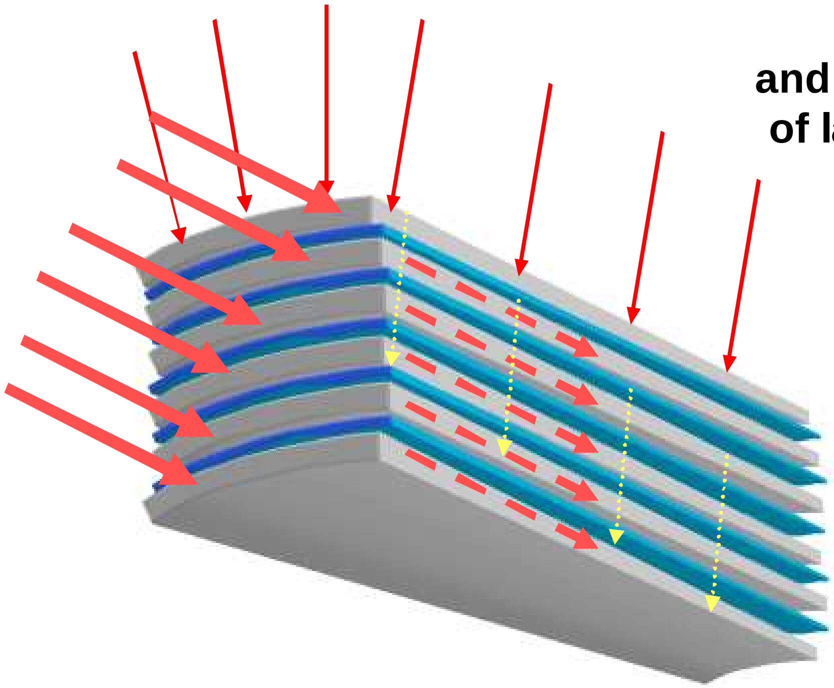
A microscopical view shows ...



Heat up physics for strip coils

90 - 95 % of heat input takes place via the face ends

That a coil consists of hundred layers of Aluminium strip



and hundreds of layers of layers of oil and air

which have an insulating effect, so that only

5 - 10 % of heat input takes place via the circum-ference

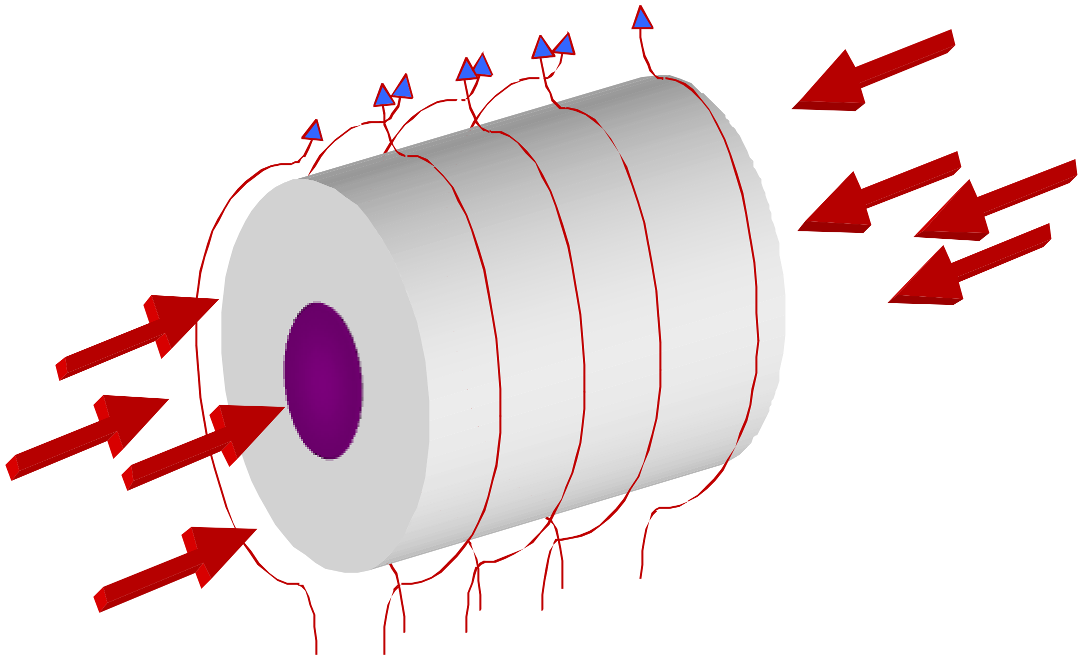
Heat up physics for strip coils

High convection heating

from the face ends is more efficient

than

mass flow around the circumference



•Concept of mathematical modelling

Production planning

• puts together most suitable charge lots from stock in “offline” mode

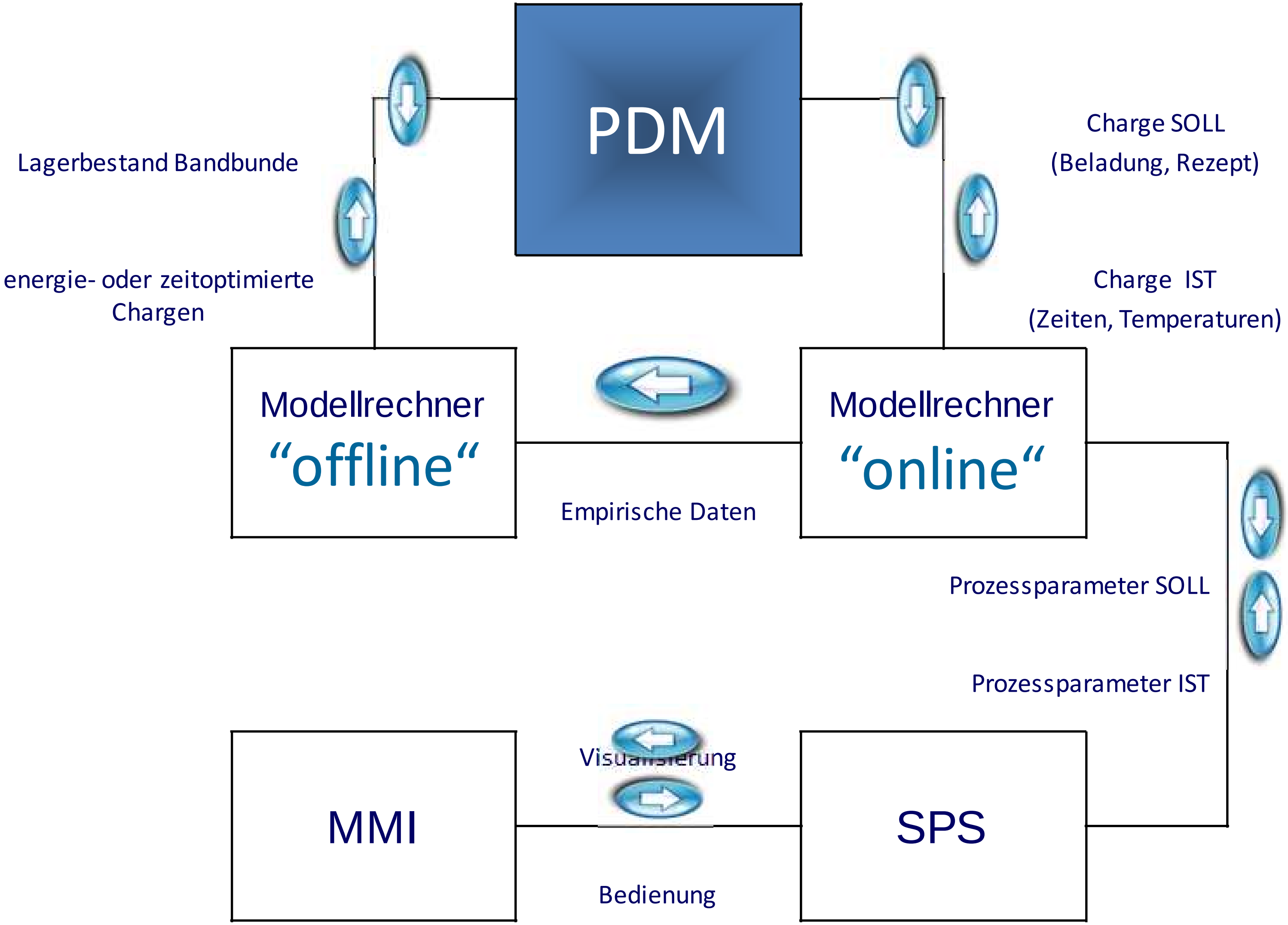
Interfacing

• optimizes production planning by introducing empirical process management data

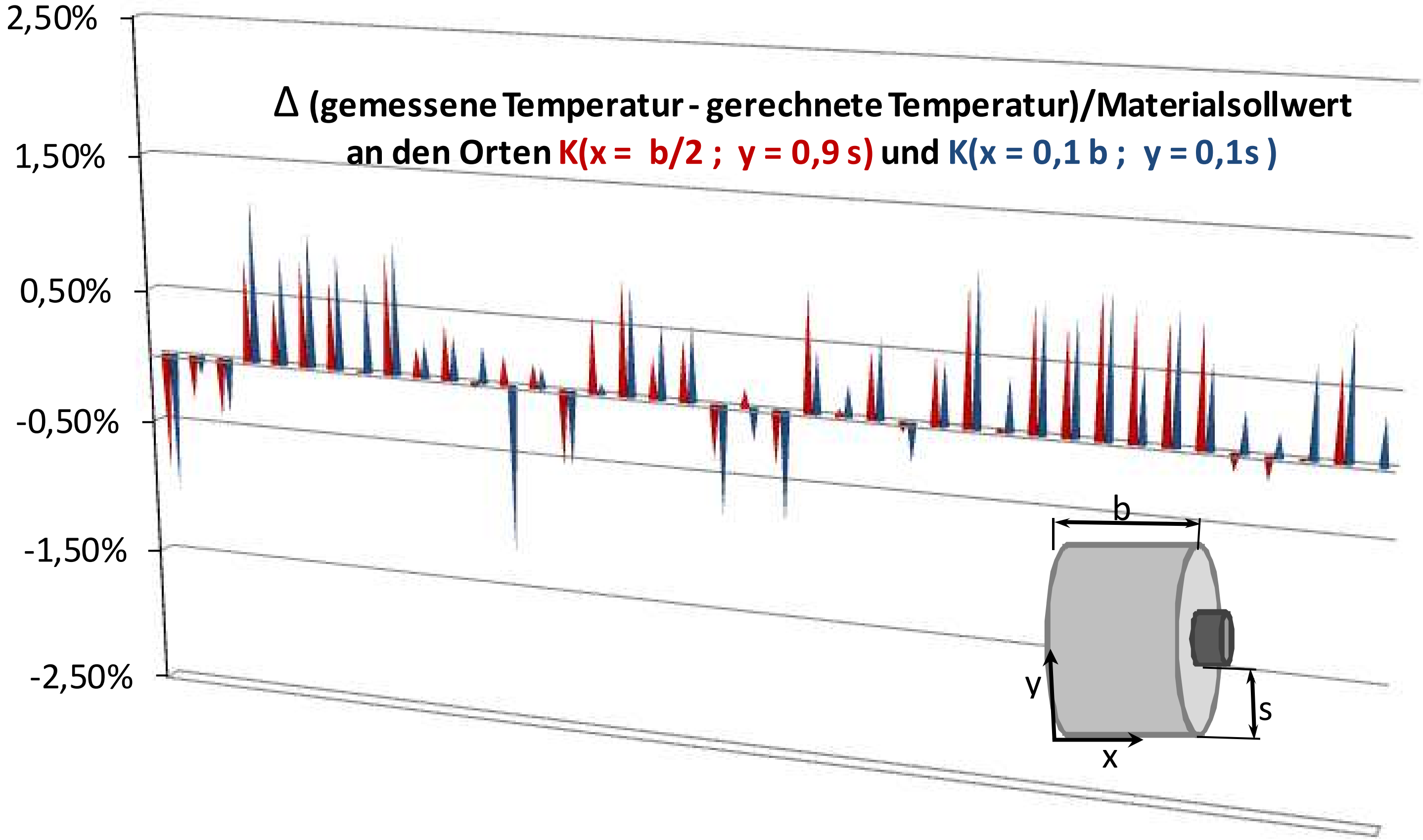
Process management

• computes metal temperatures “online” and controls influencing process parameters

Architektur



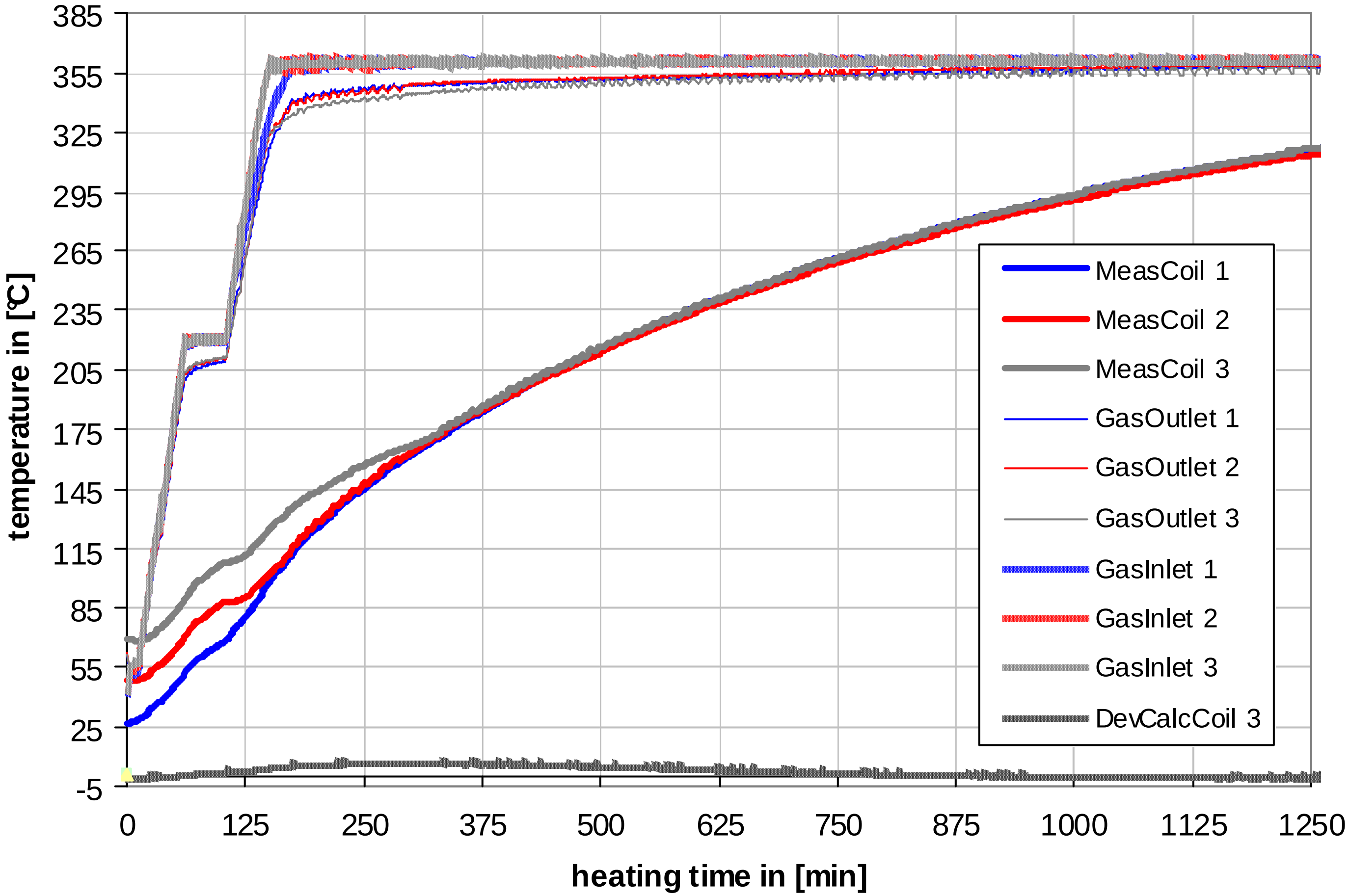
Mathematisches Modell: e) Ergebnisse



Über n=50 Chargen wurde eine Genauigkeit von besser als 1% der Zieltemperatur reproduzierbar erreicht.

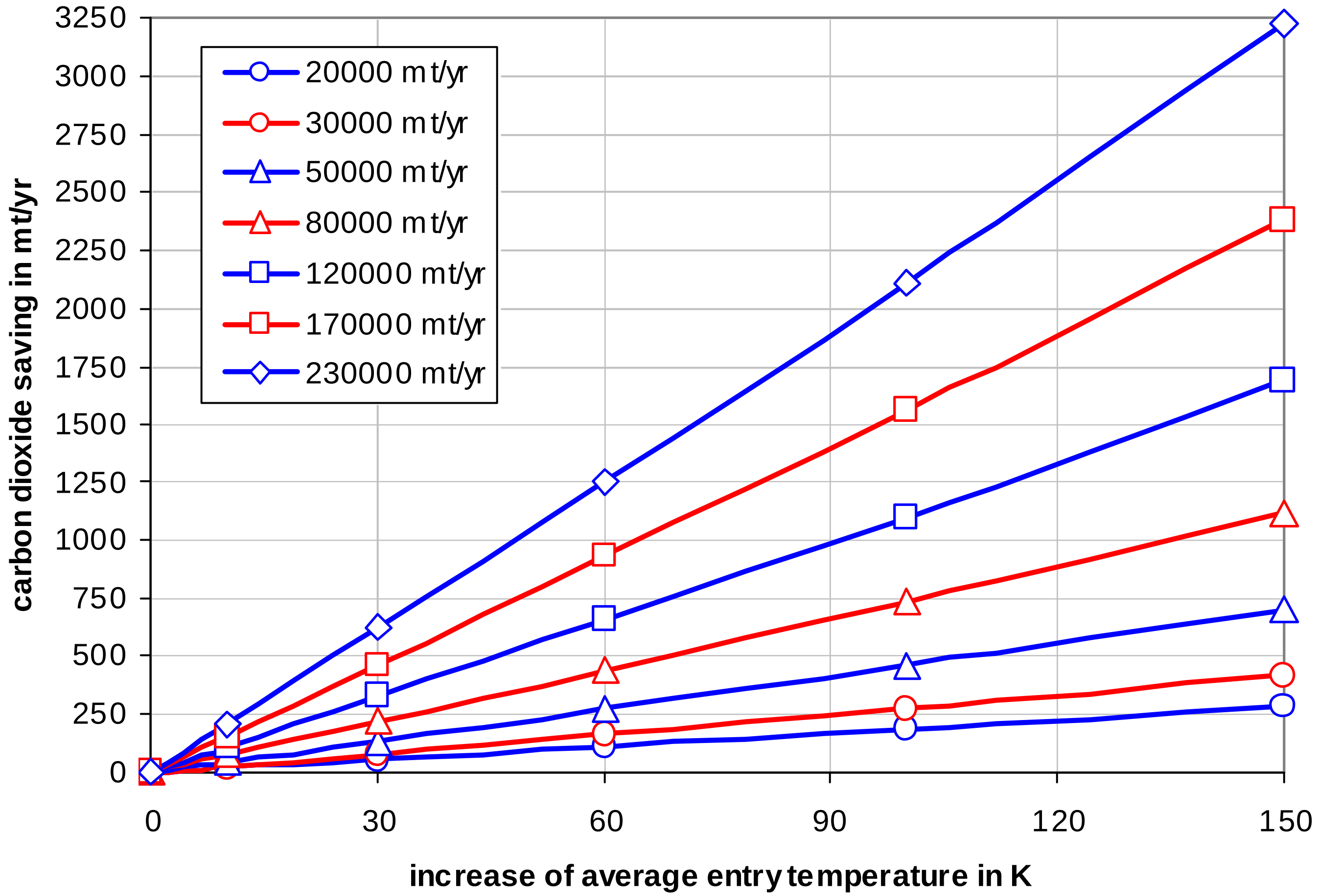
Mathematical model for increase of energy efficiency

•Operating experience:

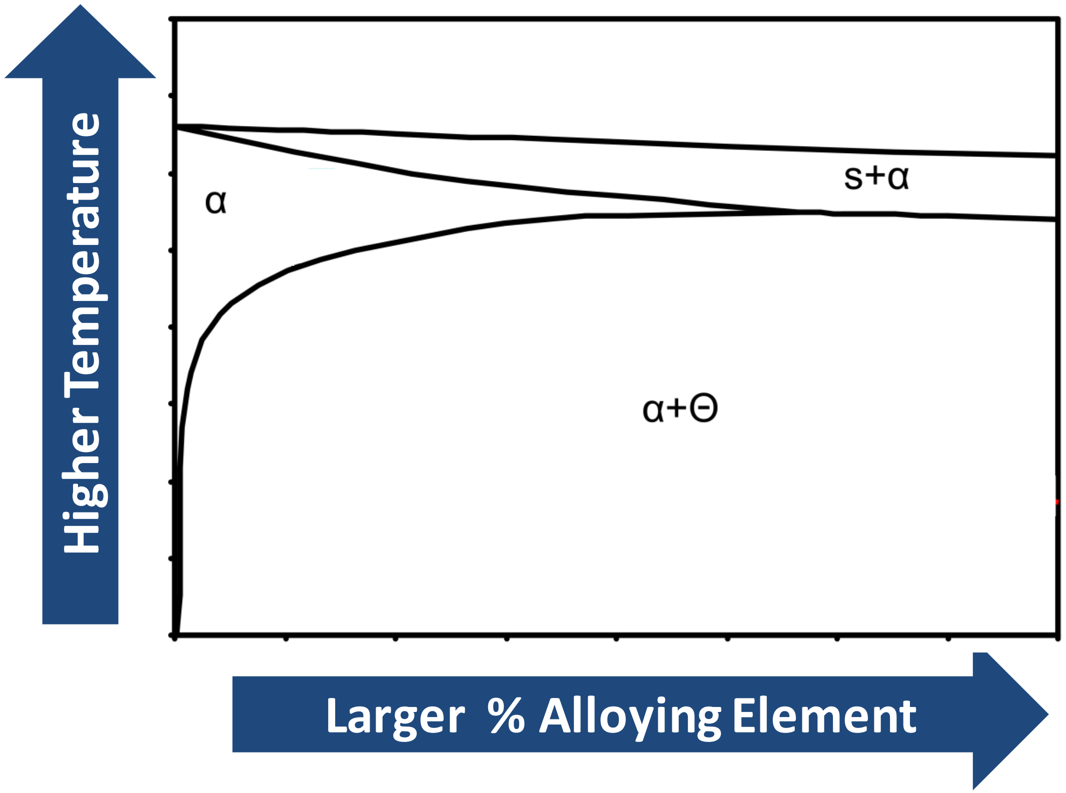


In foil annealing, the mathematical model developed by OTTO JUNKER equalizes a 50K temperature difference to ± 3 K.

- **Estimate of potential CO_2 savings**
- (⅔ from fuel savings, ⅓ from reduced electrical power demand)

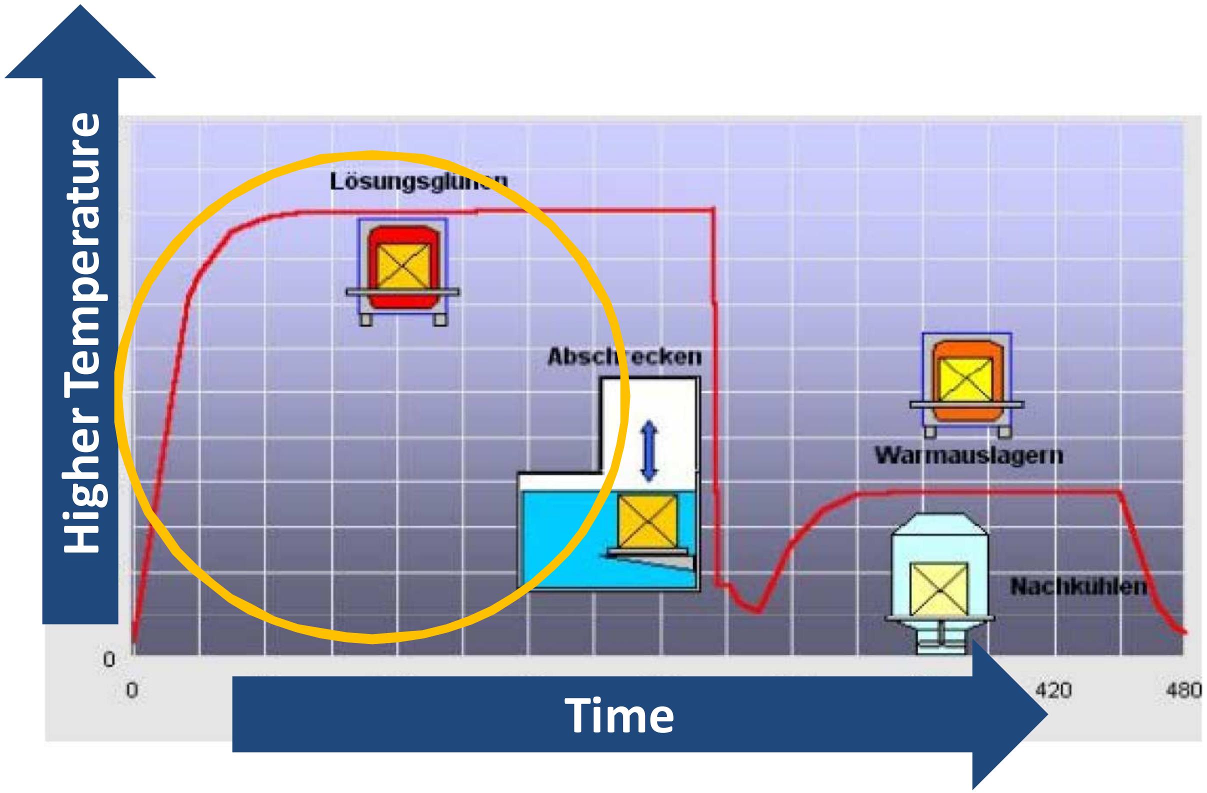


- **Possible Materials**

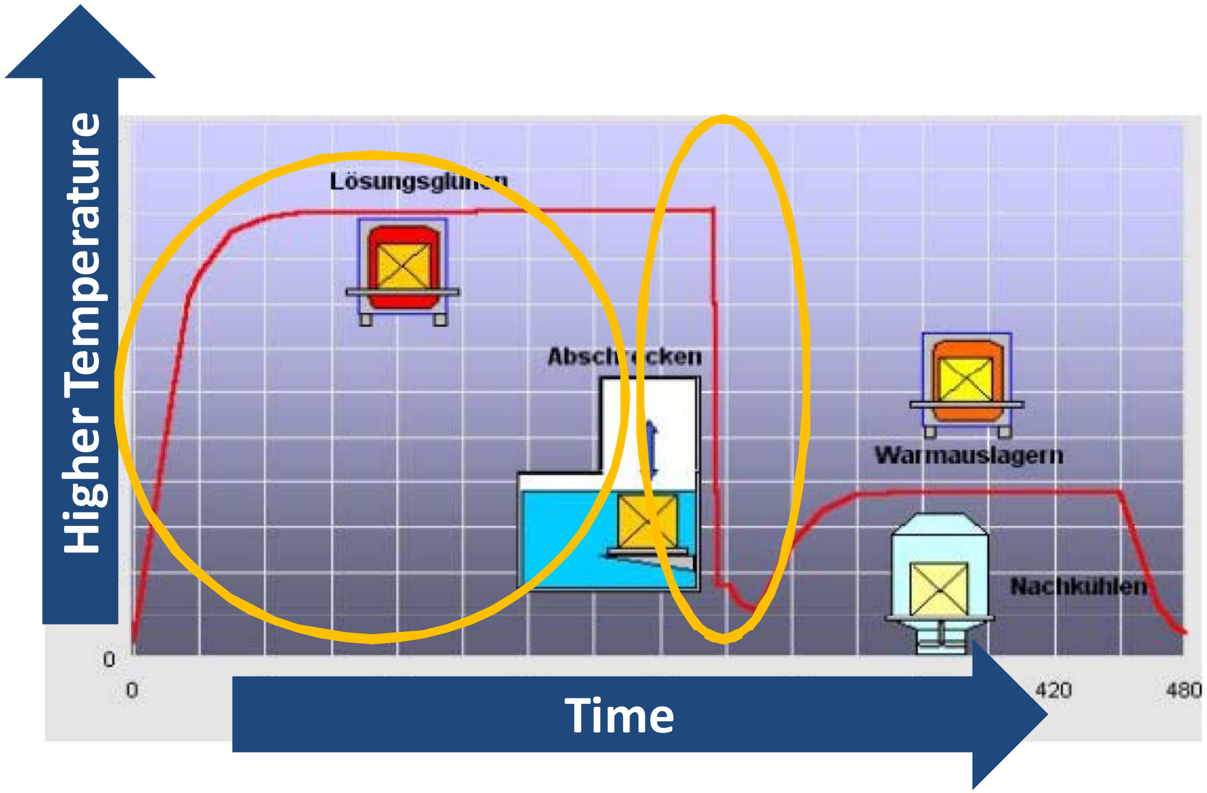


- **2xxx**
  Al-Cu
- **6xxx**
  Al-Mg-Si
- **7xxx**
  Al-Zn-Mg

- **Complete Cycle (3 steps)**



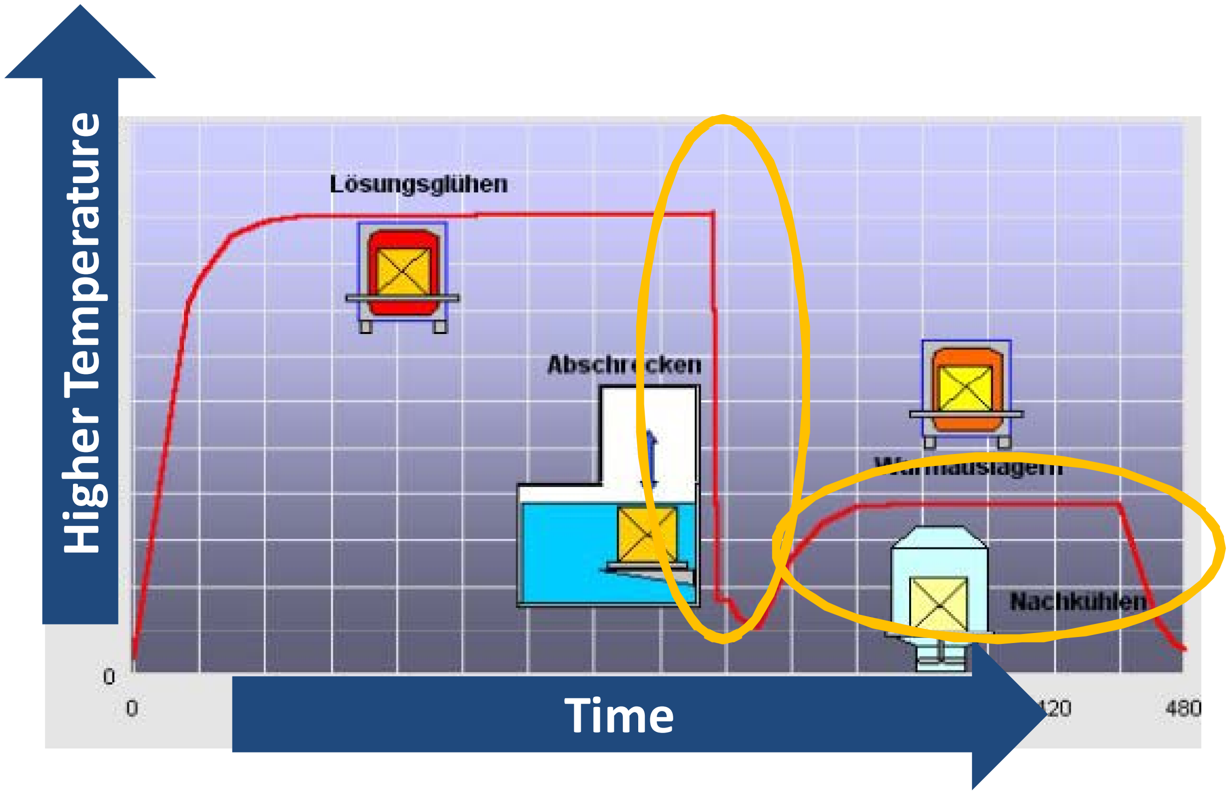
- Complete Cycle (3 steps)



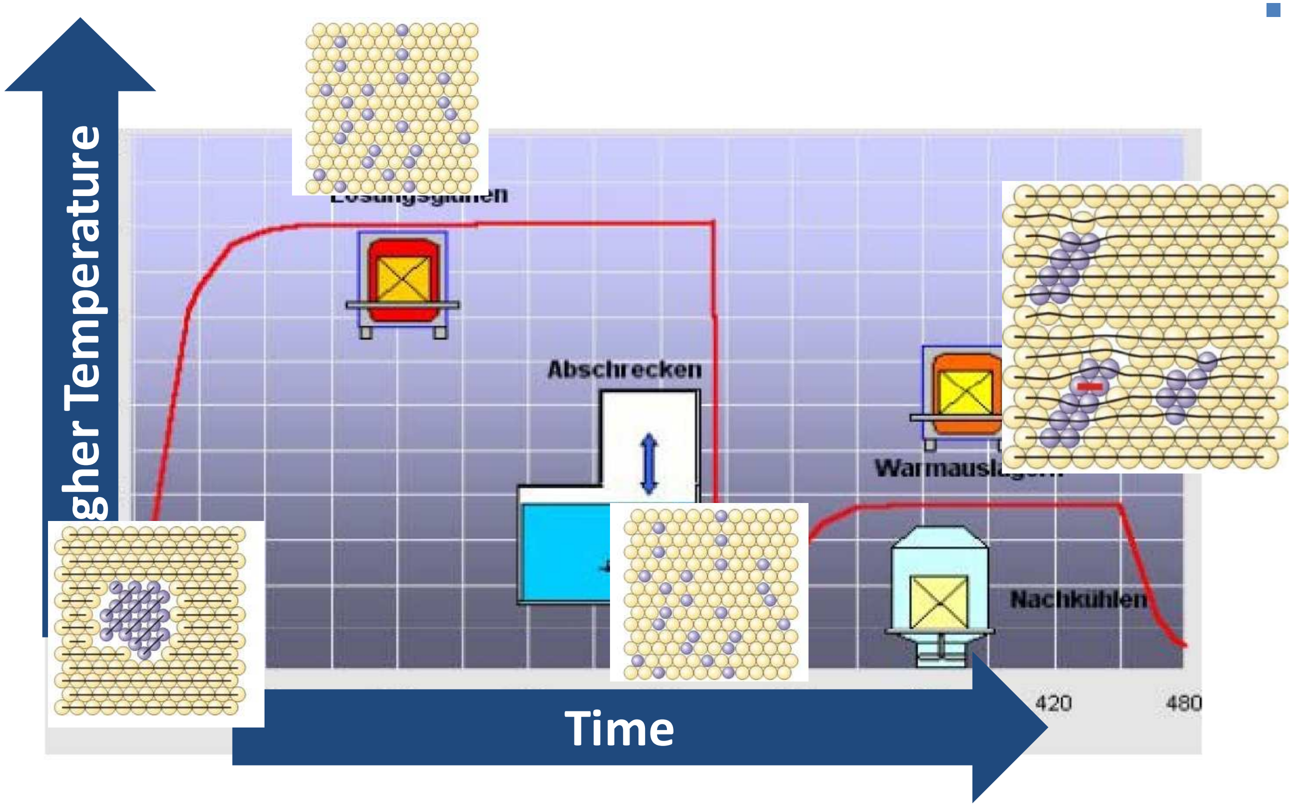
- Heating

- **Complete Cycle (3 steps)**

- **Heating**
- **Quenching**

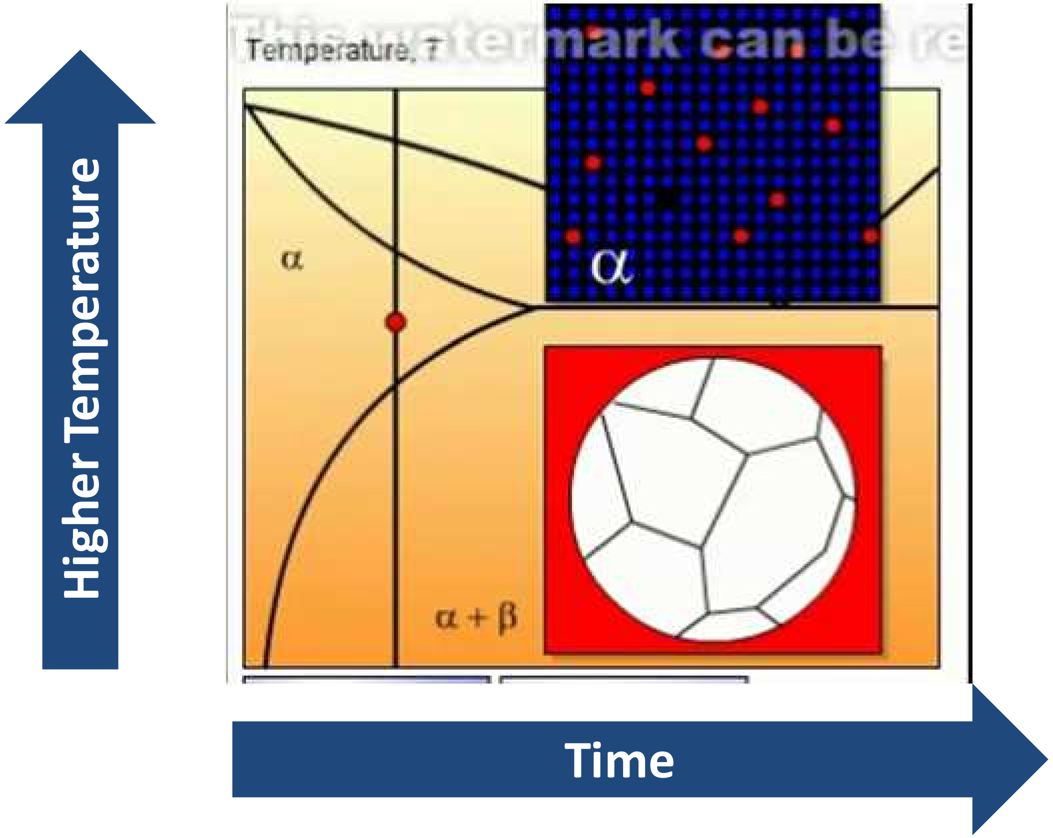


- **Complete Cycle (3 steps)**



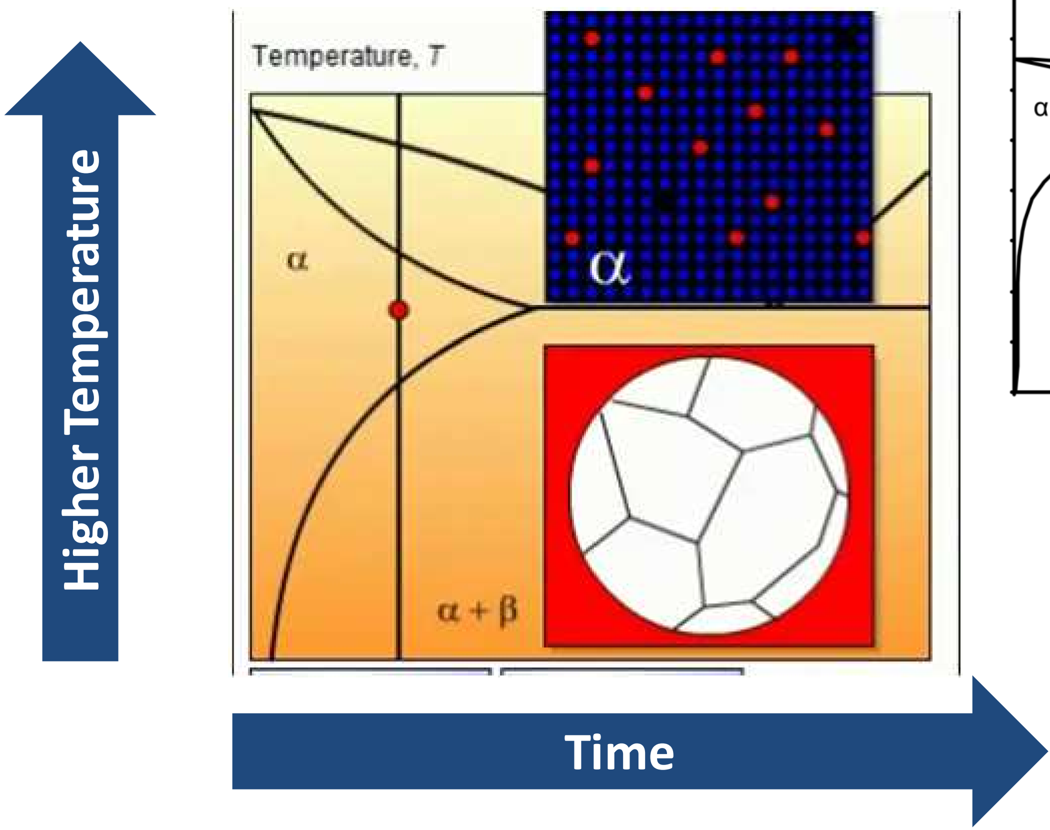
- **Heating**
- **Quenching**
- **Aging**

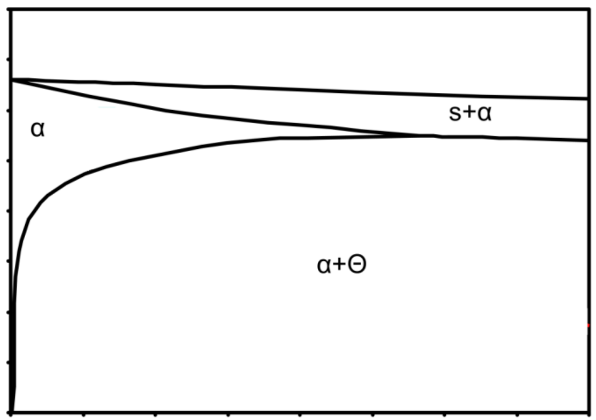
- **How to prevent alloying element from segregation?**



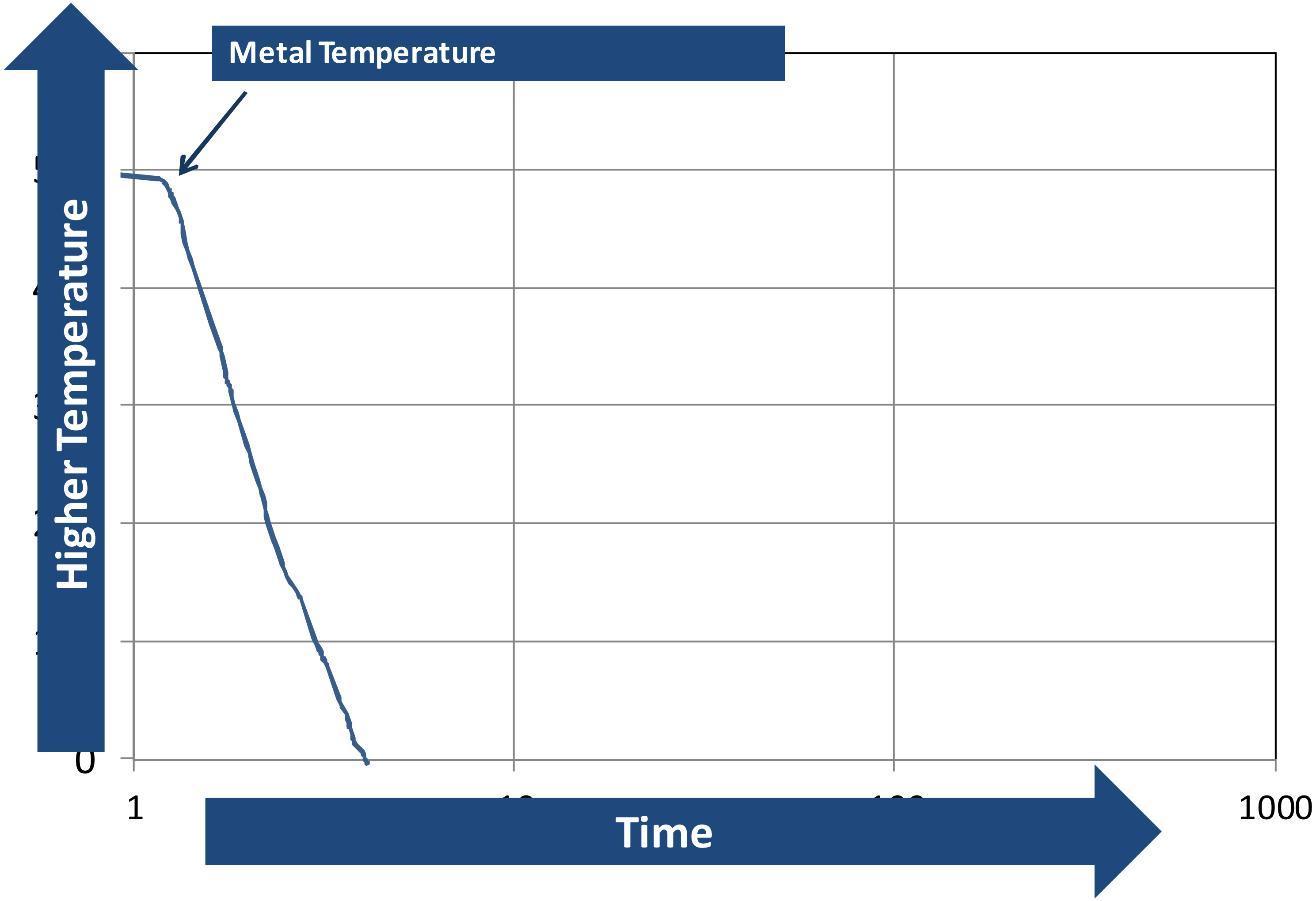
- **How to prevent alloying element from segregation?**

  …… being fast enough

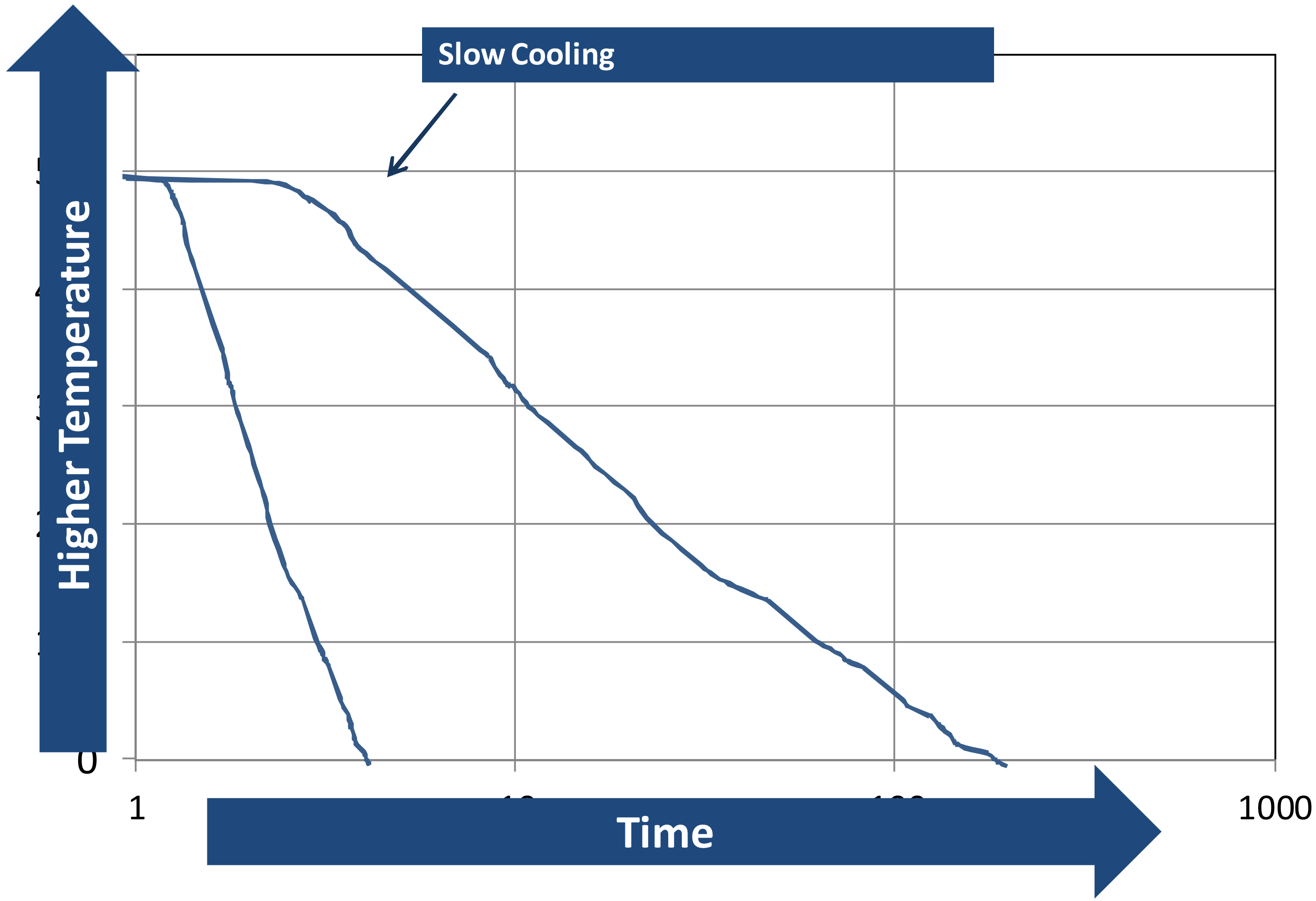




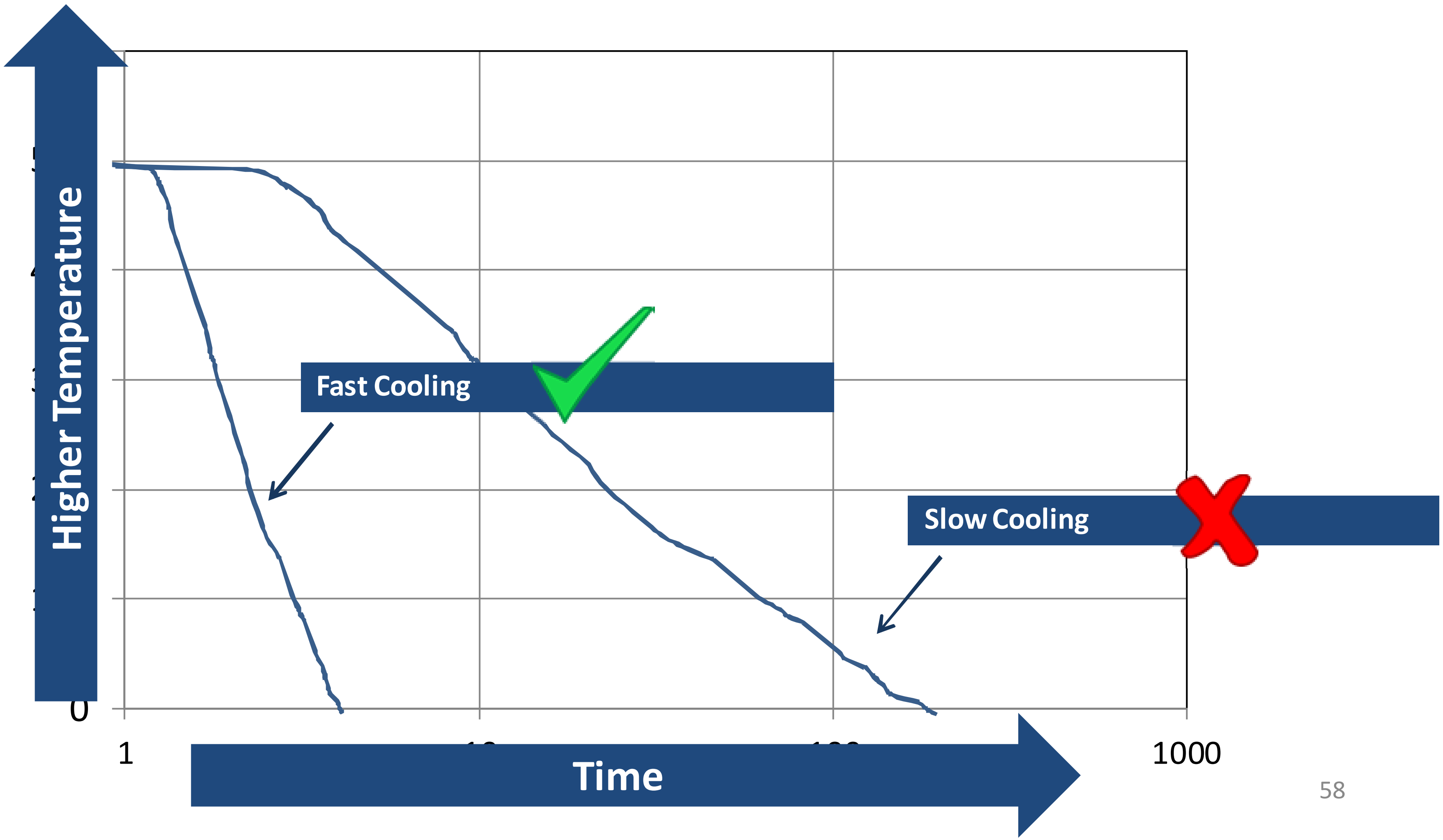
- **Speed matters**



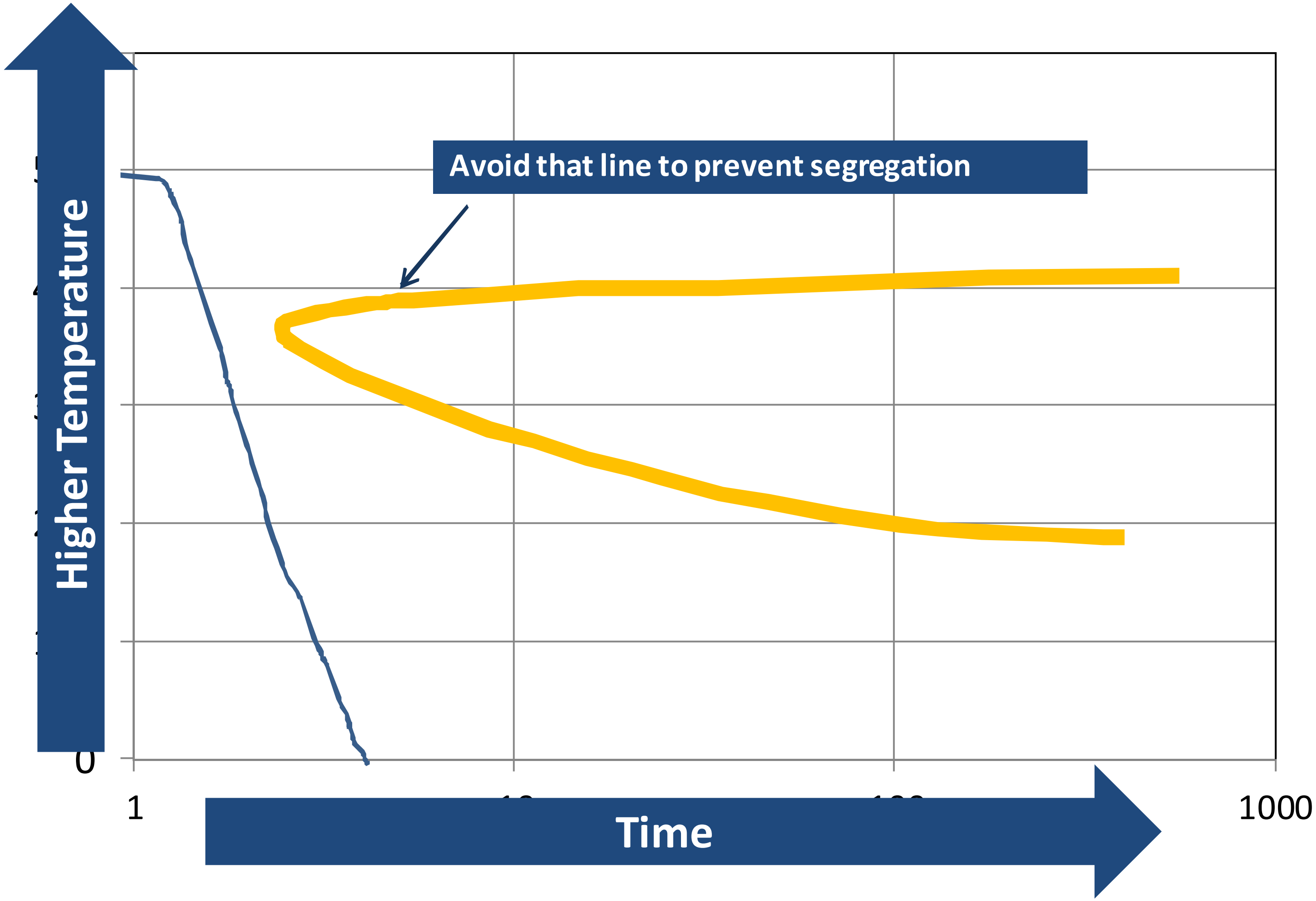
- **Speed matters**



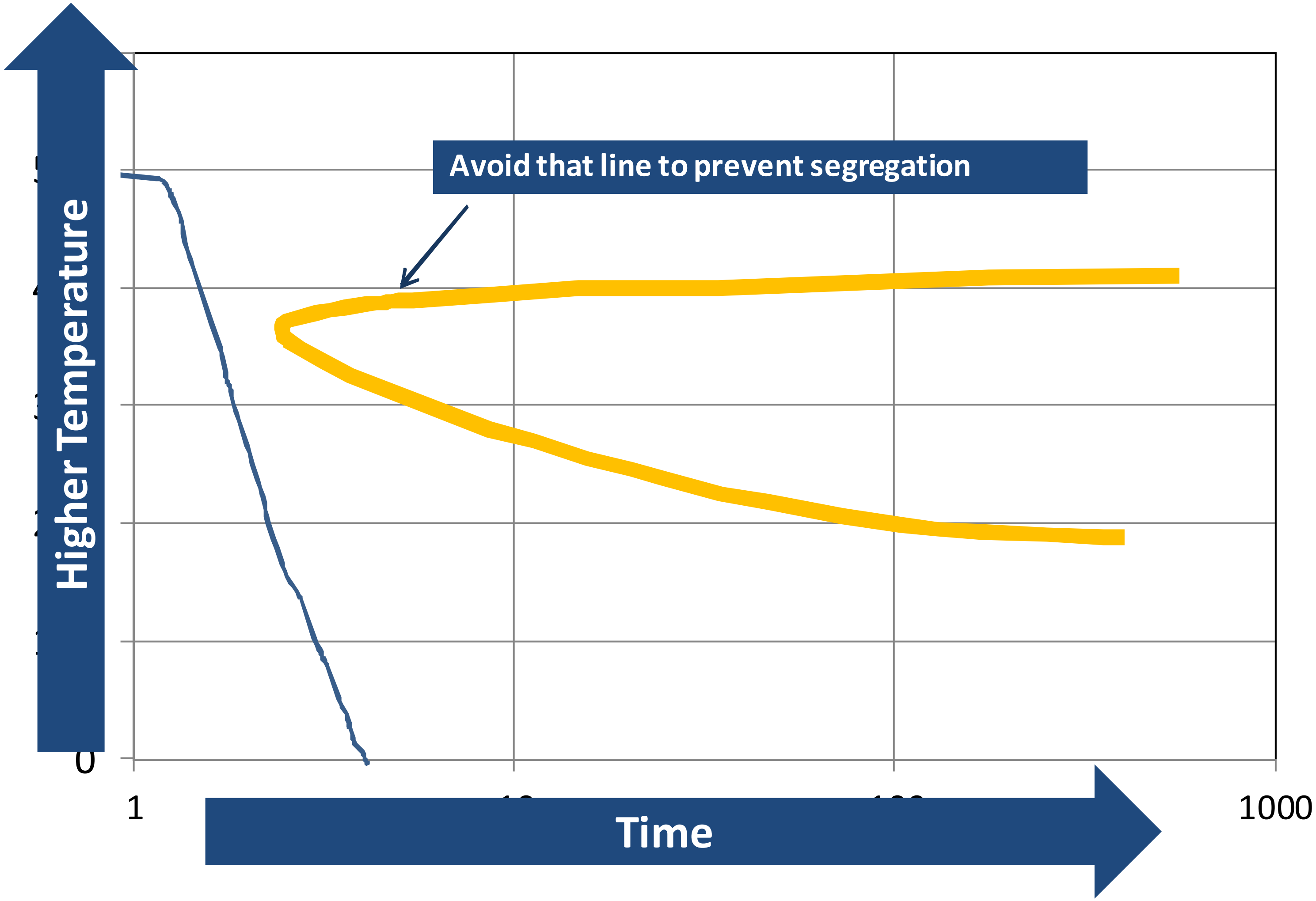
- **Speed matters**



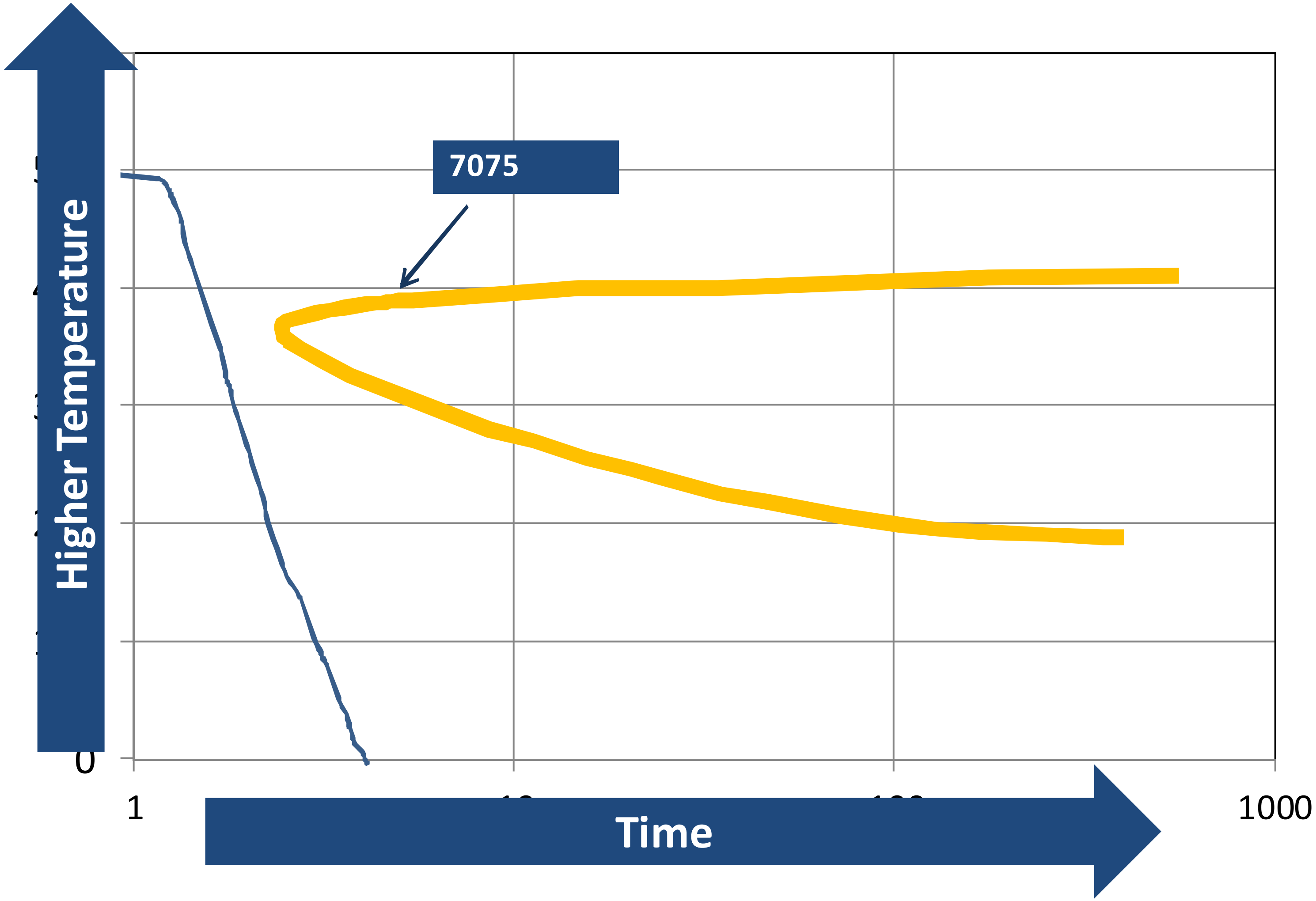
- **Speed matters – as fast as necessary………**



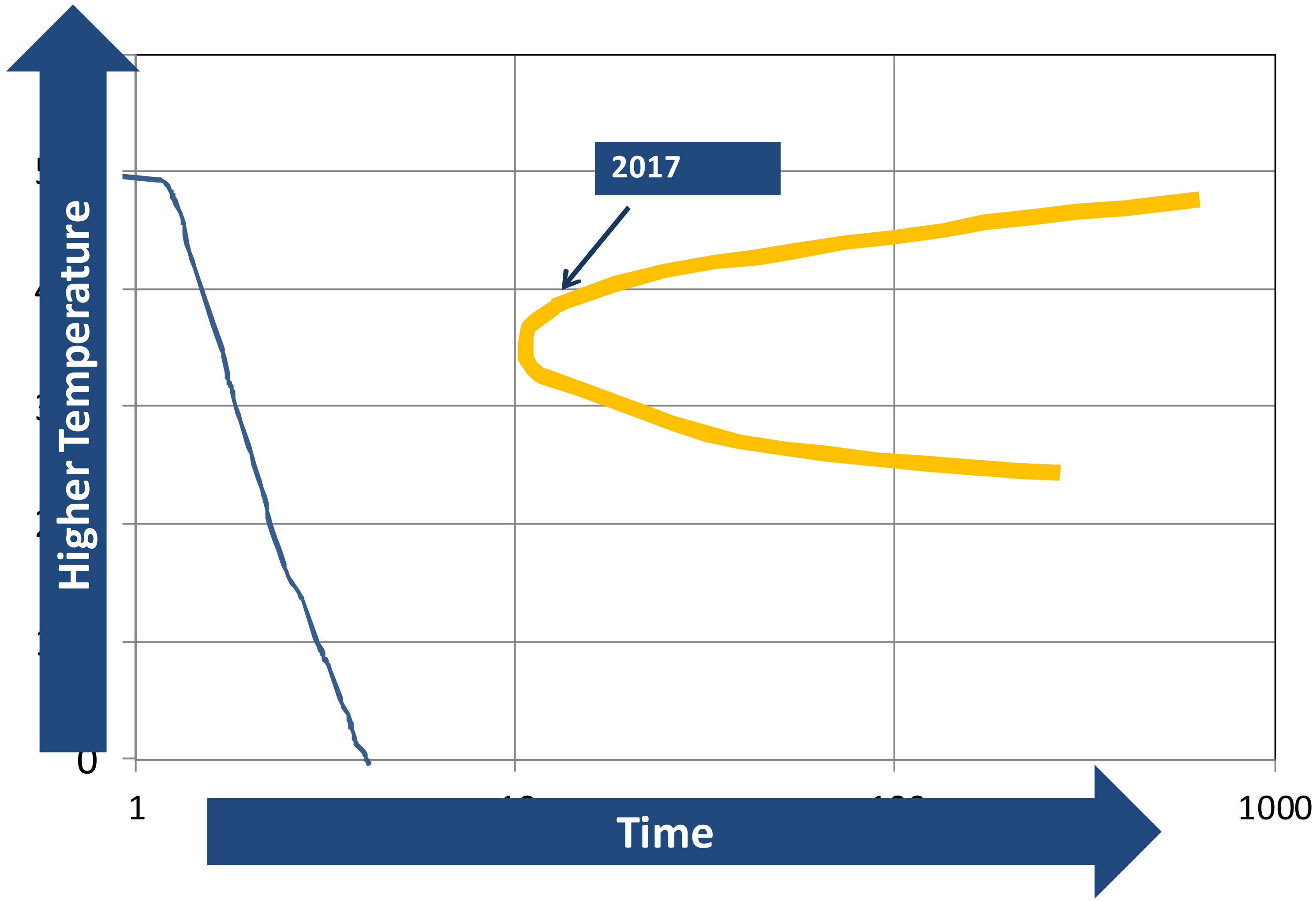
- **Speed matters – as fast as necessary - but as slow as possible**



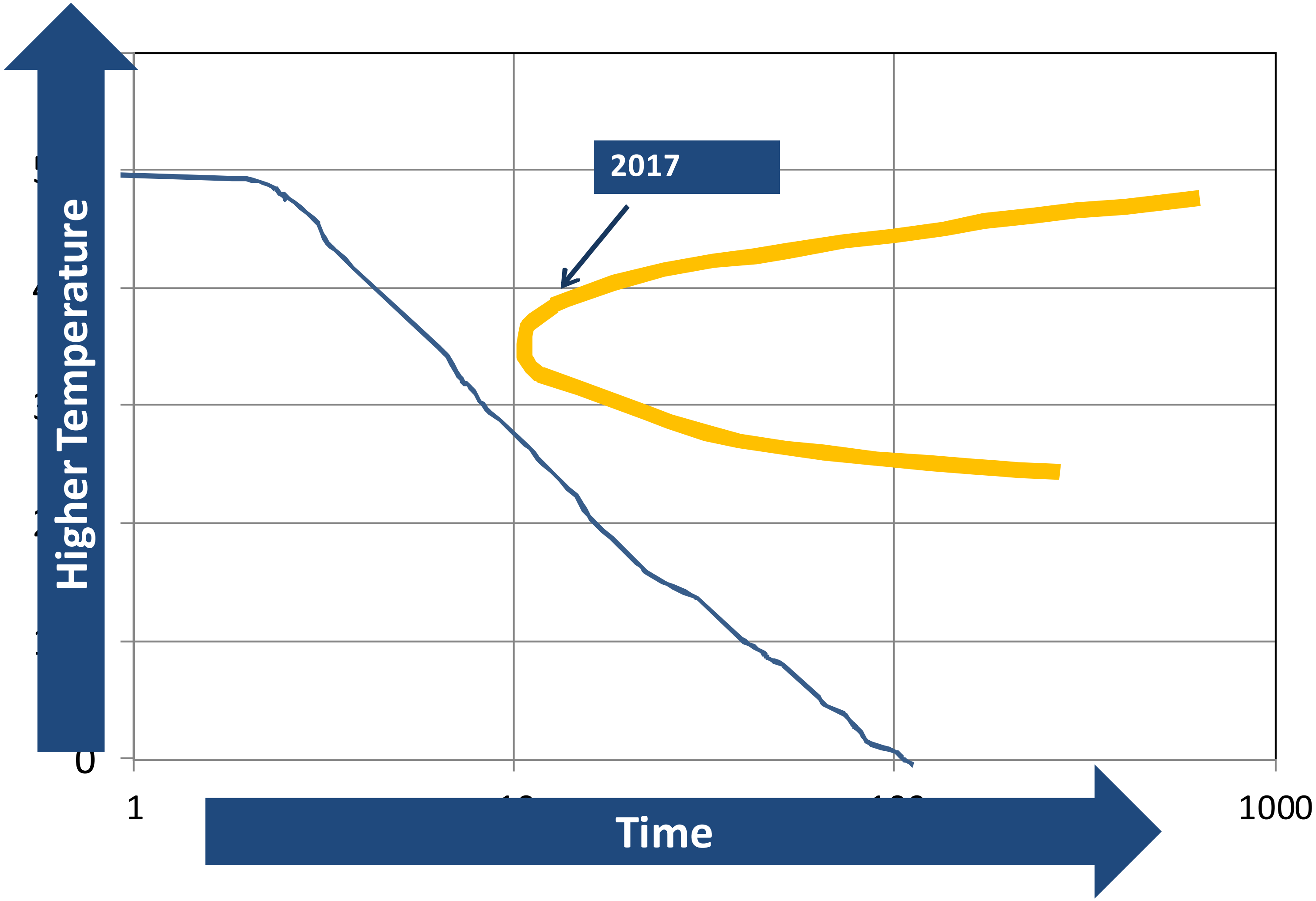
- **Different Alloys – Different Requirements**



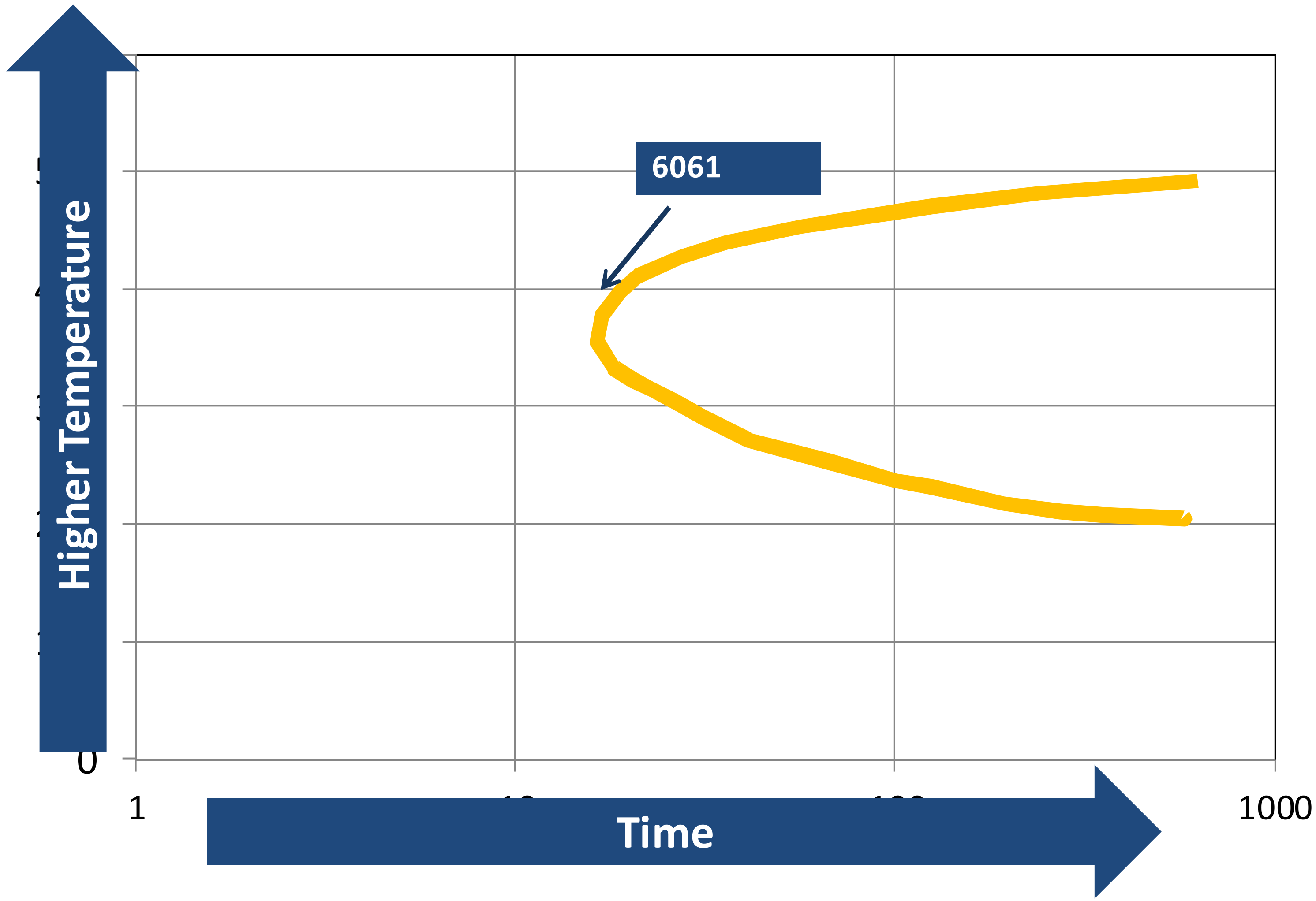
- **Different Alloys – Different Requirements**



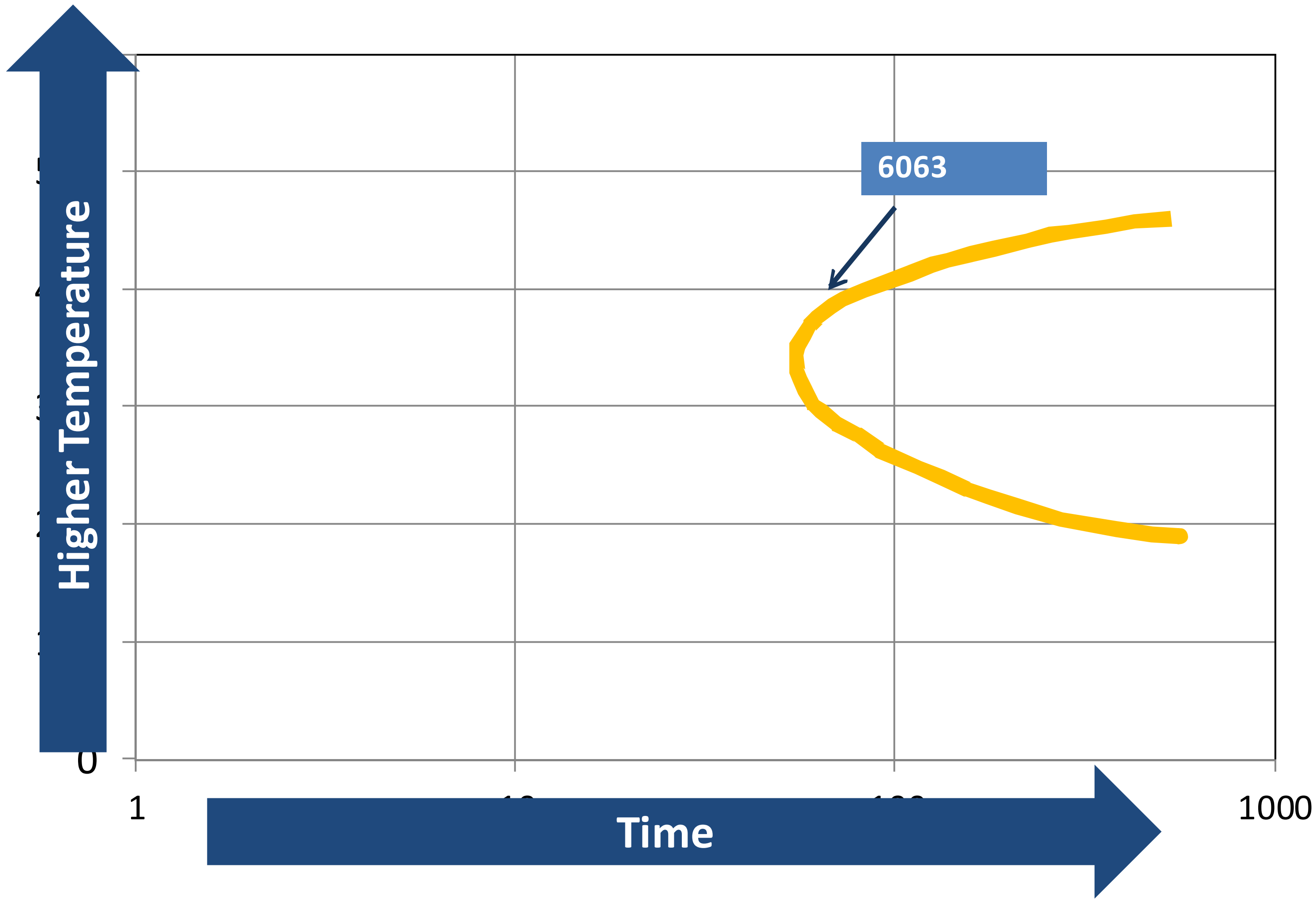
- **Different Alloys – Different Requirements**



- **Different Alloys – Different Requirements**



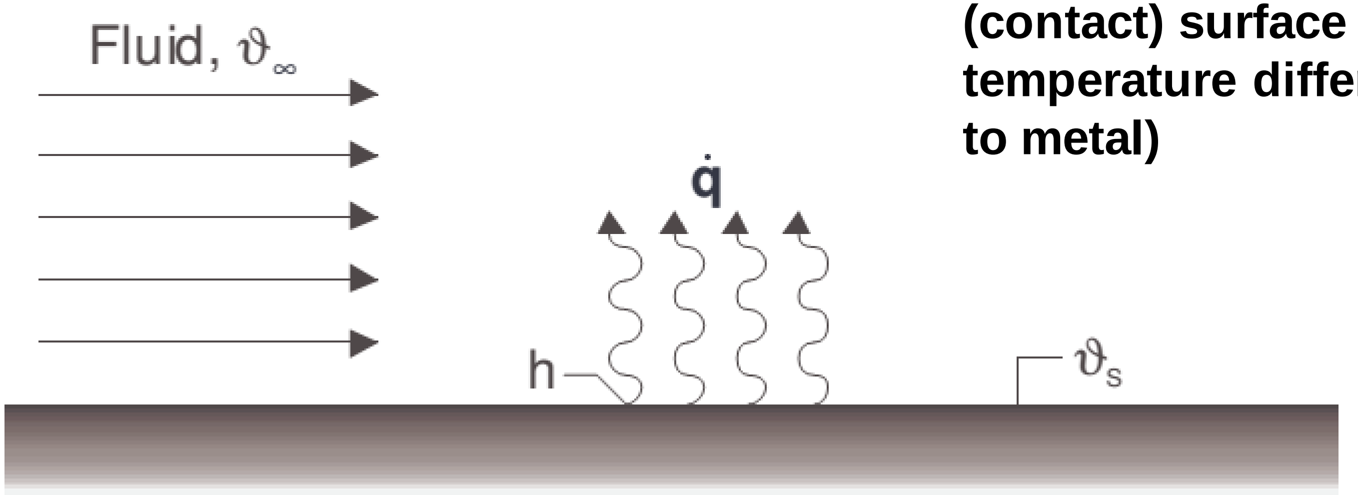
- **Different Alloys – Different Requirements**



- **Strip Flotation Line**

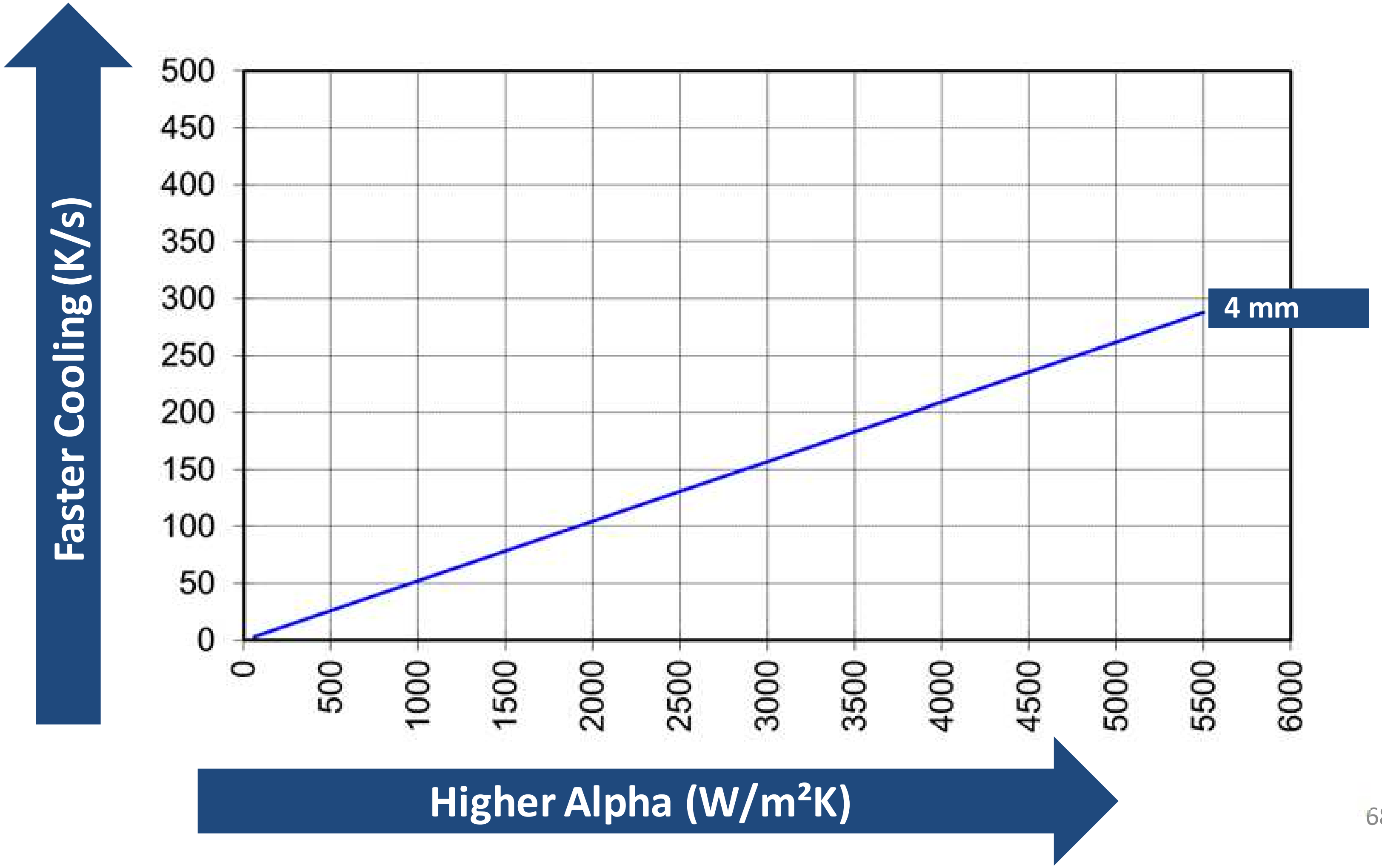
- **Min Gauge 0.3 mm**
- **Max Gauge 4 mm**
- **Min cooling rate: ~ 30 K/s**
- **Max cooling rate: > 300 K/s**

- **Alpha**

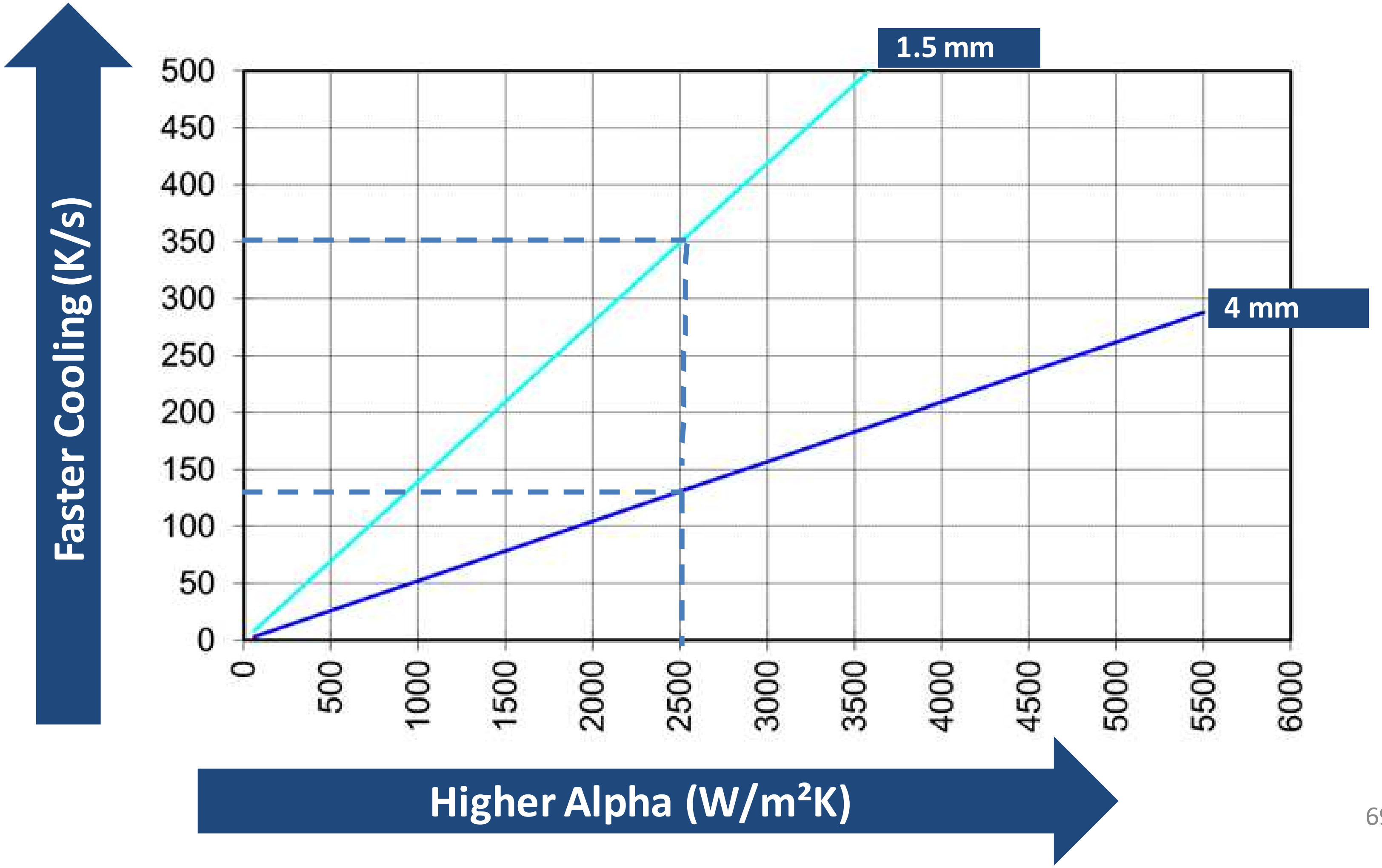


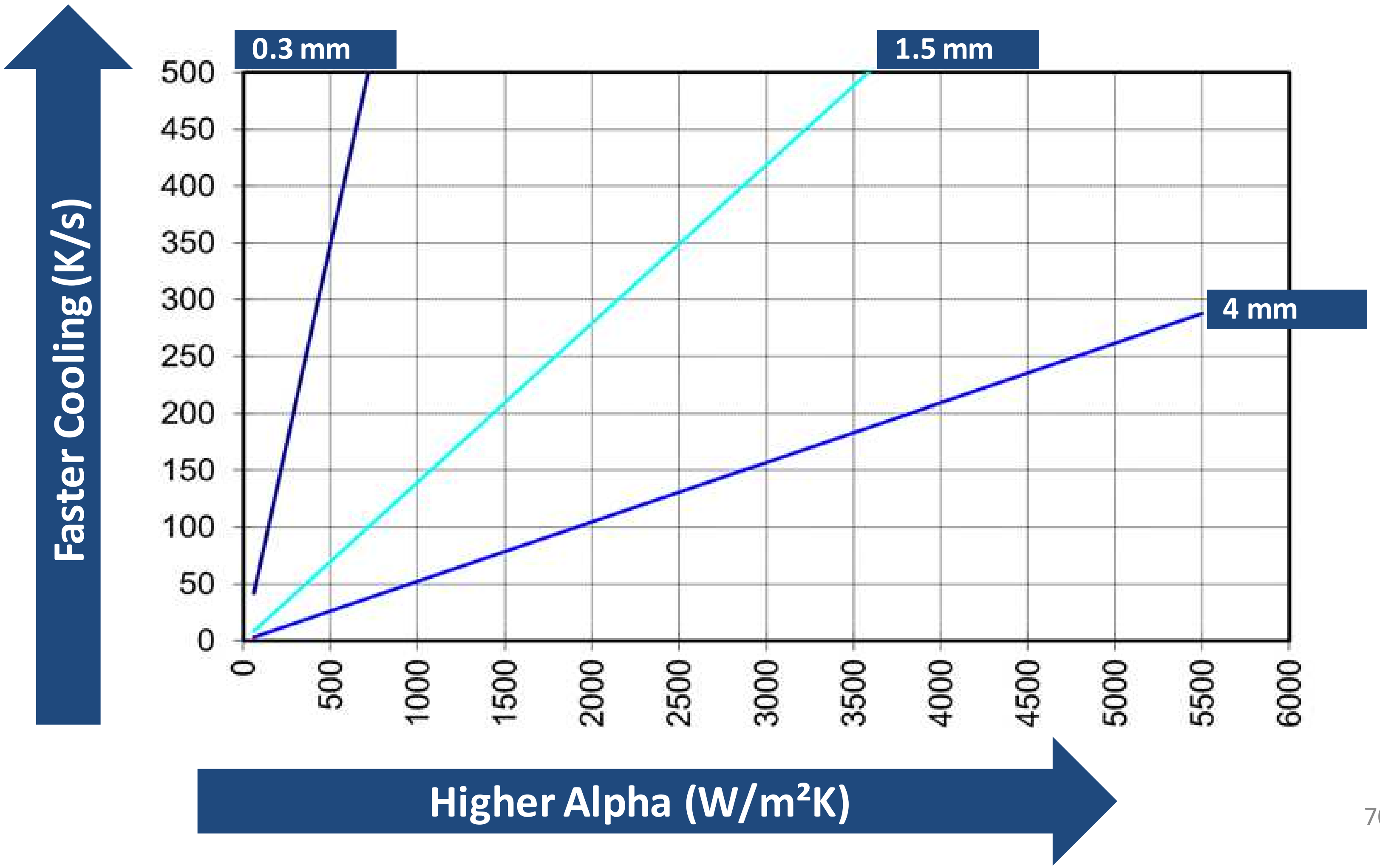
- **Alpha (α) = Heat Transfer Coefficient**
- **α ~ v 0,7 [W/m²K]**
- **Determines how much heat is transfered per each m² of (contact) surface and temperature difference (Medium to metal)**

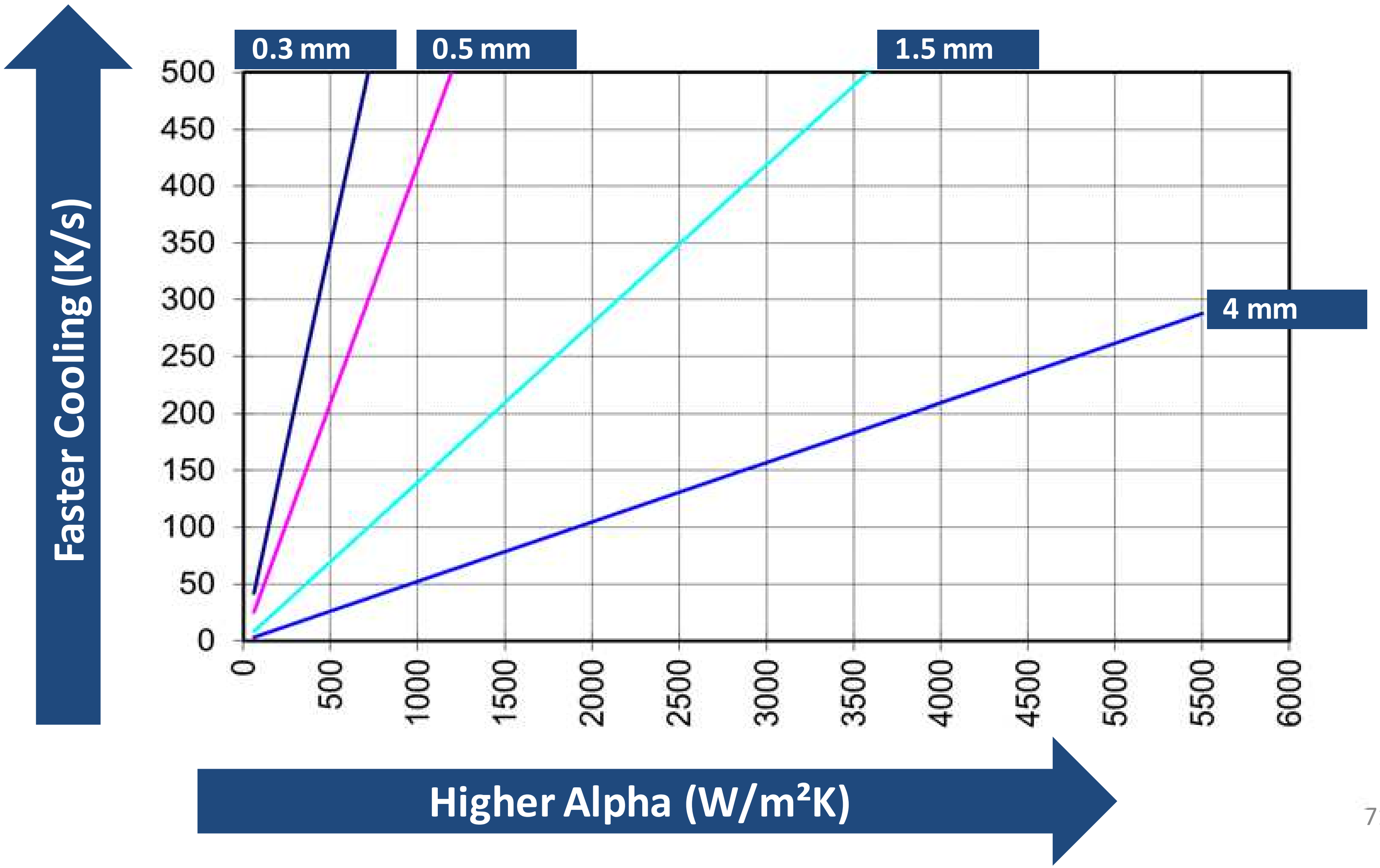
- **The higher the alpha value – the higher the cooling rate**

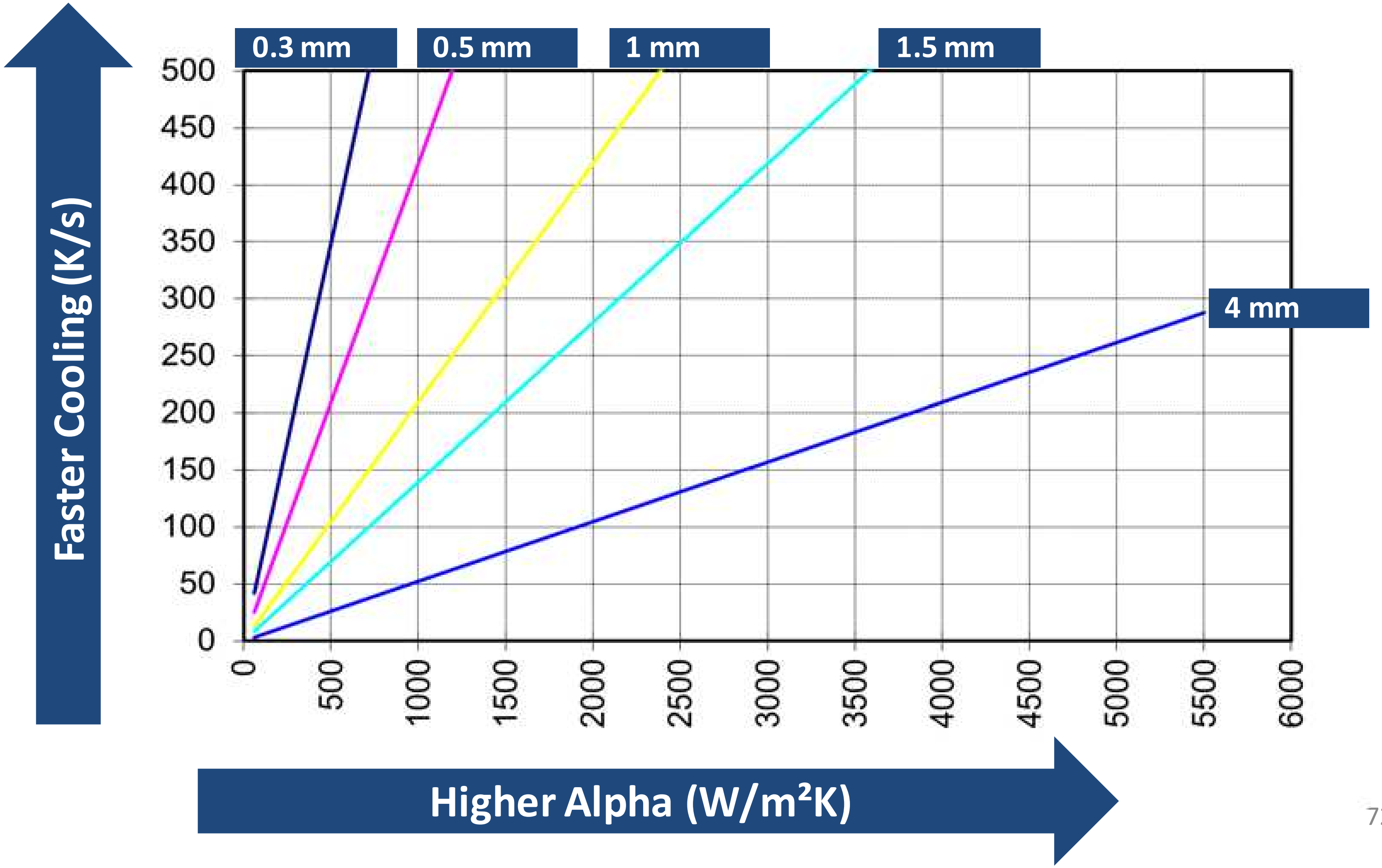


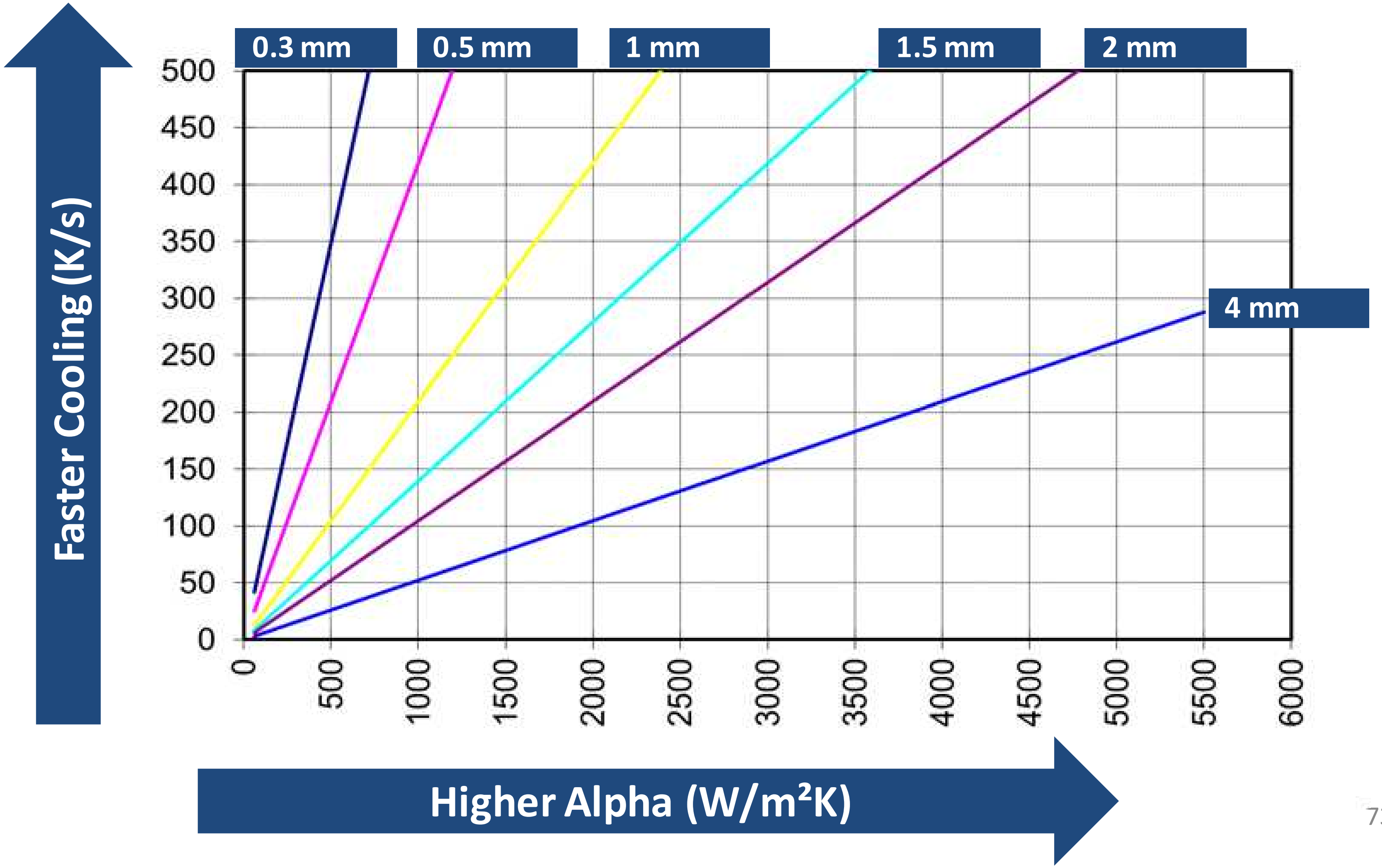
- **The thicker the strip, the lower the cooling rate (with given alpha value)**



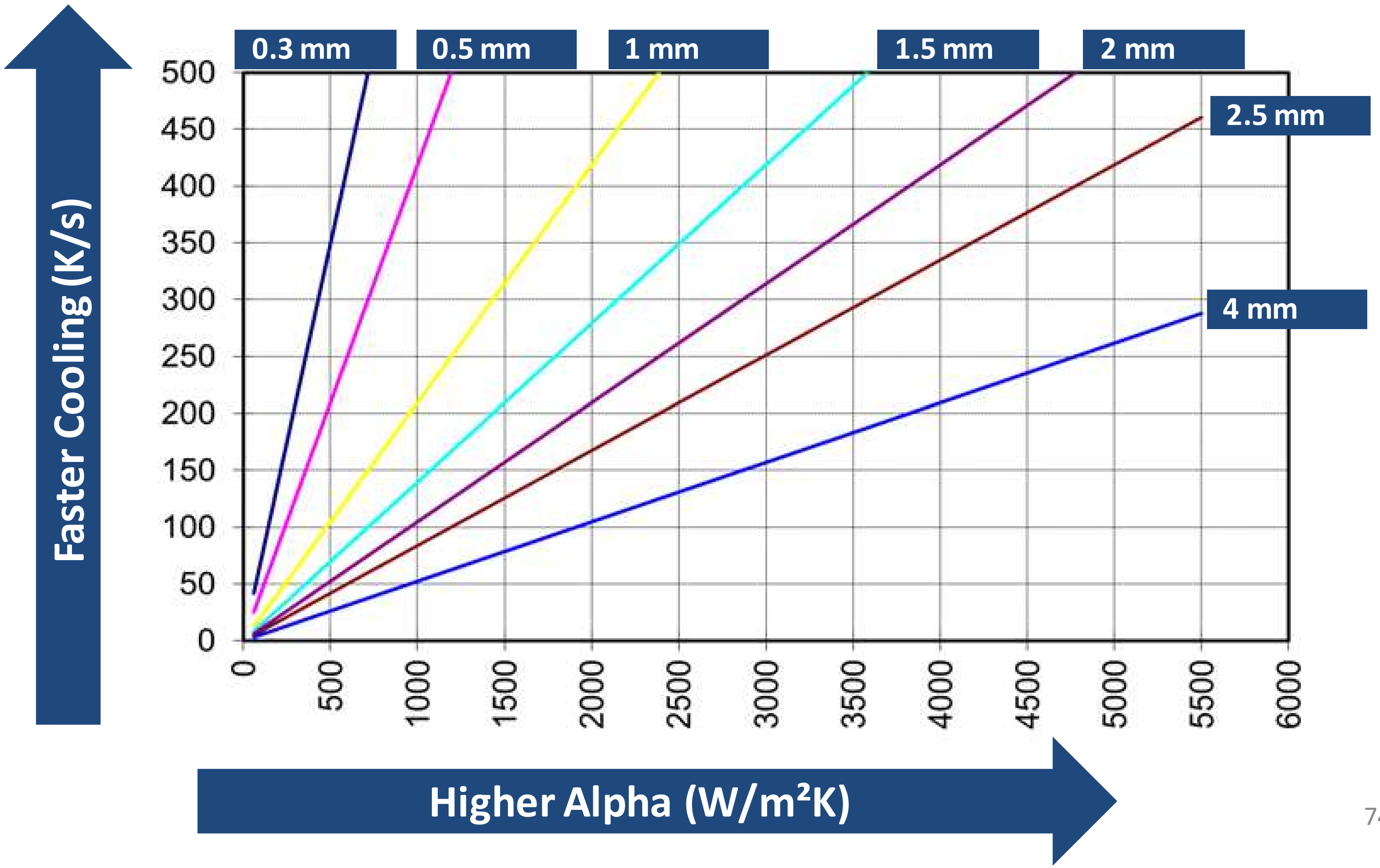

0.3 mm
1.5 mm
4 mm
Faster Cooling (K/s)
500
450
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Higher Alpha (W/m²K)


Faster Cooling (K/s)
0.3 mm
0.5 mm
1.5 mm
4 mm
500
450
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Higher Alpha (W/m²K)

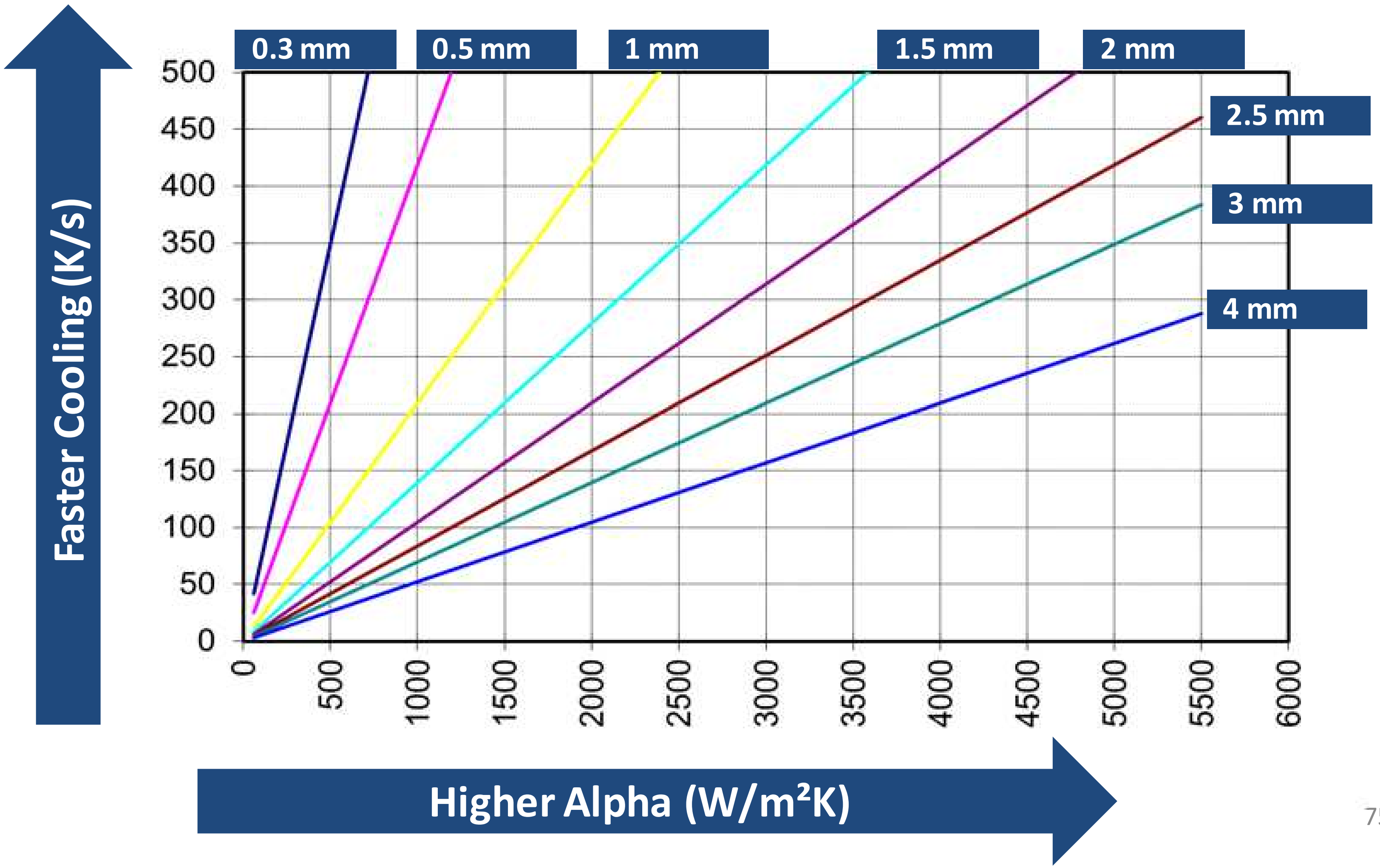

Faster Cooling (K/s)
0.3 mm
0.5 mm
1 mm
1.5 mm
4 mm
500
450
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Higher Alpha (W/m²K)

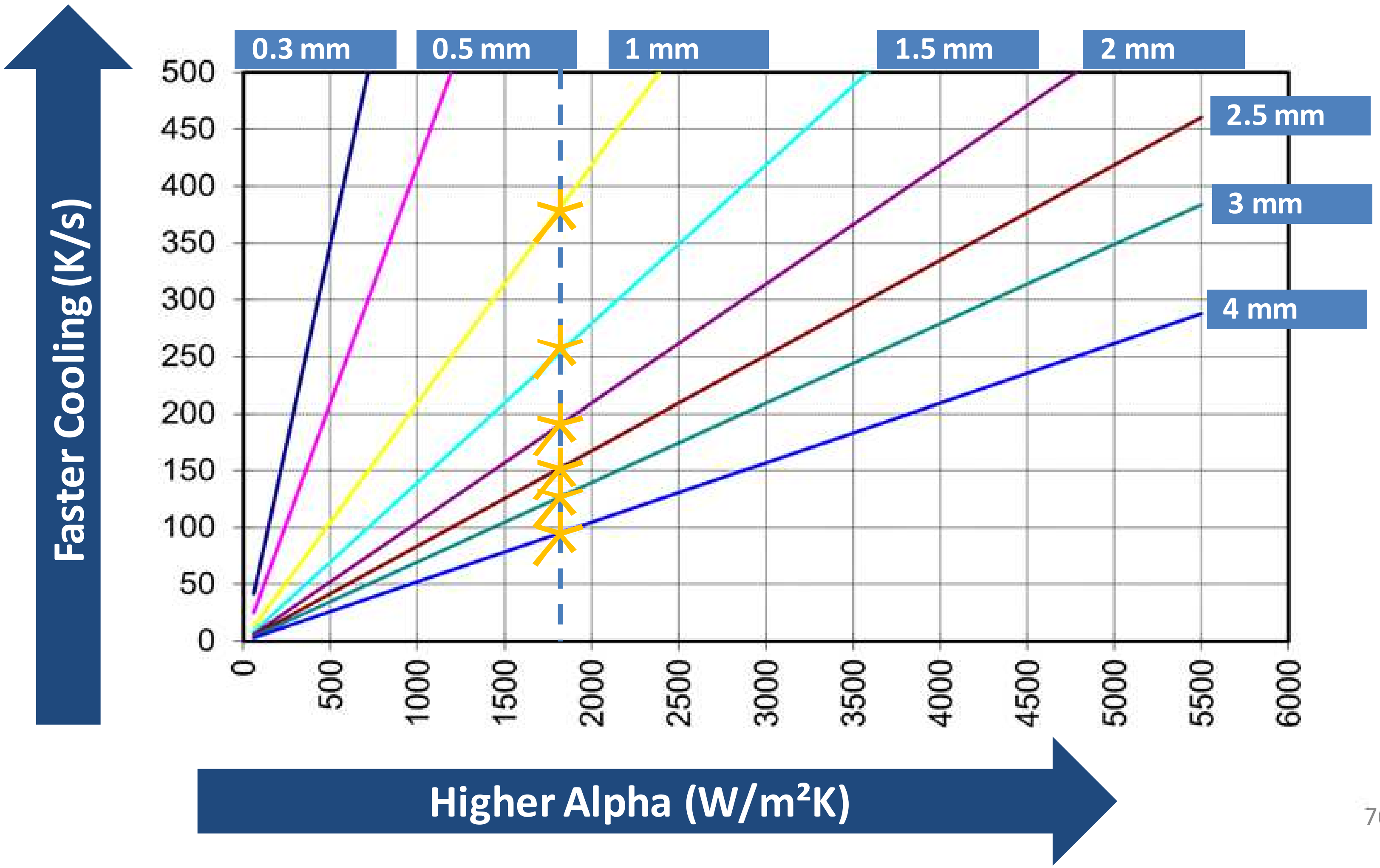


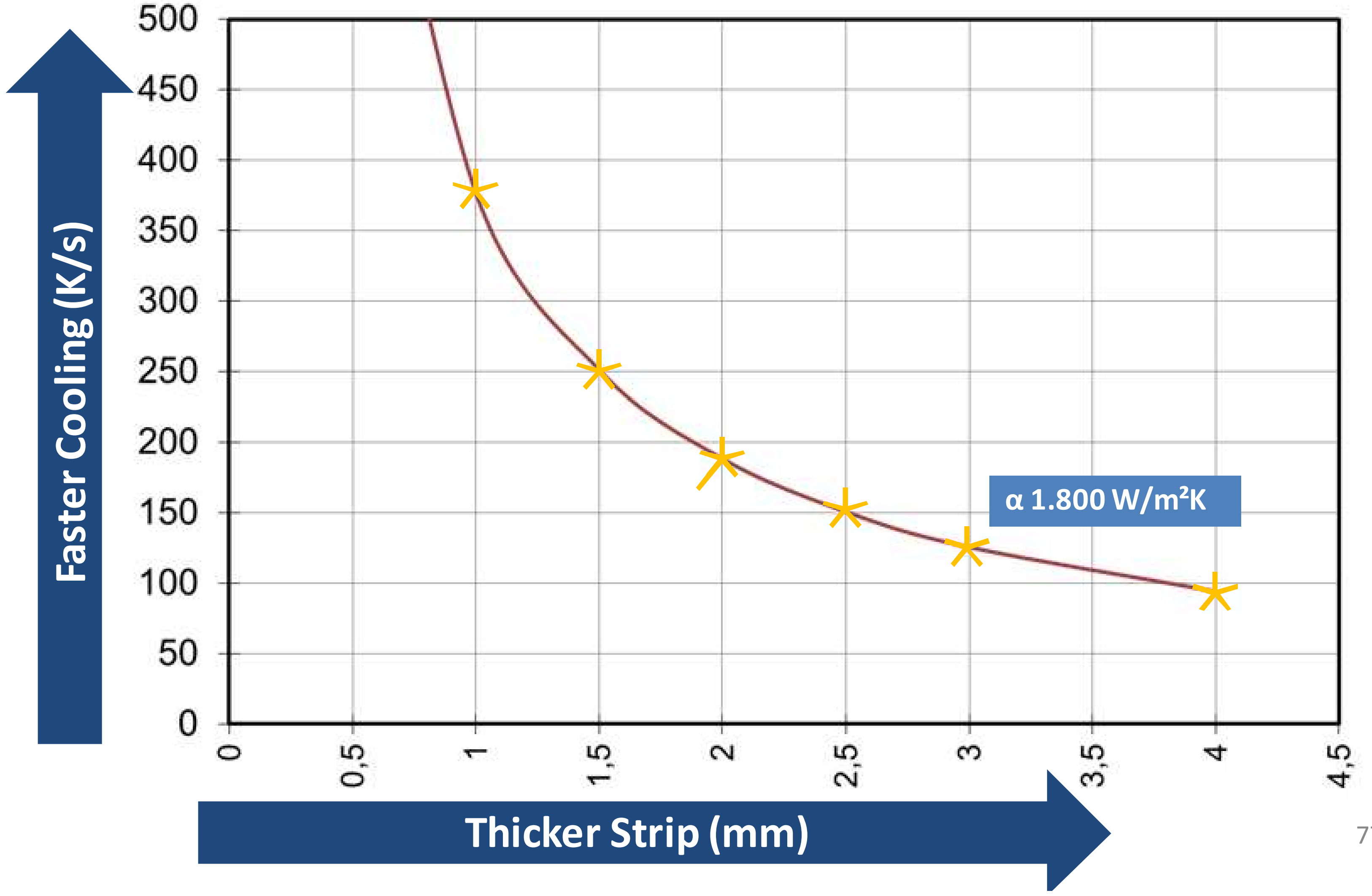
Faster Cooling (K/s)
0.3 mm
0.5 mm
1 mm
1.5 mm
2 mm
4 mm
500
450
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Higher Alpha (W/m²K)



0.3 mm
0.5 mm
1 mm
1.5 mm
2 mm
2.5 mm
4 mm
500
450
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Faster Cooling (K/s)
Higher Alpha (W/m²K)


0.3 mm
0.5 mm
1 mm
1.5 mm
2 mm
2.5 mm
3 mm
4 mm
Faster Cooling (K/s)
Higher Alpha (W/m²K)
0
50
100
150
200
250
300
350
400
450
500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000

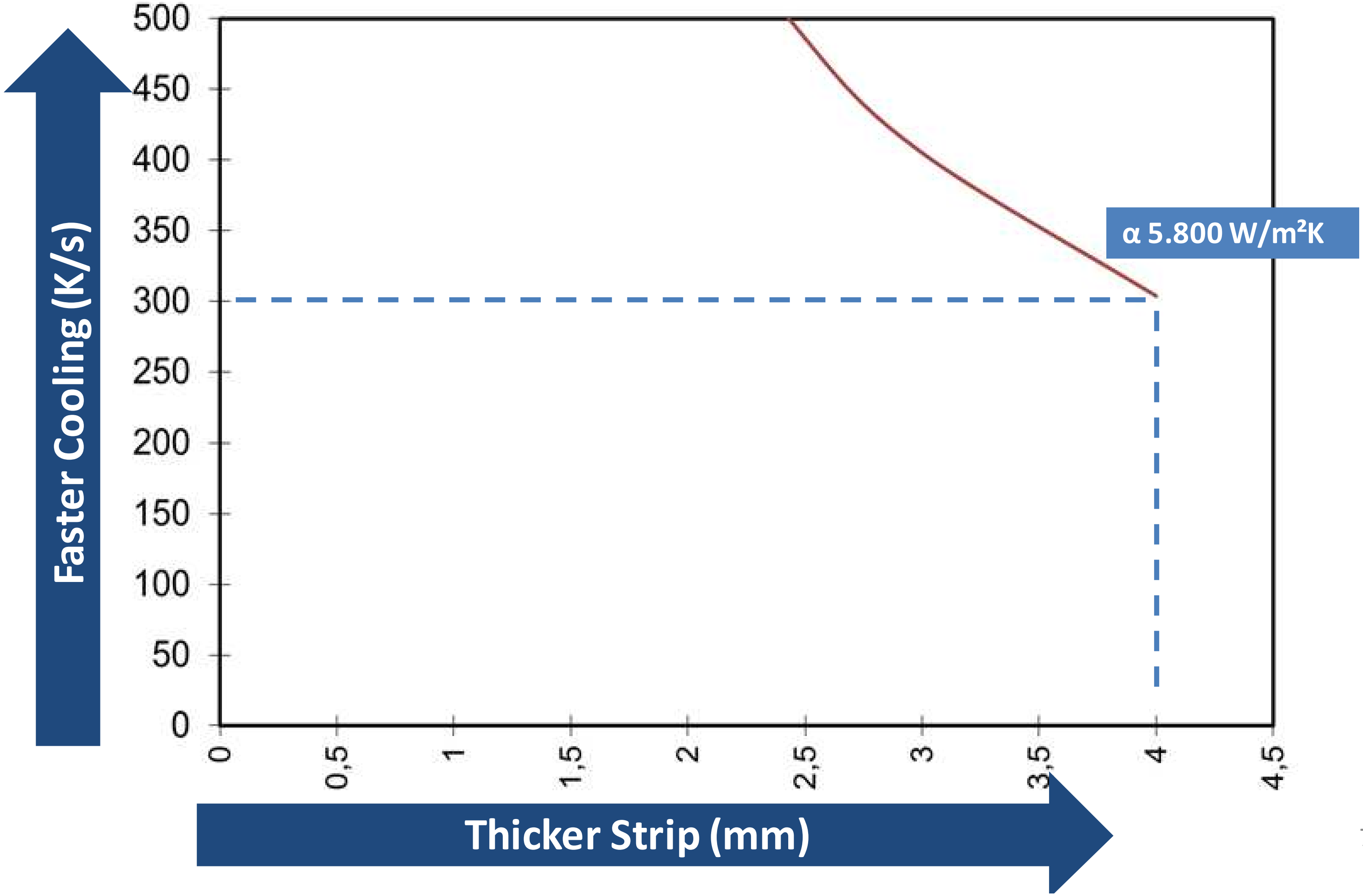

0.3 mm
0.5 mm
1 mm
1.5 mm
2 mm
2.5 mm
3 mm
4 mm
Faster Cooling (K/s)
Higher Alpha (W/m²K)
0
50
100
150
200
250
300
350
400
450
500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000



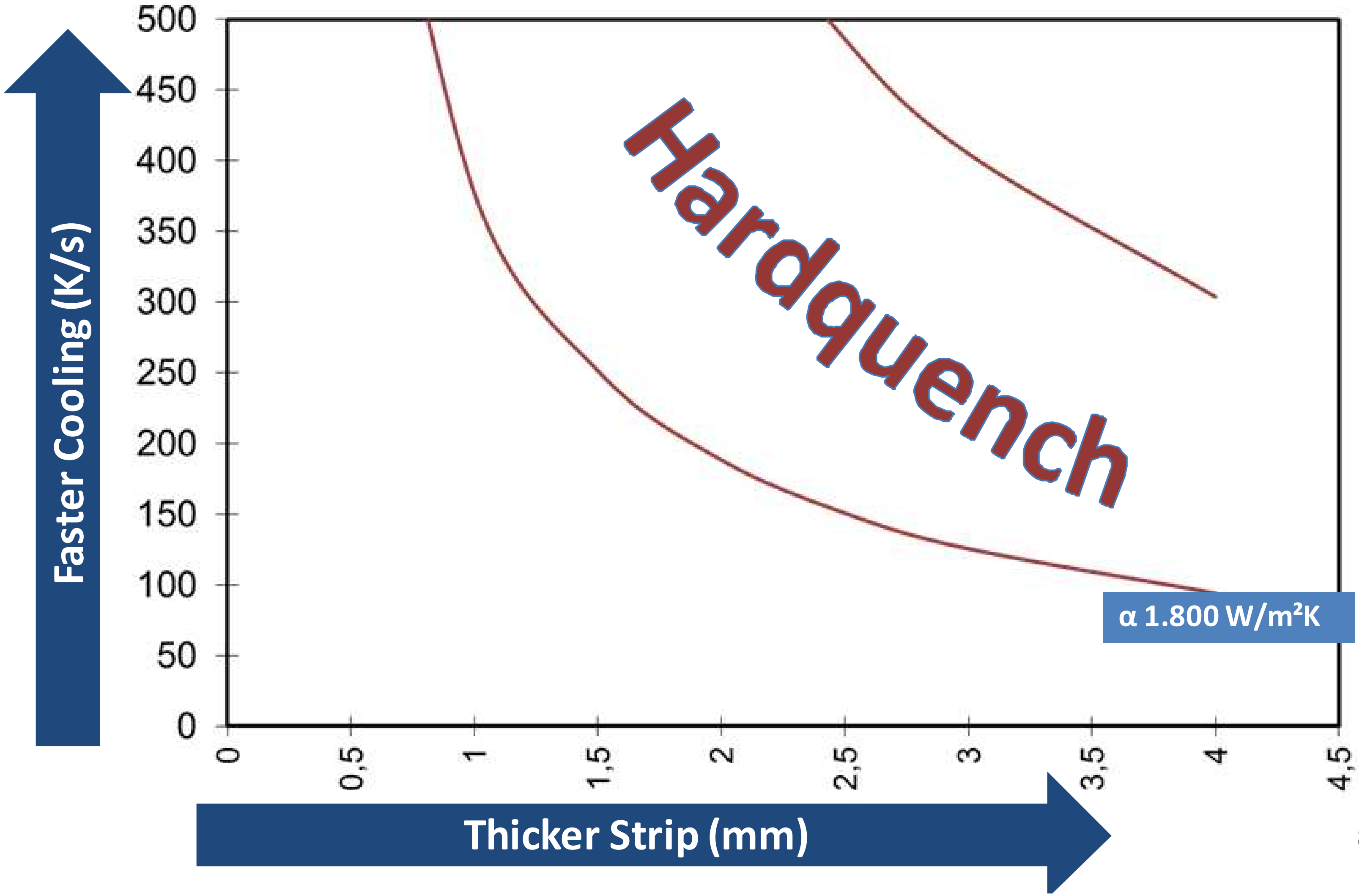
Faster Cooling (K/s)
500
450
400
350
300
250
200
150
100
50
0
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
α 1.800 W/m²K
Thicker Strip (mm)

- **Strip Flotation Line**

- **Min Gauge 0.3 mm**
- **Max Gauge 4 mm**
- **Min cooling rate: ~ 30 K/s**
- **Max cooling rate: > 300 K/s**

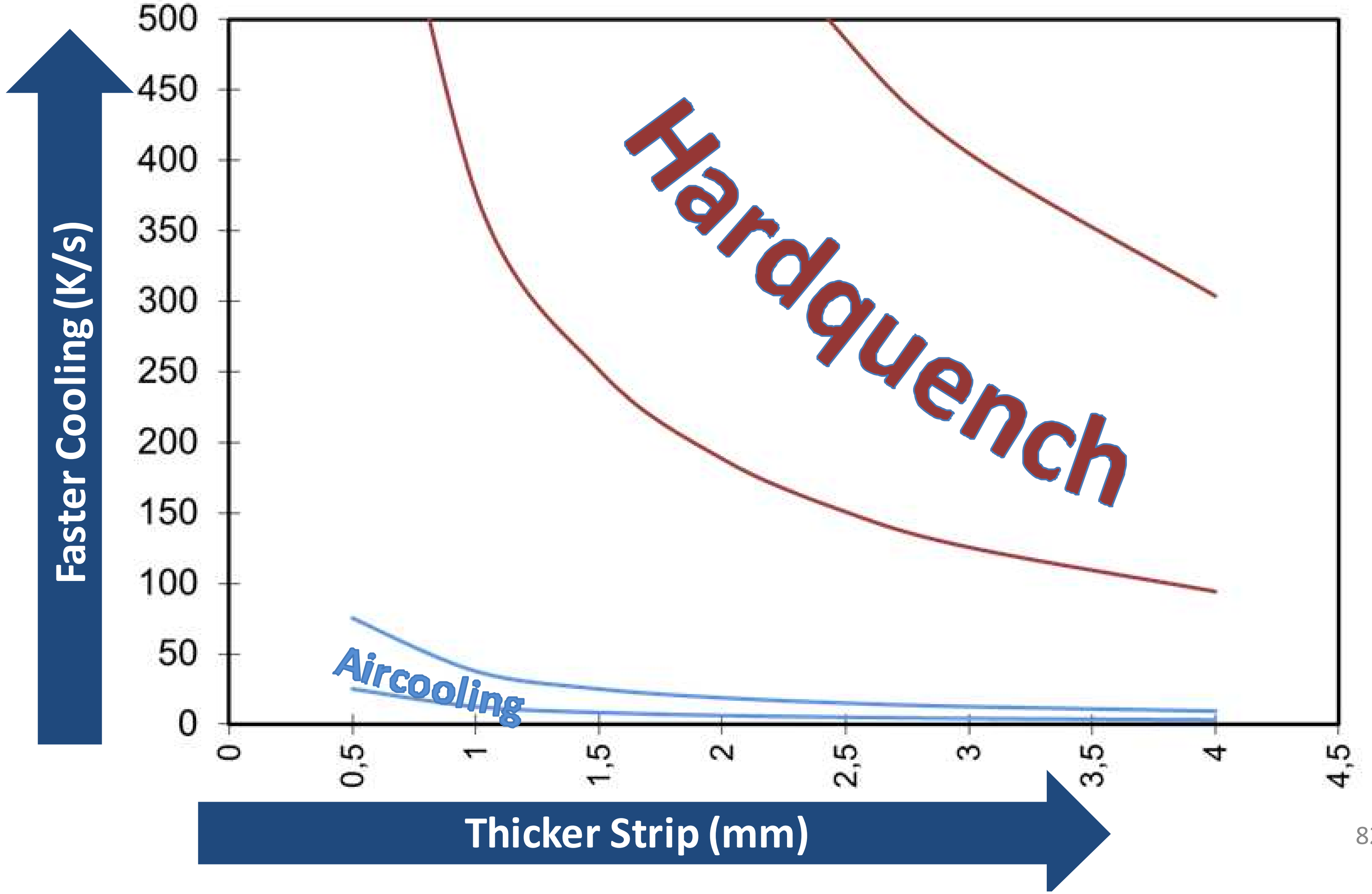


500
450
400
350
300
250
200
150
100
50
0
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
Faster Cooling (K/s)
Thicker Strip (mm)
α 5.800 W/m²K



Faster Cooling (K/s)
500
450
400
350
300
250
200
150
100
50
0
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
Hardquench
α 1.800 W/m²K
Thicker Strip (mm)

- **Water Cooling**
  α ~ 5.800 – 1.800 W/m²K



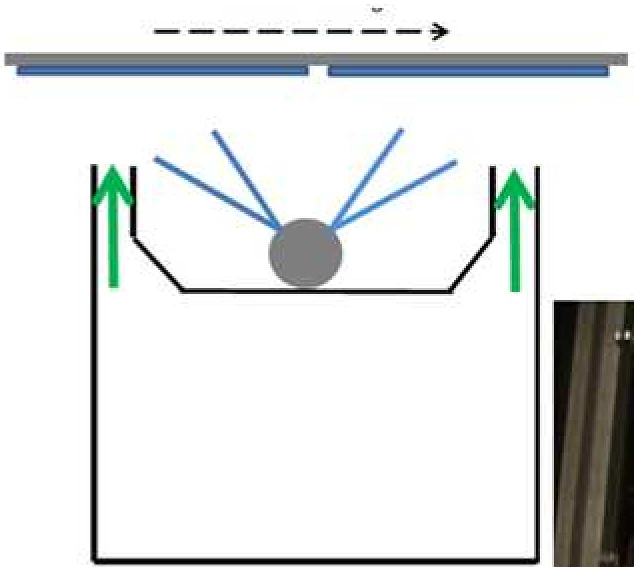
Faster Cooling (K/s)
500
450
400
350
300
250
200
150
100
50
0
Hardquench
Aircooling
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
Thicker Strip (mm)

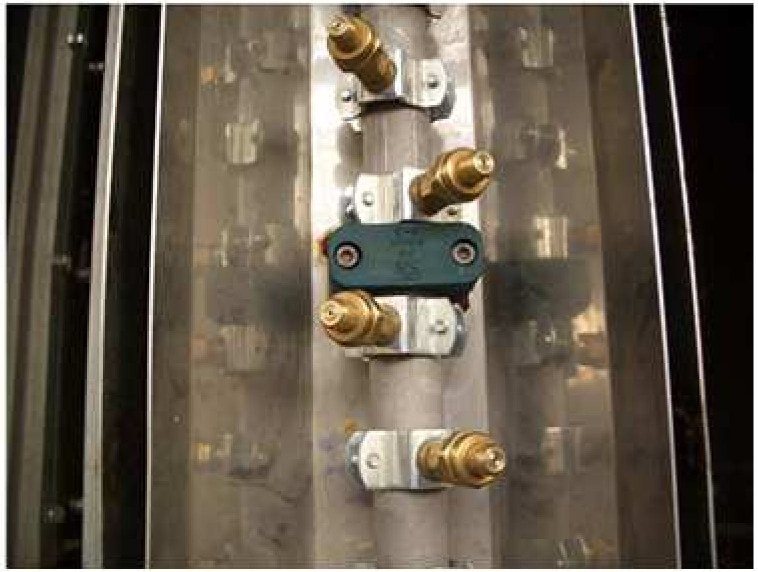
- **Otto Junker Mist Quench**

- **Water Cooling**
  α ~ 5.800 – 1800 W/m²K

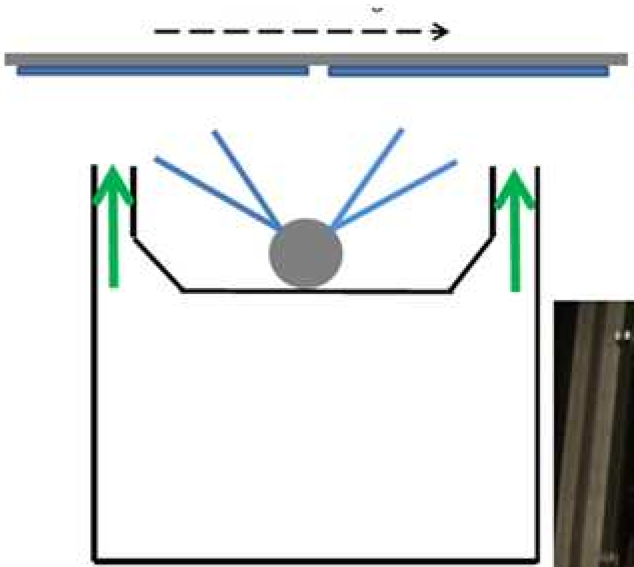
- **Air Cooling**
  α ~ 40 – 180 W/m²K

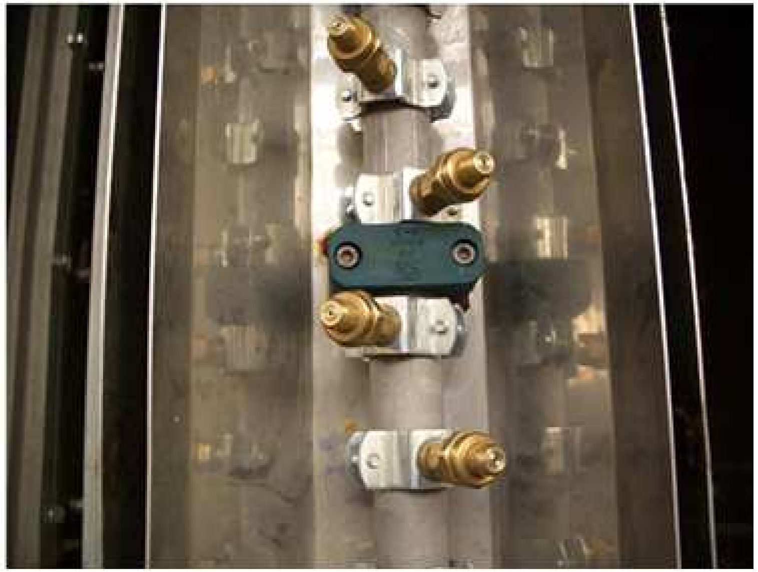
- **Water Injected into Air Stream**



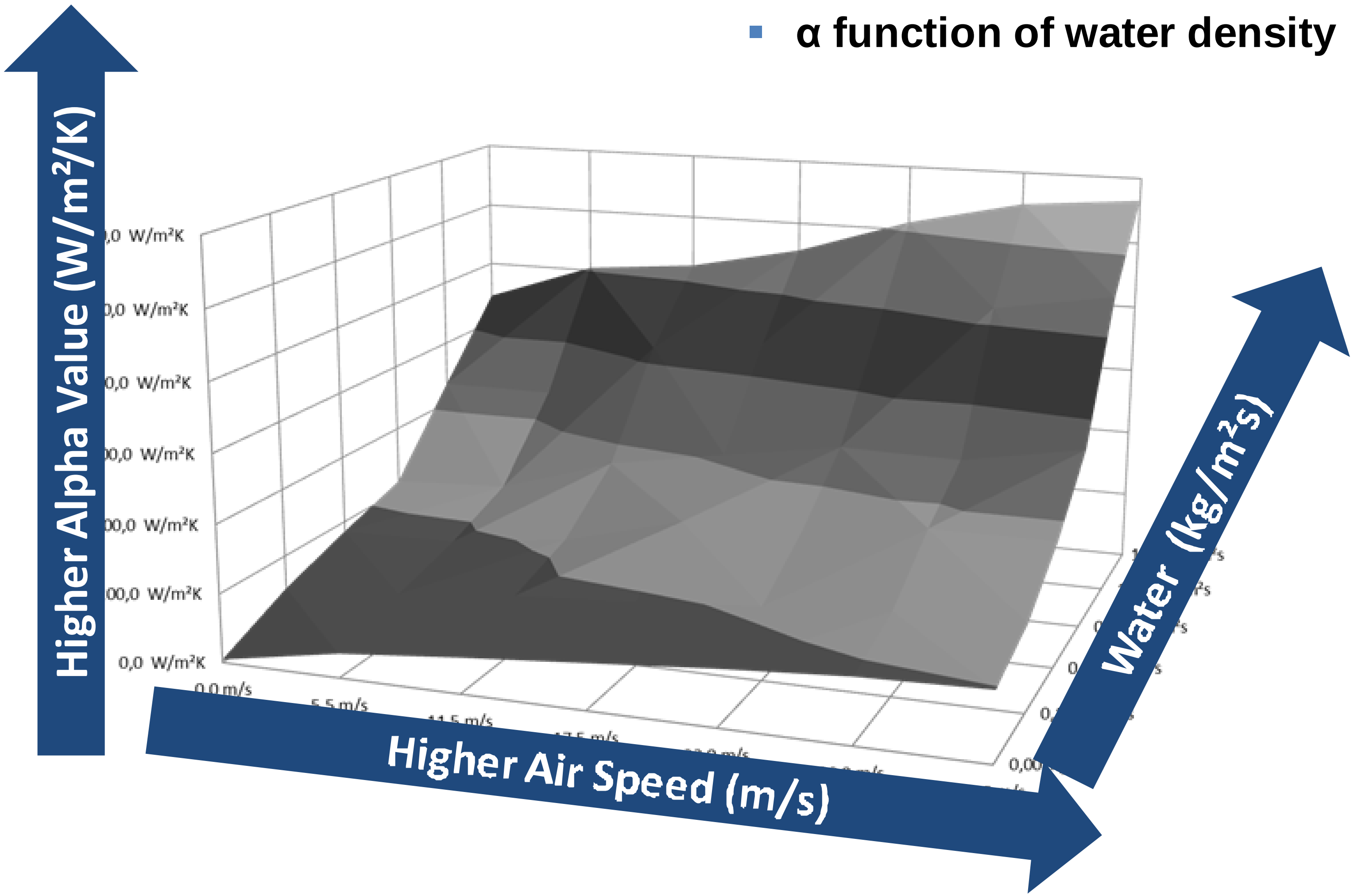


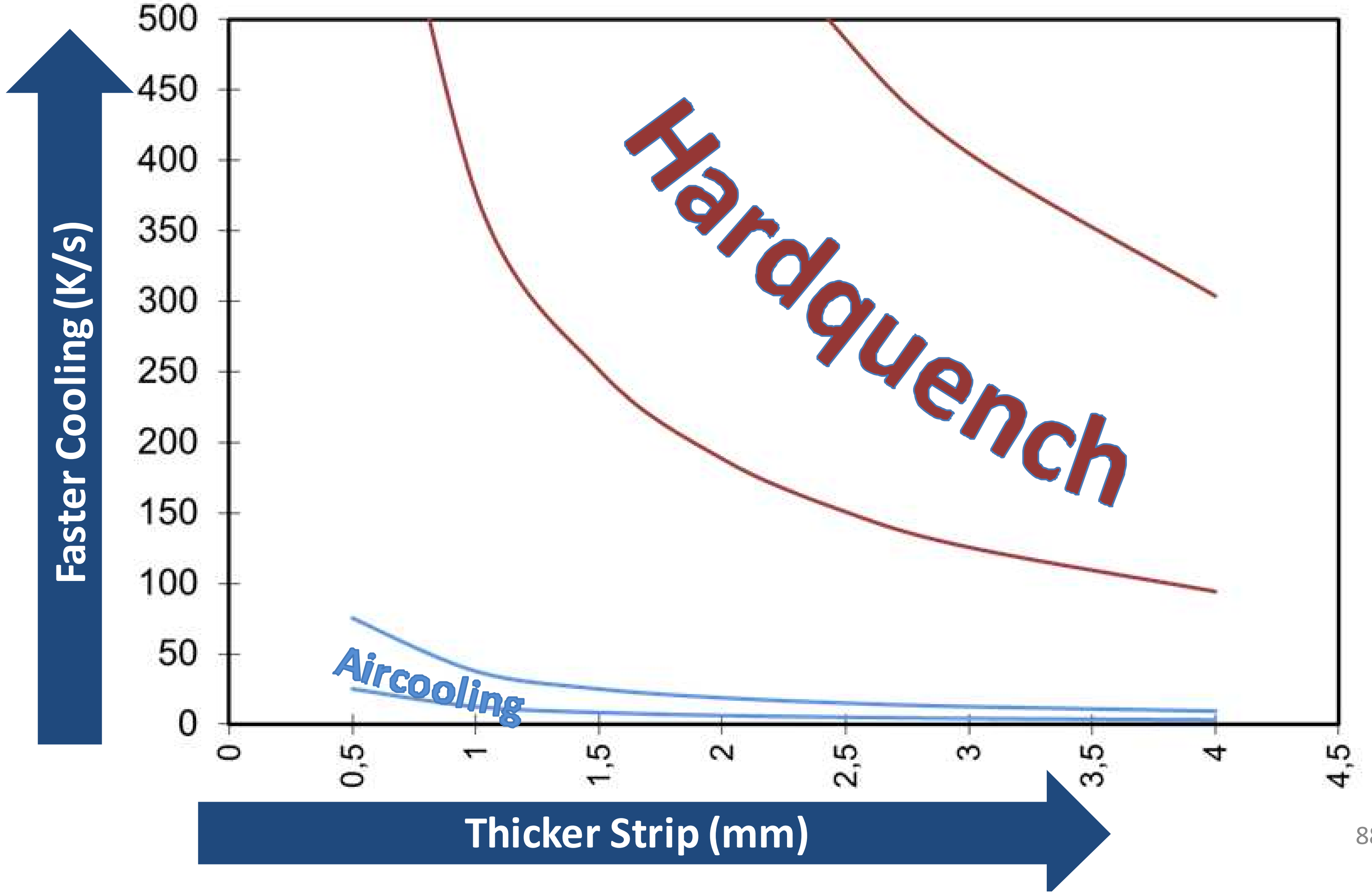
- α function of air speed
- α function of water density

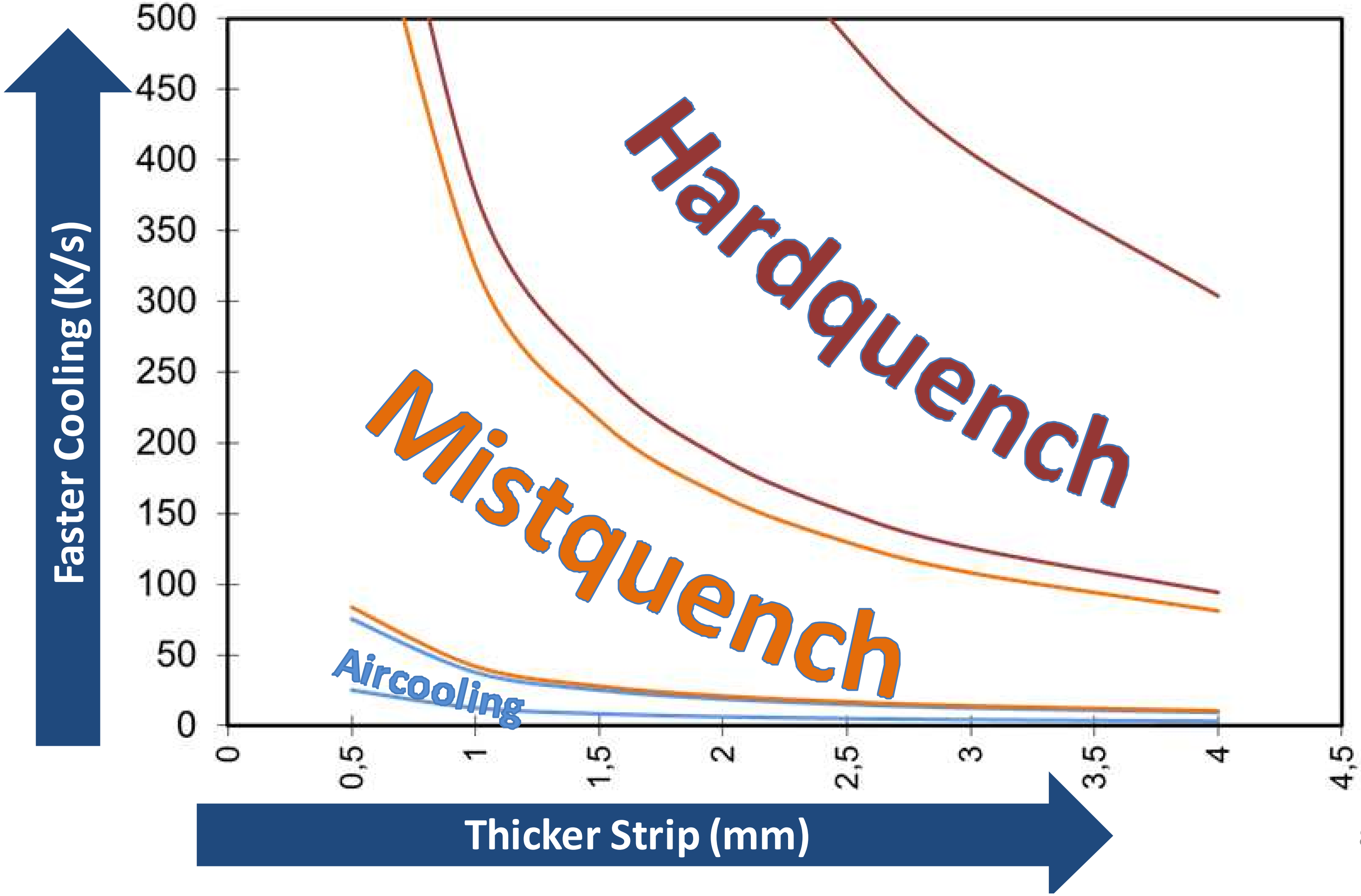




- α function of air speed
- α function of water density




Faster Cooling (K/s)
500
450
400
350
300
250
200
150
100
50
0
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
Hardquench
Aircooling
Thicker Strip (mm)



Faster Cooling (K/s)
500
450
400
350
300
250
200
150
100
50
0
Hardquench
Mistquench
Aircooling
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
Thicker Strip (mm)

Sebastian März (Otto Junker, Lammersdorf)
Prof. Dr. Herbert Pfeifer (RWTH Aachen University, Department of Industrial Furnaces and Heat Engineering)

„Modern Furnaces for the Aluminium Industry “

Thursday, December 11st 2014