DissTec

Valorisation and dissemination of technologies for measurement, modelling and control in secondary metallurgy

Dynamic process models for on-line monitoring and control of secondary metallurgy processes

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Dynamic process models for secondary metallurgy processes – Introduction and general considerations

- Secondary metallurgy processes involve a large variety of complex metallurgical reactions as e.g.
  - Decarburisation
  - Removal of dissolved gases (degassing)
  - Desulphurisation by steel / slag interaction
  - Deoxidation
  - Removal of non-metallic inclusions
- The process behaviour and the relevant state variables of the process (temperature and composition of steel and slag) can be monitored only based on spot measurements (T, O) as well as analysis of steel and slag samples
- Thus one important topic of R&D work on Secondary metallurgy processes has been and is still the development and application of dynamic process models for description of the process behaviour
- Within this presentation the results of several selected ECSC and RFCS projects are discussed regarding the following topics:
  - Dynamic models for vacuum degassing processes (RH, VD)
  - Dynamic models for stainless steel refining processes (AOD, VOD)
  - Through process modelling of the complete secondary steelmaking route

Dynamic process models – Basic principles

Dynamic process models

- are based on energy and mass balances
- use calculations for thermodynamic equilibrium states and reaction kinetics
- assume an homogeneous melt, i.e. no concentration or temperature profiles
- are solved cyclically along the time axis
- take into account the relevant cyclic process input data (e.g. process gas flow rates, vessel pressure, offgas data) as well as acyclic event data (e.g. material additions)

Off-line applications

- Process analysis by simulation of heat state evolution based on recorded process data
- Process layout and optimisation by simulation of heat state evolution under varied operating conditions

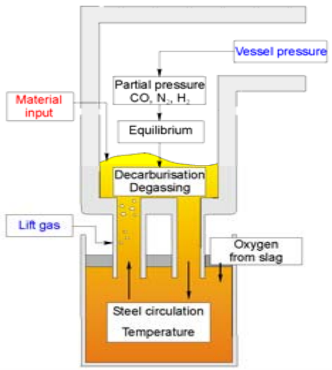
On-line applications

- Monitoring of evolution of the current heat state (temperature, composition)
- Prediction of the further heat state evolution
- Calculation of set-points for an optimised process control

Principles of development and application of dynamic models

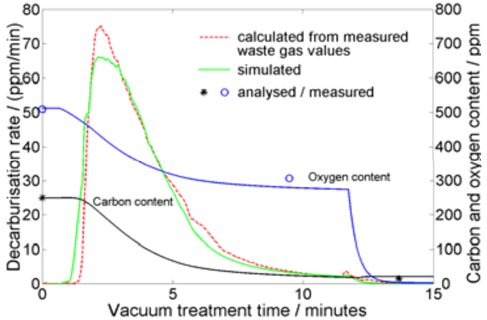
Implementation (e.g. with Matlab – Simulink) for dynamic simulation on Personal Computer

Model structure

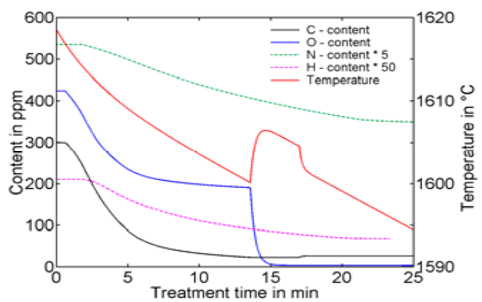


Simplification for on-line observation of heat state: C, O, N, H content and steel temperature

Process Simulation



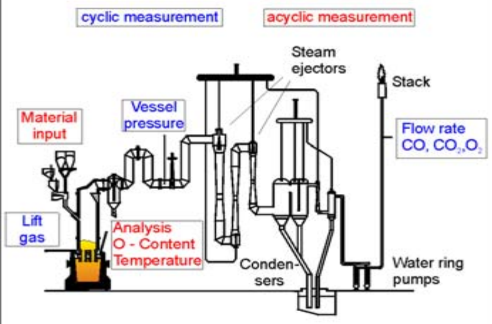
On-line Process Observation



Model verification and parameter identification with measured process data

Model development based on fundamentals of physics, thermodynamics and reaction kinetics

Process data acquisition



Vacuum Circulation (RH) plant

Development and implementation of model-based control strategies and setpoint calculations, e.g. for

- lance oxygen input
- alloy materials
- deoxidation materials
- cooling scrap

Selected ECSC research projects dealing with aspects of process modelling for vacuum degassing (RH, VD)

Excellence in Applied Research

ECSC

Contract Report	Title	Participants	Date Start / End	Topic regarding modelling
ECSC 7210-CC/104	Development of a model for the vacuum circulating process	BFI	01.08.1990 to 31.01.1994	**RH process** Decarburisation model
ECSC 7210-CC/116,407,117	Improvement of vacuum circulation plant operation on the basis of the BFI simulation model	BFI, voestalpine, CSM	01.07.1995 to 30.06.1999	**RH process** Degassing and temperature model
ECSC 7210-CC/121/122/936	Dynamic modelling and control of the vacuum degassing process	Buderus, Sidenor, BFI	01.07.1996 to 30.06.1999	**VD process** Degassing and temperature model
ECSC 7210-PR/207	Operation and control of vacuum circulation (RH) process with lance oxygen input	BFI, voestalpine, Sollac Fos, Technometal	01.07.1997 to 31.12.2000	**RH process** Extension of process model to lance oxygen input
ECSC 7210-PR/079	Control of inclusion, slag foaming and temperature in vacuum degassing	MEFOS, ABS, OVAKO, Sidenor, BFI	01.07.1998 to 30.06.2001	**VD process** Temperature and inclusion removal model
ECSC 7210-PR/135	Production of EAF steels with low contents in N2 and S through vacuum treatment	Sidenor, ProfilARBED, IRSID, MEFOS, BFI	01.07.1999 to 30.06.2002	**VD process** Denitrogenation and desulphurisation model

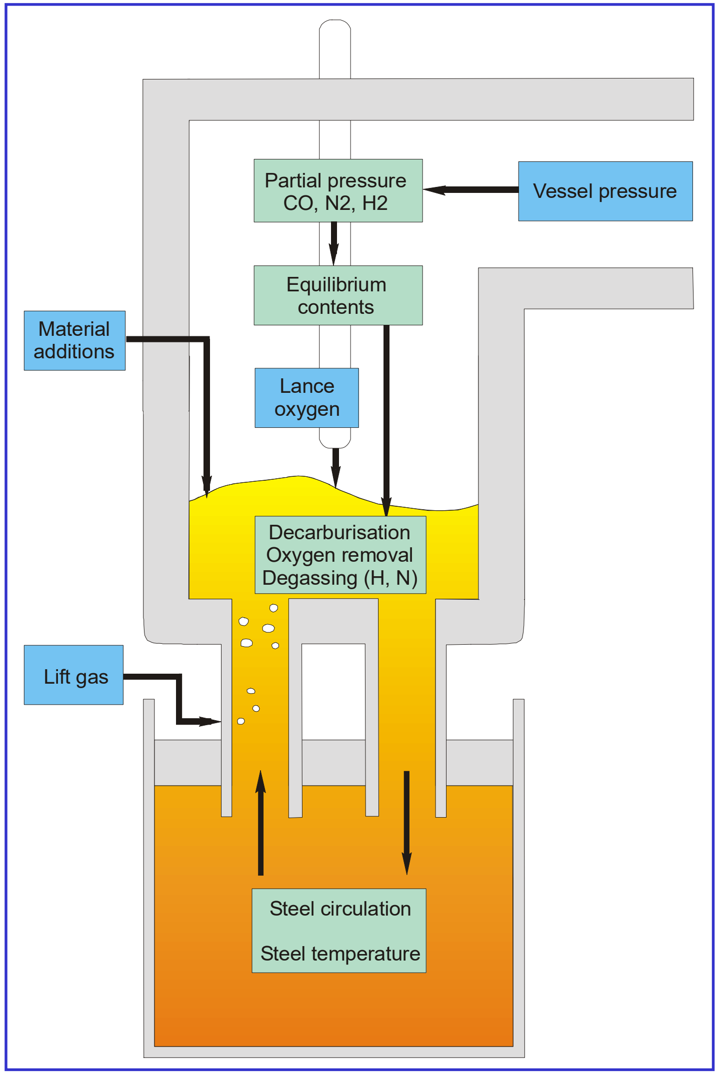
Dynamic process model for the RH process

Functions of the process model

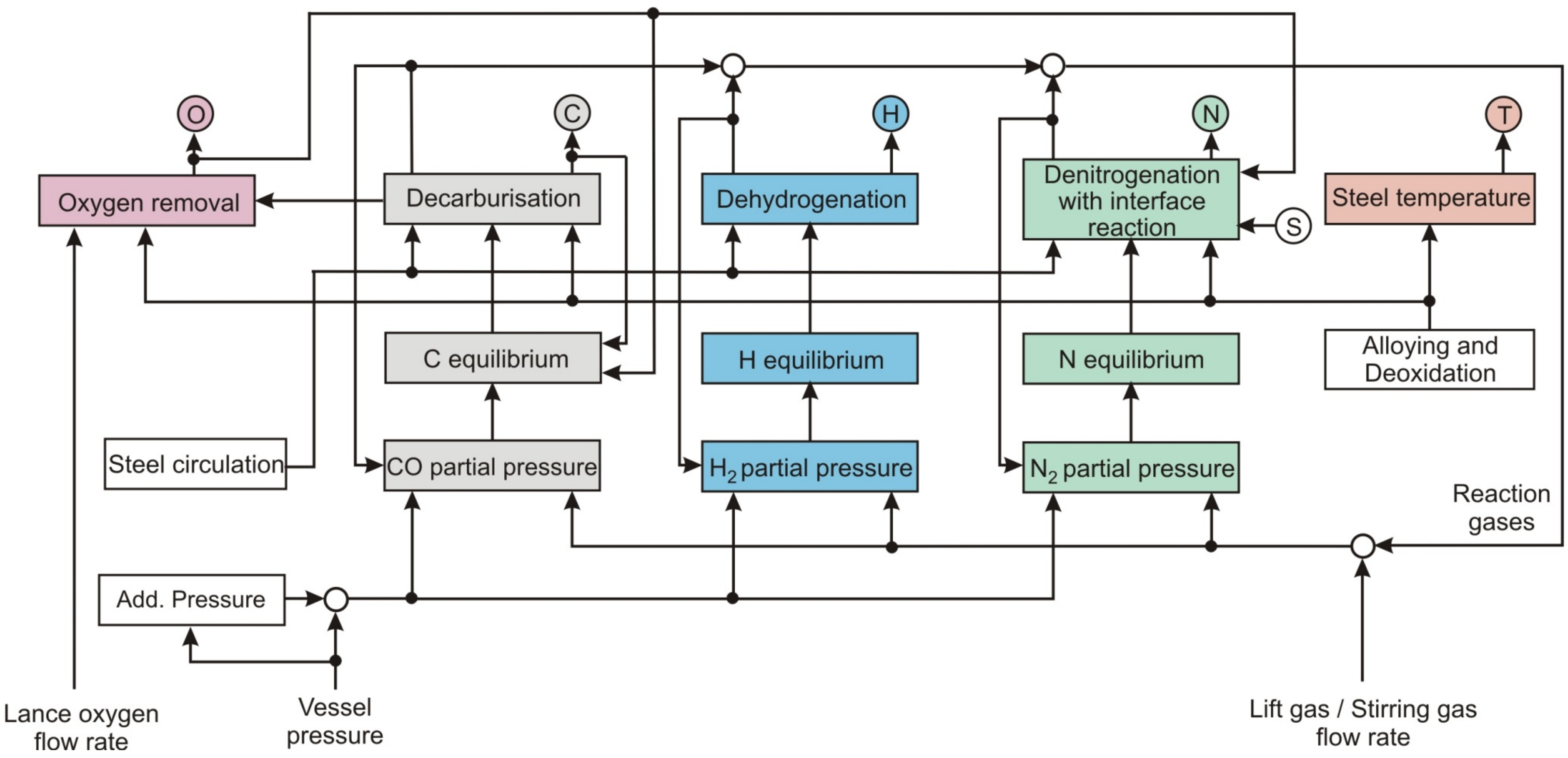
- On-line observation of decarburisation, denitrogenation, dehydrogenation and steel temperature
- Dynamic prediction of temperature evolution during remaining treatment time
- Dynamic control of oxygen input via top lance for forced decarburisation and chemical heating
- Dynamic control of deoxidation and cooling scrap addition

Required input data

- Vessel pressure and Lift gas flow rate (cyclic)
- Start contents of C, O, N, S, (H)
- Start steel temperature
- Steel weight
- Material additions during vacuum treatment
- Optional: Off-gas measurement (flow rate, CO and CO_2 content) to monitor decarburisation behaviour



Structure of the RH process model



Equations for degassing reactions

Decarburisation and Dehydrogenation

- Degassing reaction under vacuum described as diffusion process in the liquid phase with reaction time constant T_X and equilibrium content X_Q

$$-\frac{dC}{dt} = \frac{1}{T_C} \cdot (C - C_Q) \qquad -\frac{dH}{dt} = \frac{1}{T_H} \cdot (H - H_Q)$$

Denitrogenation

- Reaction at the liquid / gas interface in addition to mass transfer in liquid phase
- Equilibrium content N_Q substituted by interfacial content N_i
- Second order differential equation for interface reaction

$$-\frac{dN}{dt} = \frac{1}{T_N} \cdot (N - N_i) \qquad -\frac{dN}{dt} = \frac{k_{N2}}{k_N \cdot T_N} \cdot (N_i^2 - N_Q^2)$$

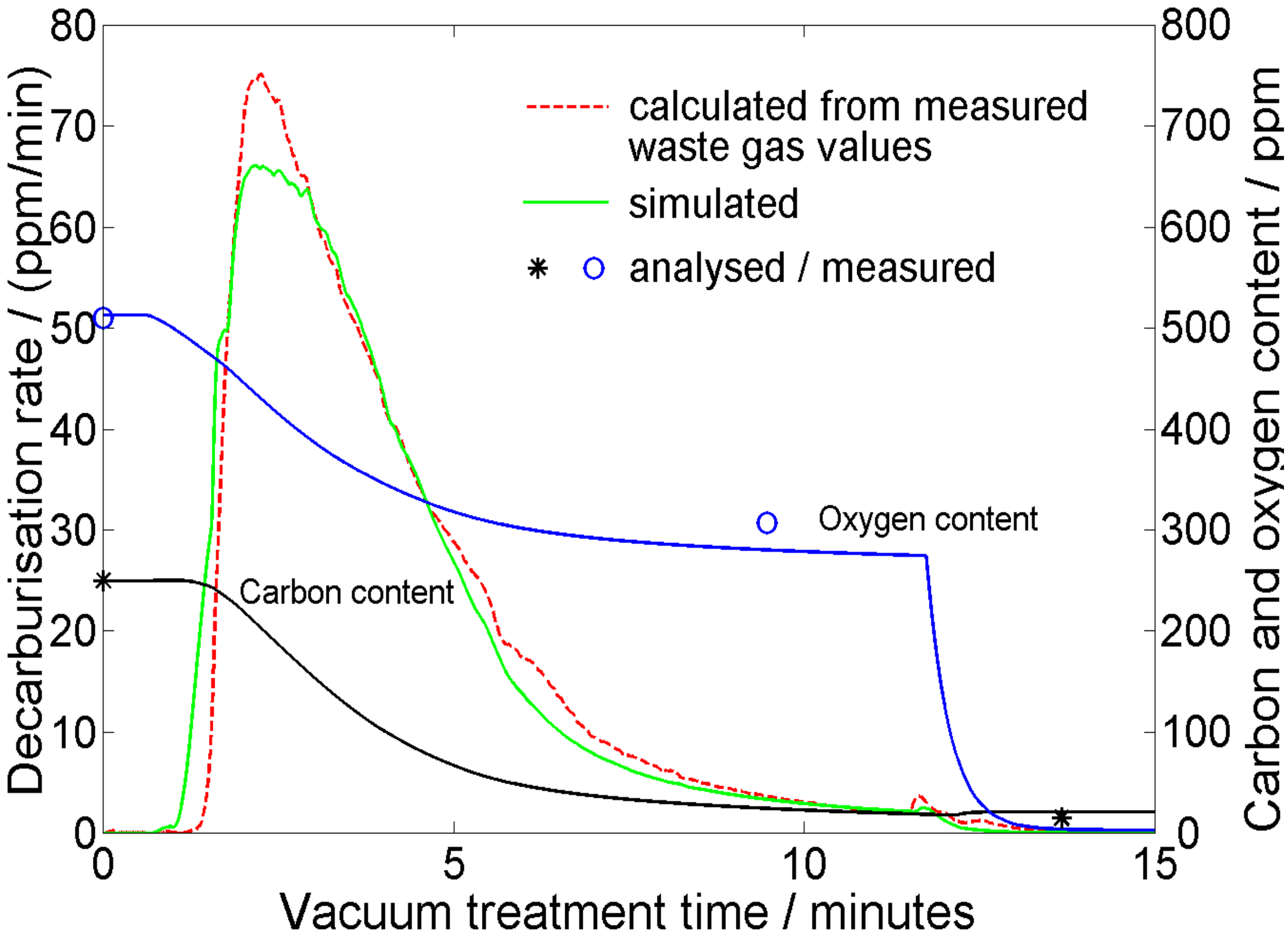
- Ratio of kinetic coefficients depending on contents of surface-active elements

$$\frac{k_N}{k_{N2}} = R_N \cdot (1 + A_O \cdot O + A_S \cdot S)$$

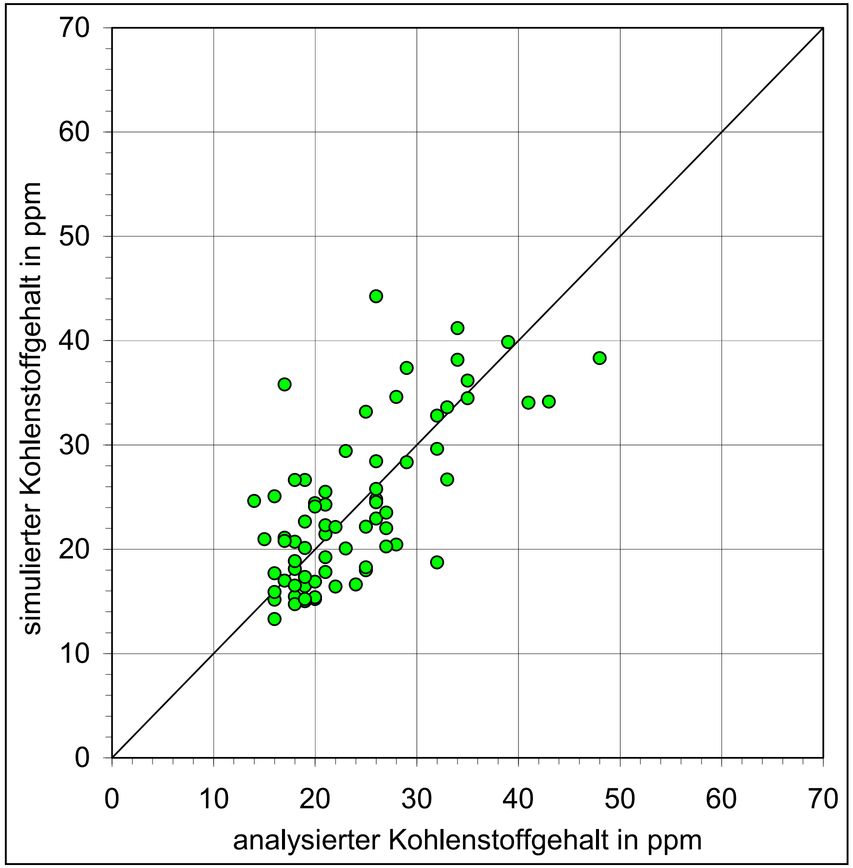
Calculation of equilibrium contents

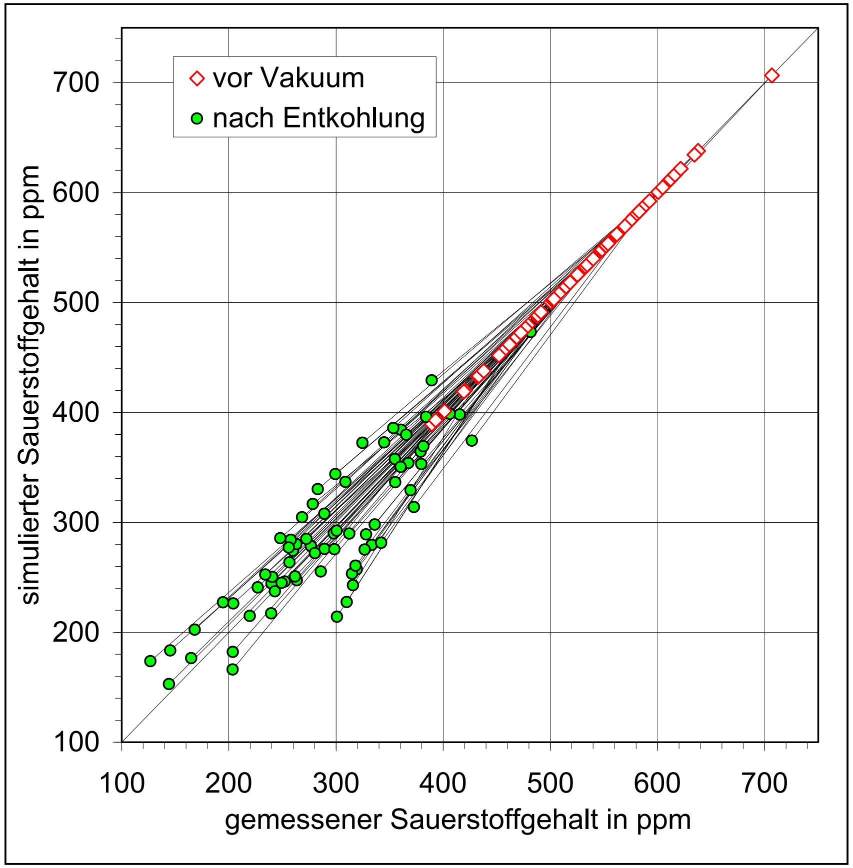
	Decarburisation	Dehydrogenation	Denitrogenation
Equilibrium constant	$K_C = \frac{P_{CO}}{f_C \cdot C_Q \cdot f_O \cdot O_Q}$	$K_H = \frac{\sqrt{P_{H2}}}{f_H \cdot H_Q}$	$K_N = \frac{\sqrt{P_{N2}}}{f_N \cdot N_Q}$
Equilibrium content	$C_Q = F_{CO} \cdot P_{CO}$	$H_Q = F_{H2} \cdot \sqrt{P_{H2}}$	$N_Q = F_{N2} \cdot \sqrt{P_{N2}}$
Conversion equilibrium content	$F_{CO} = \frac{0.002}{f_C \cdot f_O \cdot O_Q} \cdot \frac{\%^2}{\text{bar}}$	$F_{H2} = \frac{0.0025}{f_H} \cdot \frac{\%}{\text{bar}^{1/2}}$	$F_{N2} = \frac{0.0434}{f_N} \cdot \frac{\%}{\text{bar}^{1/2}}$
Conversion gas flow rate	$F_{DC} = \frac{22.4\,\text{m}^3}{12\,\text{kg}} \cdot \frac{W}{100\%}$	$F_{DH} = \frac{22.4\,\text{m}^3}{2\,\text{kg}} \cdot \frac{W}{100\%}$	$F_{DN} = \frac{22.4\,\text{m}^3}{28\,\text{kg}} \cdot \frac{W}{100\%}$
Partial pressure	$P_R = (P_G + P_Z) \cdot \frac{F_{DX} \cdot D_X}{F_{DX} \cdot D_X + Q_D}$	Q_D = diluting process gas flow rate	

Calculation results: Decarburisation



Calculation results: Carbon and Oxygen content (for heats without oxygen blowing)





Modelling error of final Carbon content

$\Delta C = 0.1$ ppm

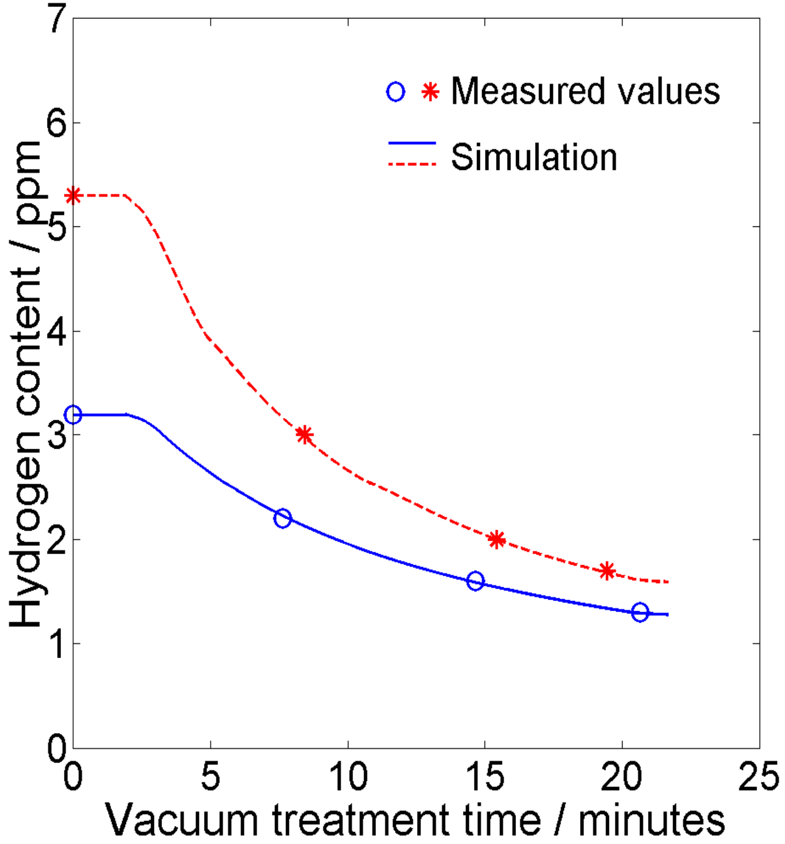
$\sigma(\Delta C) = 5.8$ ppm

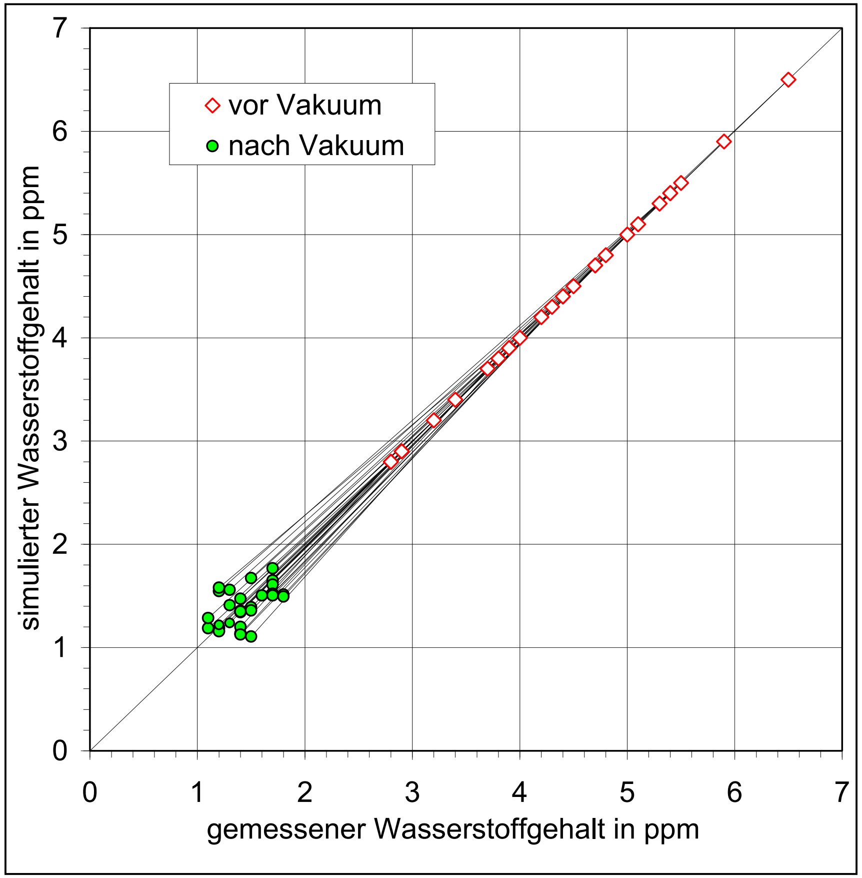
Modelling error of Oxygen content before deoxidation

$\Delta O = -5.5$ ppm

$\sigma(\Delta O) = 33.8$ ppm

Calculation results: Hydrogen removal



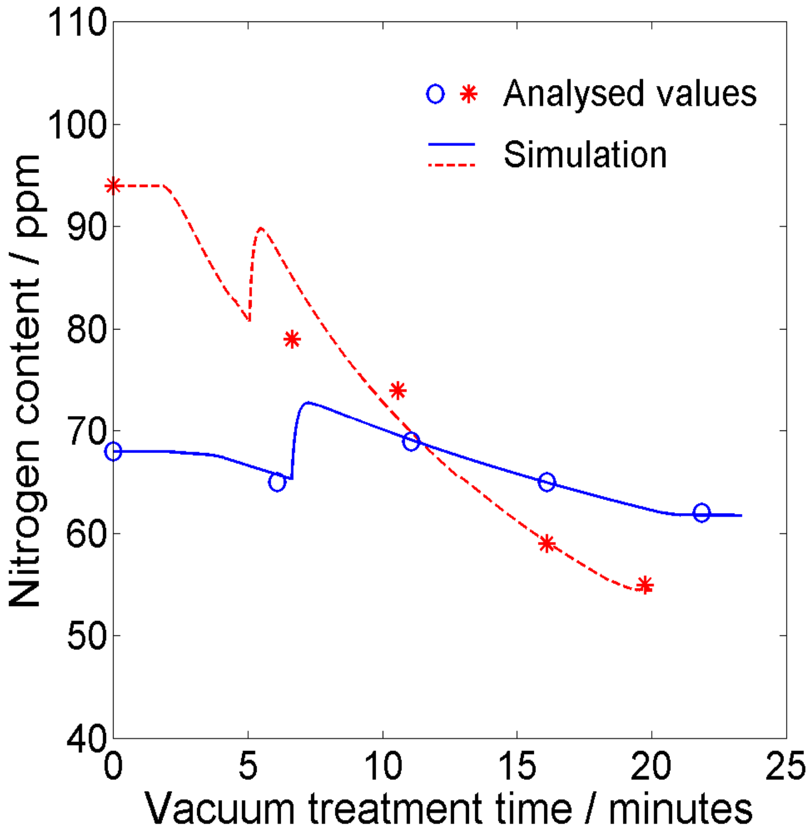


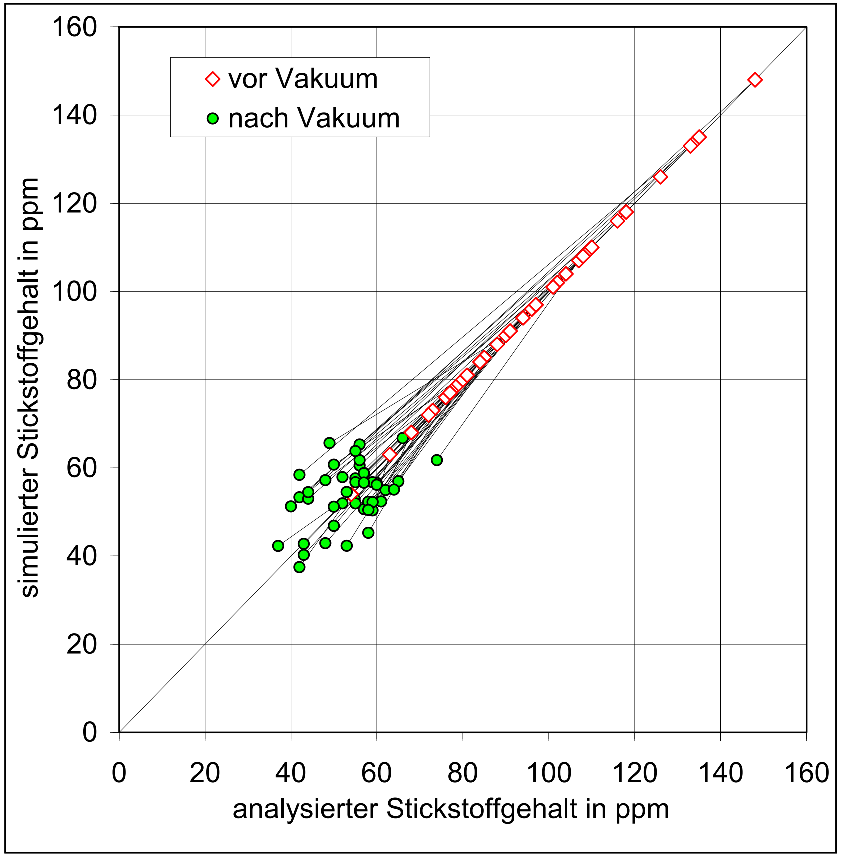
Modelling error of Hydrogen content

ΔH = 0.002 ppm

$\sigma (\Delta H)$ = 0.2 ppm

Calculation results: Nitrogen removal





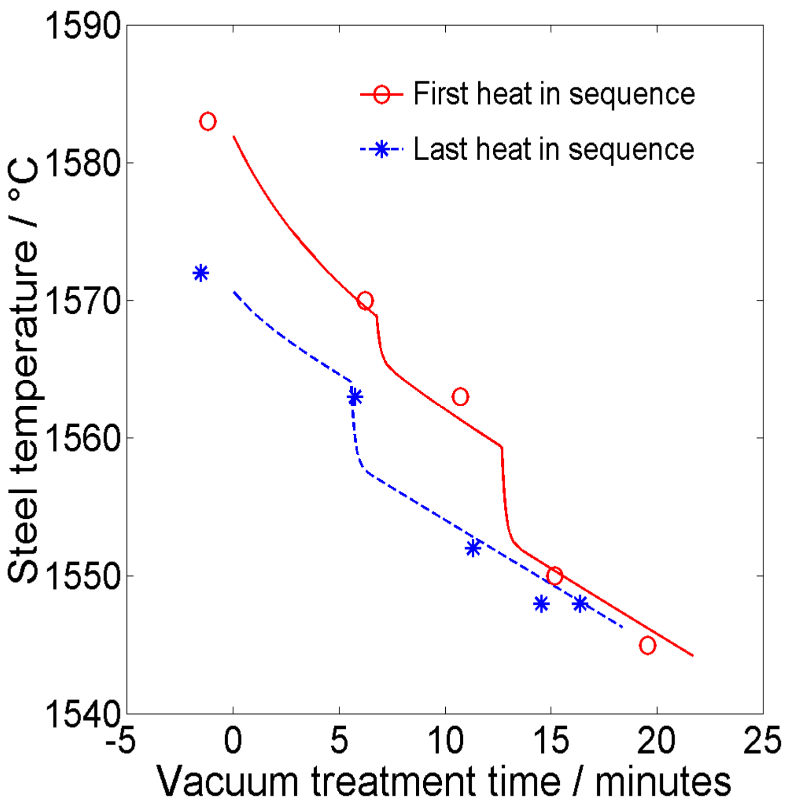
Modelling error of Nitrogen content

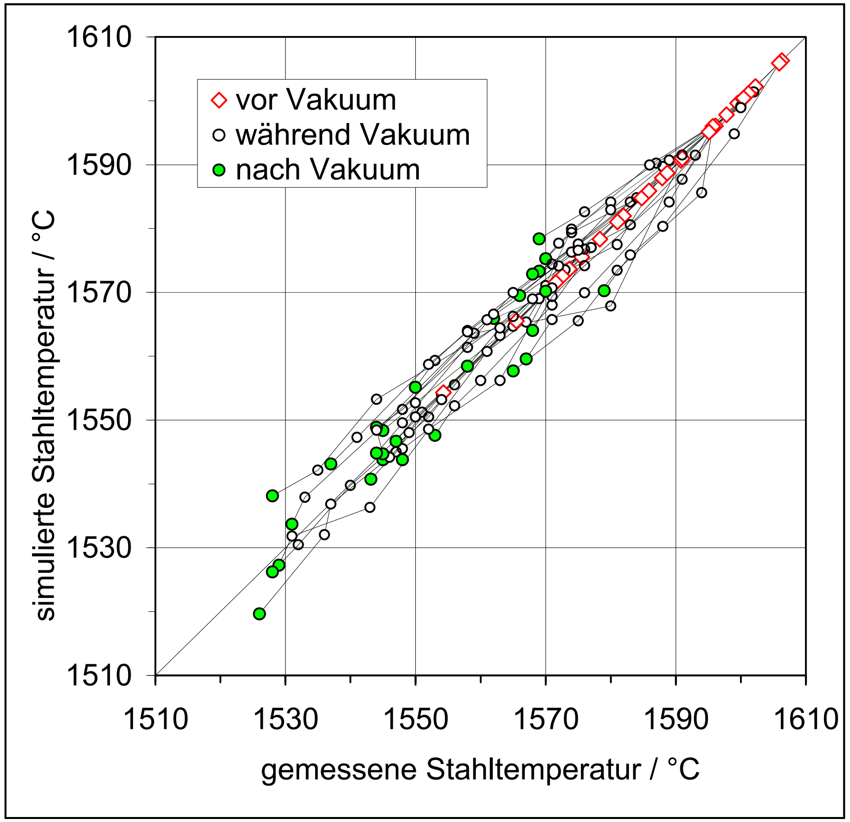
ΔN = -0.02 ppm

$\sigma (\Delta N)$ = 7.6 ppm

Calculation results: Steel temperature

Example: Temperature evolution of deoxidised heats



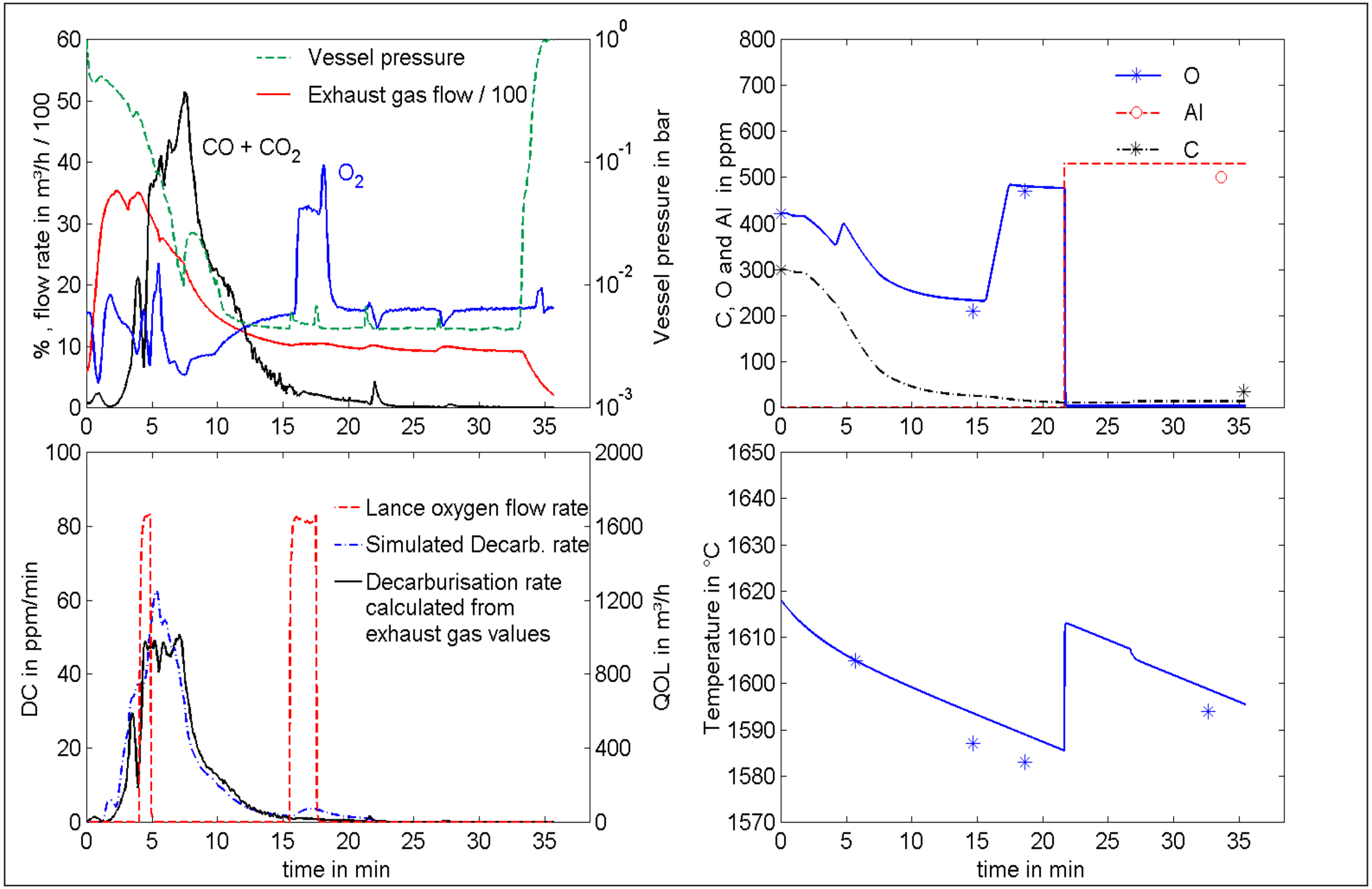


Modelling error of steel temperature

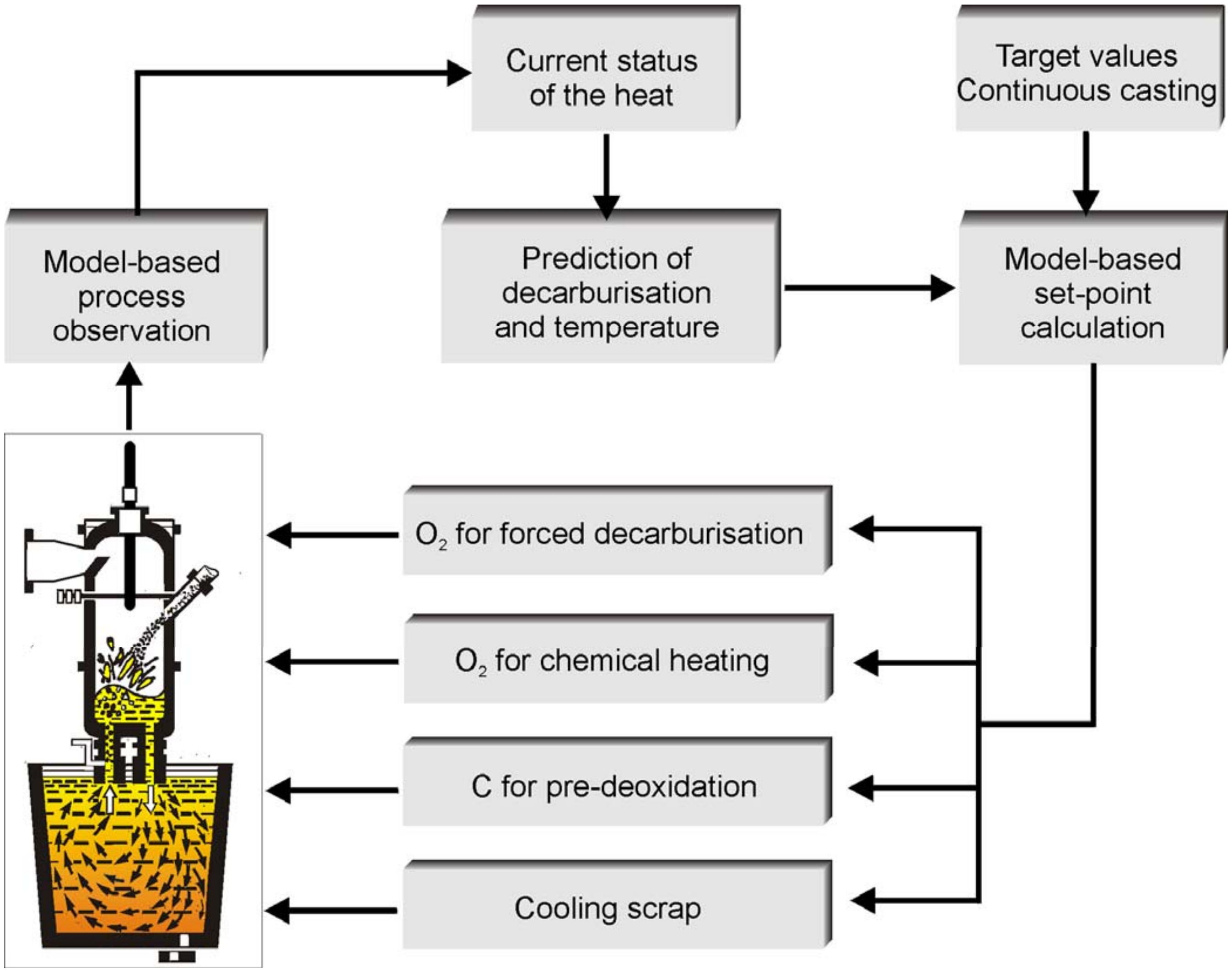
$\Delta T = 0.4$ K

$\sigma (\Delta T) = 5.4$ K

Calculation results for example heat with oxygen blowing



Model-based process control for RH plants with oxygen top lance



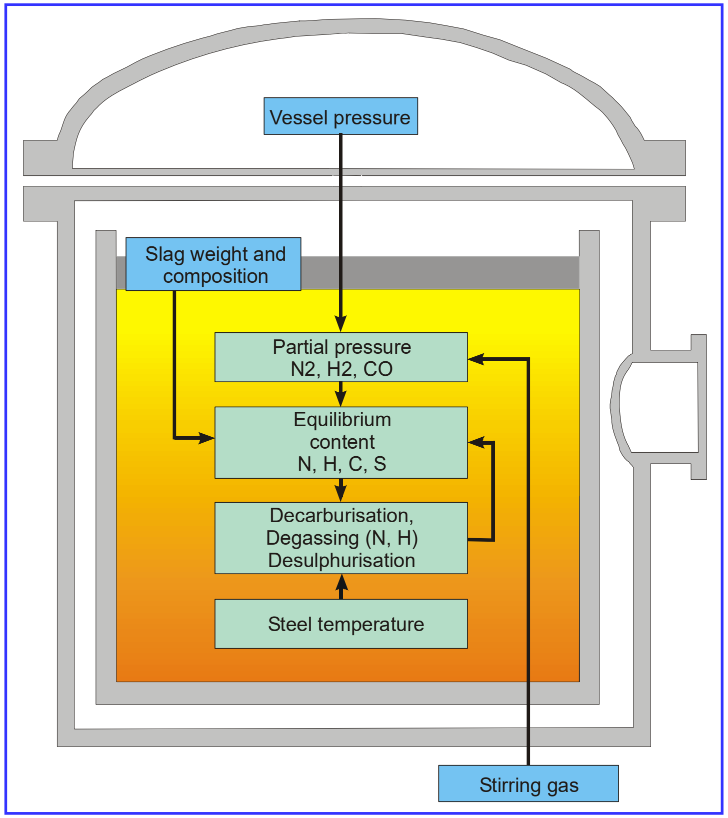
Dynamic model of the Ladle Tank Degassing (VD) process

Functions of the process model

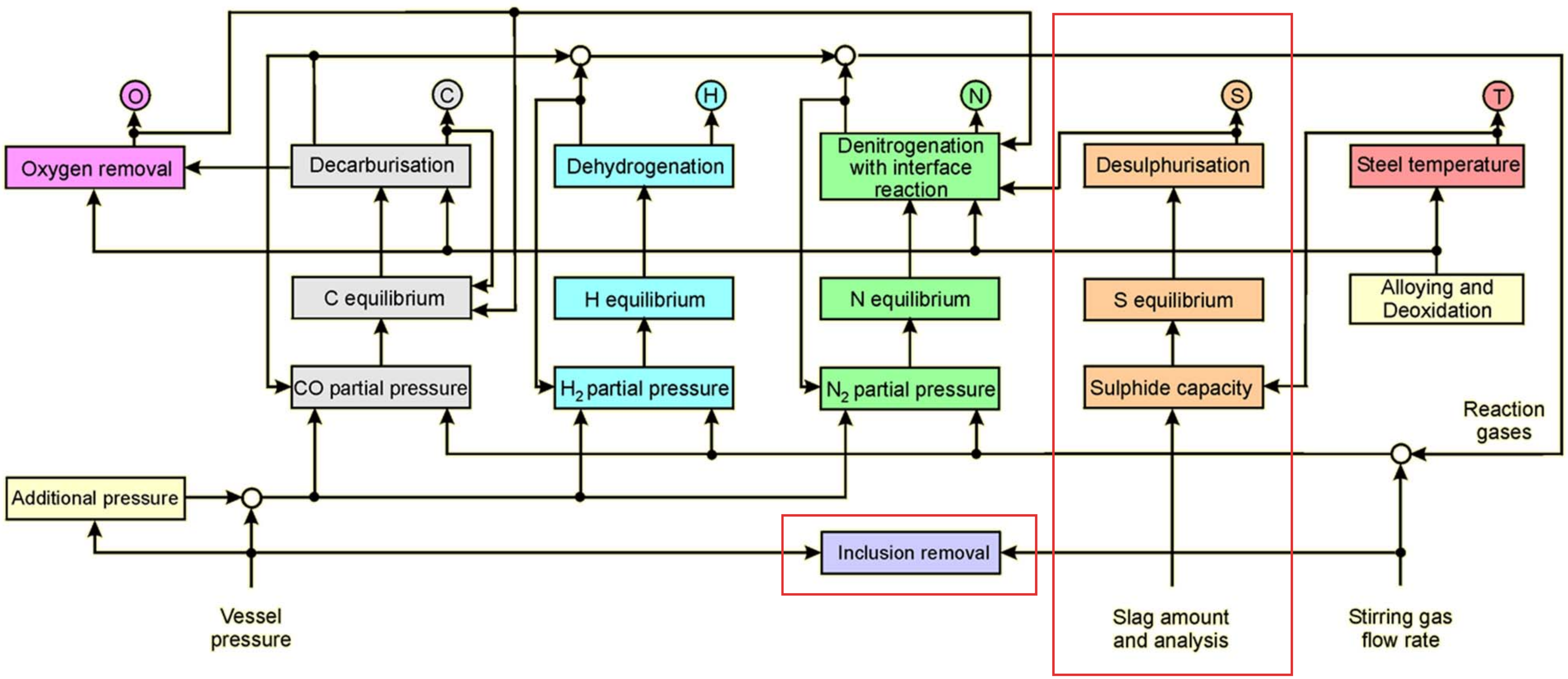
- On-line observation of decarburisation, denitrogenation / nitrogen pick-up, dehydrogenation, desulphurisation and steel temperature
- Monitoring of inclusion removal
- Dynamic prediction of remaining degassing time and corresponding temperature losses

Required input data

- Vessel pressure
- Bottom stirring gas flow rate
- Cooling water flow rate and temperature difference for water-cooled roof
- Heat state at start of treatment
- Weights and types of all charged materials



Structure of the VD process model



Equations for desulphurisation

Chemical steel / slag reaction :

$$[S]+(CaO)+\frac{2}{3}[Al]=(CaS)+\frac{1}{3}(Al_2O_3)$$

Equilibrium sulphur distribution L_S:

$$L_S=\frac{S_{SQ}}{S_Q}$$

S_{SQ}	Sulphur equilibrium content in the slag
S_Q	Sulphur equilibrium content of steel
C_S	Sulphide capacity of the slag
f_S	Sulphur activity coefficient (≈1)
a_O	Oxygen activity

$$\log L_S=-\frac{935}{T}+1.375+\log C_S+\log f_S-\log a_O$$

$$\log a_O = f(Al_2O_3)$$

Sulphide capacity C_S of the slag (IRSID model):

$$logC_S=\frac{5.62\cdot CaO+4.15\cdot MgO-1.15\cdot SiO2+1.46\cdot AL_2O_3}{CaO+1.39\cdot MgO+1.87\cdot SiO2+1.65\cdot AL_2O_3}-\frac{12364}{T}+1.445$$

Sulphur balance for slag (W_S) and steel (W):

$$S_{SQ}\cdot W_S=S_{S0}\cdot W_{S0}+(S_0-S_Q)\cdot W$$

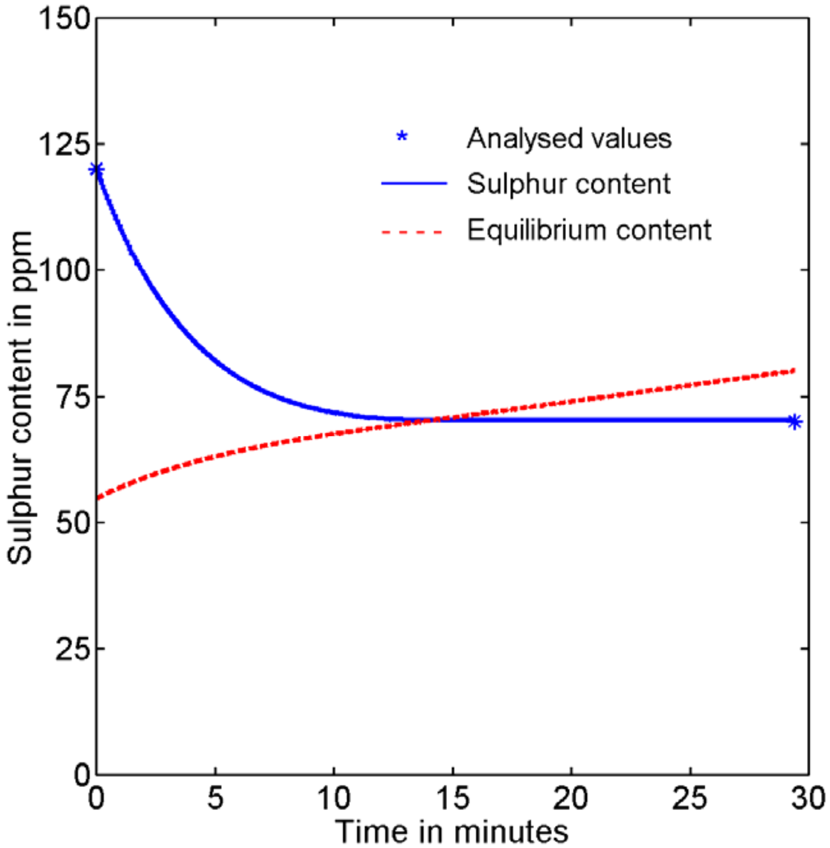
Sulphur equilibrium content of steel:

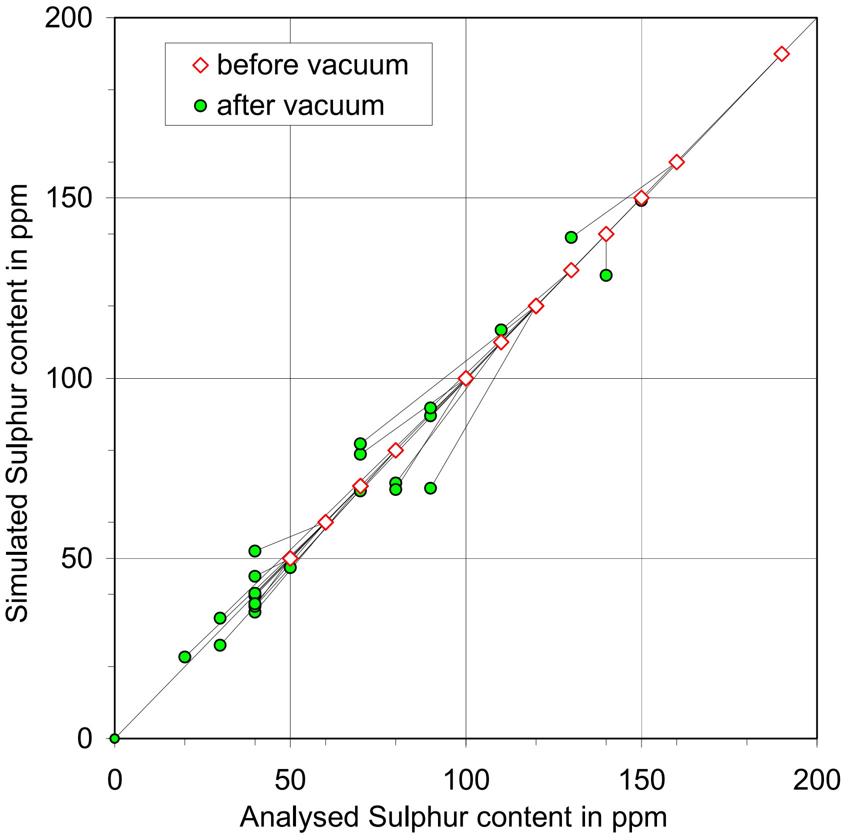
$$S_Q=\frac{S_0+S_{S0}\cdot W_S/W}{L_S\cdot W_S/W+1}$$

Desulphurisation rate:

$$D_S=-\frac{dS}{dt}=\frac{1}{T_S}\cdot(S-S_Q)$$

Calculation results for desulphurisation



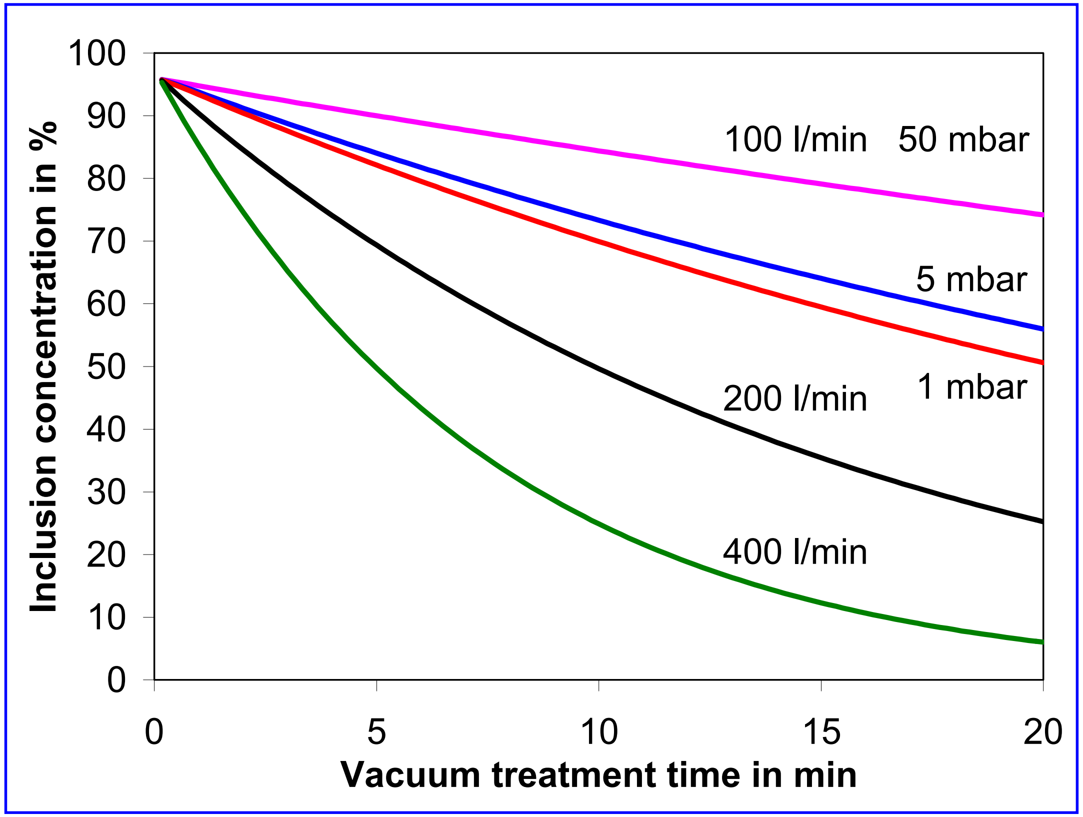


Model error of final Sulphur content:

Error mean value	=	-0.6	ppm
Error standard deviation	=	7.7	ppm

Dynamic model for inclusion removal

Effect of vessel pressure and stirring gas flow rate on kinetics of inclusion removal was investigated based on CFD simulations



Equation for time-dependent inclusion concentration C_{In}:

$$C_{In}(t) = C_{In}(0) * e^{-t / T_{DIn}}$$

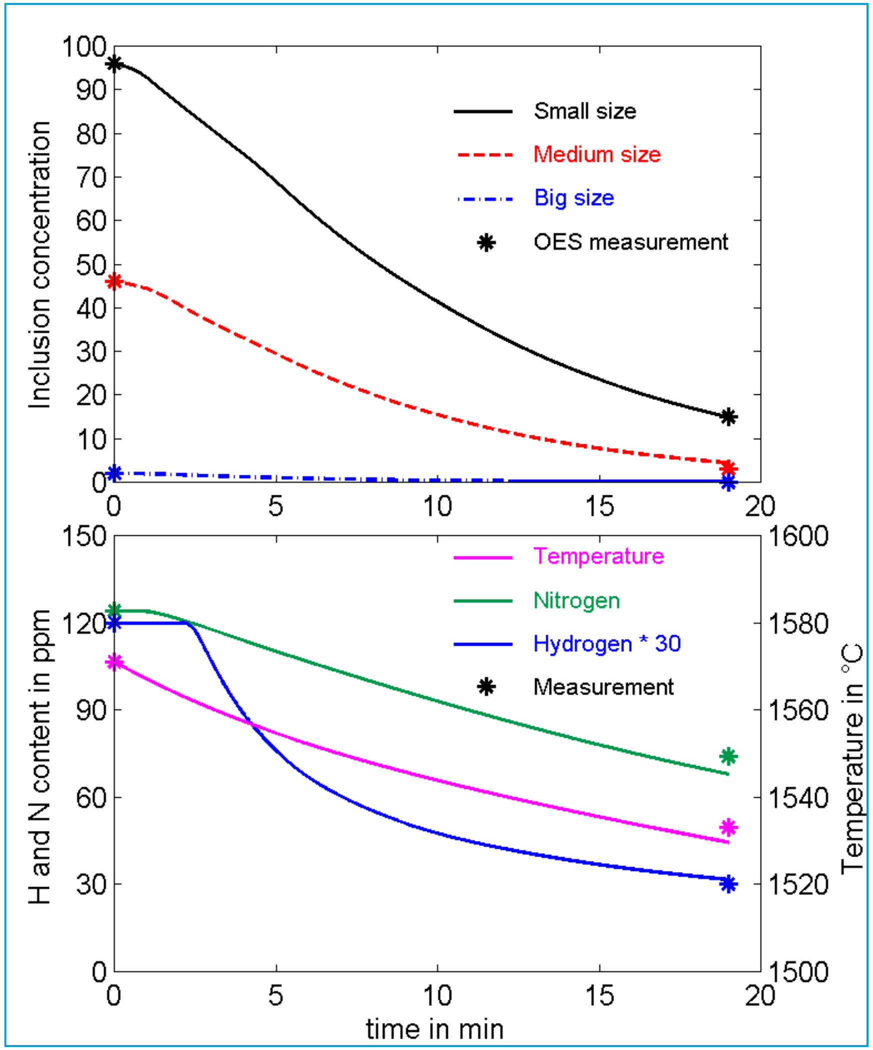
Time constant T_{DIn} depends on:

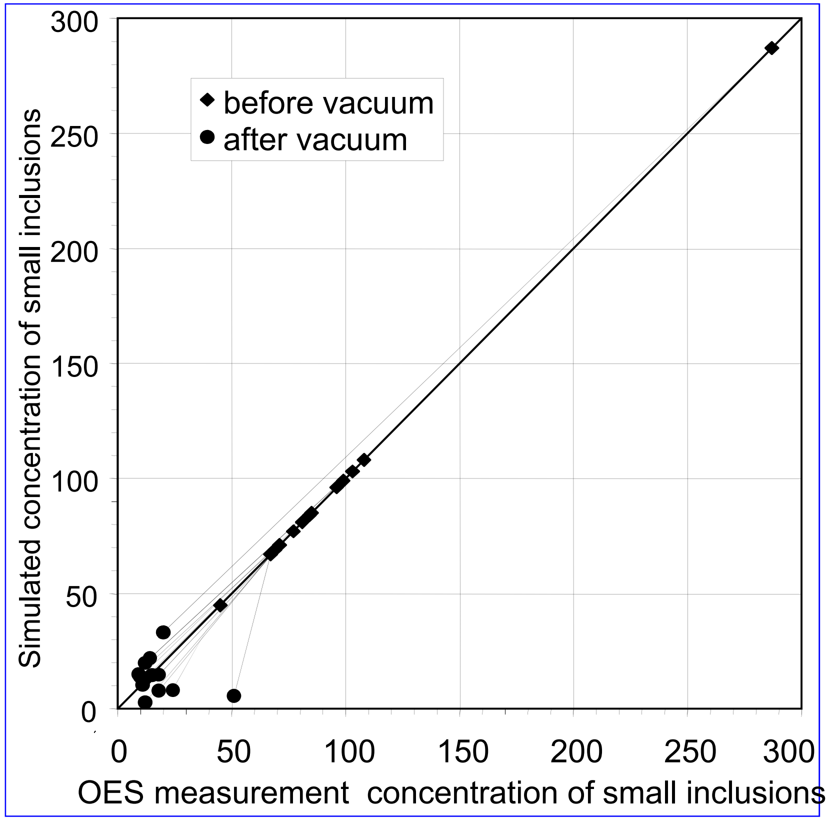
- Vessel pressure
- Stirring gas flow rate
- Inclusion size

Quantitative dependence of T_{DIn} was determined by CFD simulation parameter studies

As result a Look-up Table for the time constant values of three inclusion size classes was defined

Calculation results for inclusion removal





Small size inclusions:

Error mean value	=	0.0
Error standard deviation	=	8.6

Results and conclusions regarding model-based control of vacuum degassing (RH and VD) processes

› The model-based on-line monitoring provides accurate information on the current heat status concerning the contents of Carbon, Oxygen, Hydrogen, Nitrogen and Sulphur as well as the steel temperature

↳ Number of steel samples as well as Oxygen and Temperature measurements can be reduced

› The time when final aim contents are reached can be determined

↳ Reduction of vacuum treatment time

› The model-based set-point calculation for the lance oxygen input (RH)

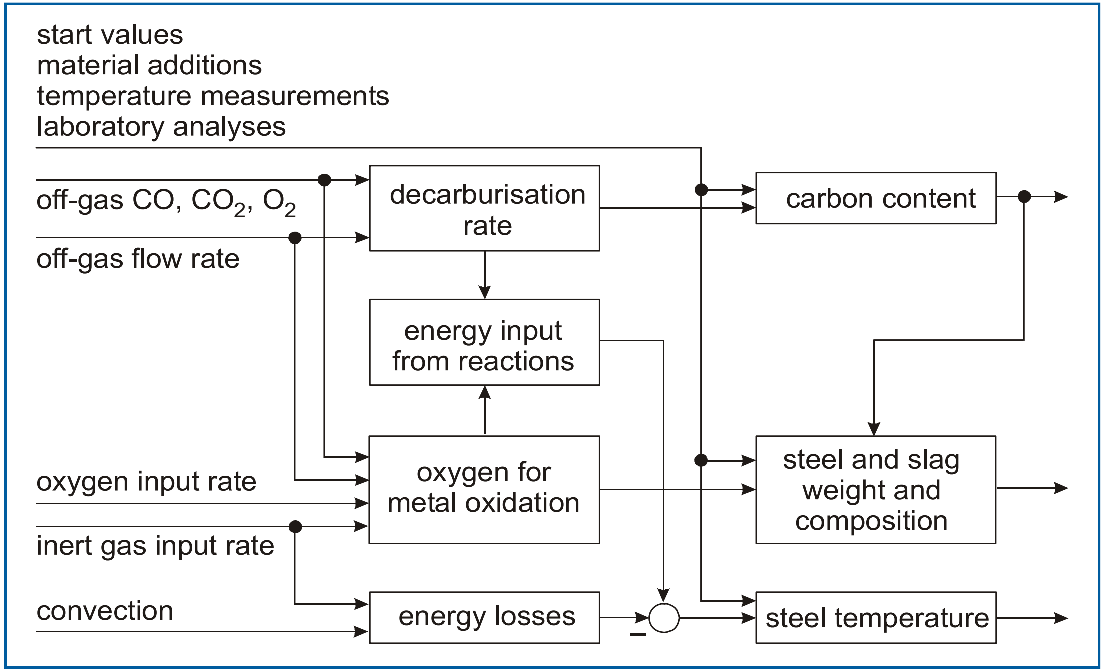
↳ increases the accuracy in meeting the aim temperature

↳ leads on the average to a lower amount of blown oxygen and therefore to a reduced consumption of aluminium for deoxidation

Selected ECSC and RFCS research projects dealing with aspects of process modelling for stainless steelmaking (AOD, VOD)

	Contract Report	Title	Participants	Date Start / End	Topic regarding modelling and control
ECSC	ECSC 7210-PR/011	Dynamic process control of AOD converter	CSM, AST, TKN, BFI	01.07.1997 to 31.12.2000	**AOD process** Decarburisation model
	ECSC 7210-PR/269	Improvement of process control and refractory performance of the AOD converter	AST, CSM, TKN, BFI	01.07.2001 to 30.06.2004	**AOD process** Denitrogenation and temperature model
RFCS	RFSR-CT-2007-00007	Resource-saving operation and control of stainless steel refining in VOD and AOD process **(OPConStainless)**	Kobolde, KTH, Outokumpu, SMS Mevac, Arconi, BFI	01.07.2007 to 30.06.2010	**AOD process** Decarburisation and slag model **VOD process** Comprehensive model

Starting point for AOD process model: Observation based on carbon balance from off-gas values



- Carbon balance based on measured off-gas values
- Oxygen balance with calculation of metal loss (especially chromium)
- Energy balance to calculate the melt temperature

↳ Carbon balance is with an error of 0.07 % for final C content not accurate enough
$\Rightarrow$ development of a thermodynamic decarburisation model

Thermodynamic decarburisation model

Equilibrium constants for oxidation reactions:

$$[C] + [O] = \{CO\} \qquad K_C = \frac{P_{CO}}{(f_C \cdot C_Q) \cdot (f_O \cdot O_Q)}$$

$$2\,[Cr] + 3\,[O] = (Cr_2O_3) \qquad K_{Cr} = \frac{a_{OX}}{(f_{Cr} \cdot Cr_Q)^2 \cdot (f_O \cdot O_Q)^3}$$

Carbon equilibrium content:

$$C_Q = \frac{(f_{Cr} \cdot Cr_Q)^{2/3}}{f_C} \cdot \frac{K_{Cr}^{1/3}}{K_C} \cdot \frac{1}{a_{OX}^{1/3}} \cdot P_{CO} = F_{CO} \cdot P_{CO} \ ,$$

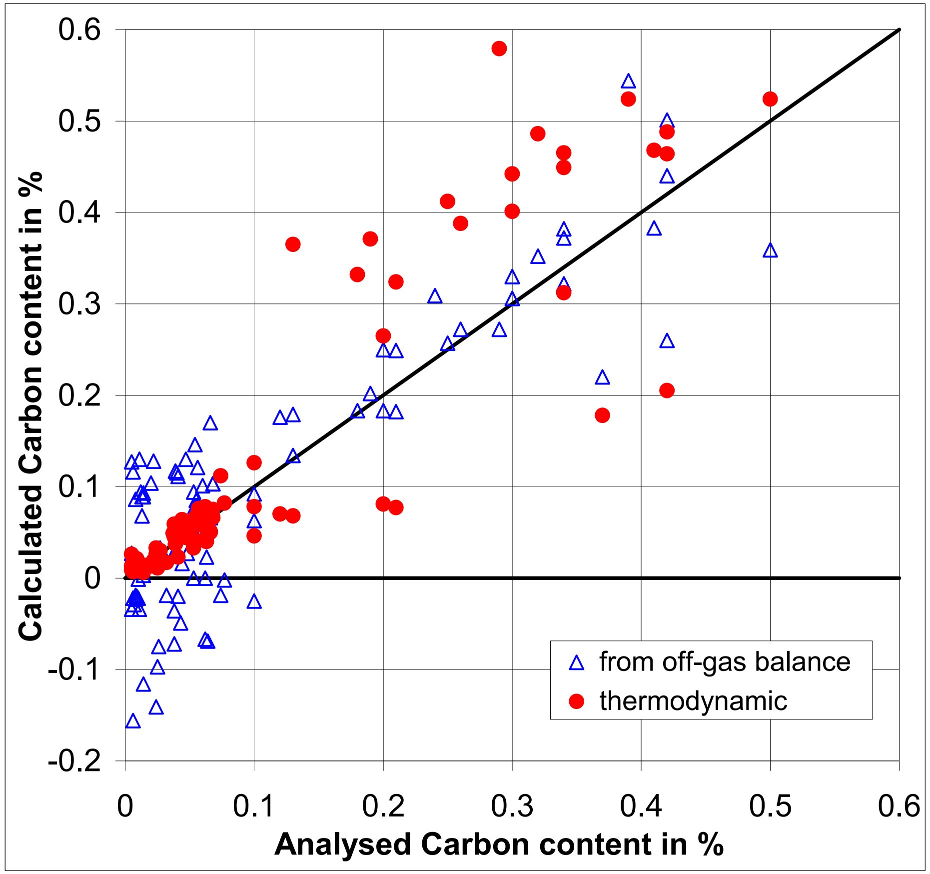
Equilibrium carbon content at P_{CO} = 1 bar :

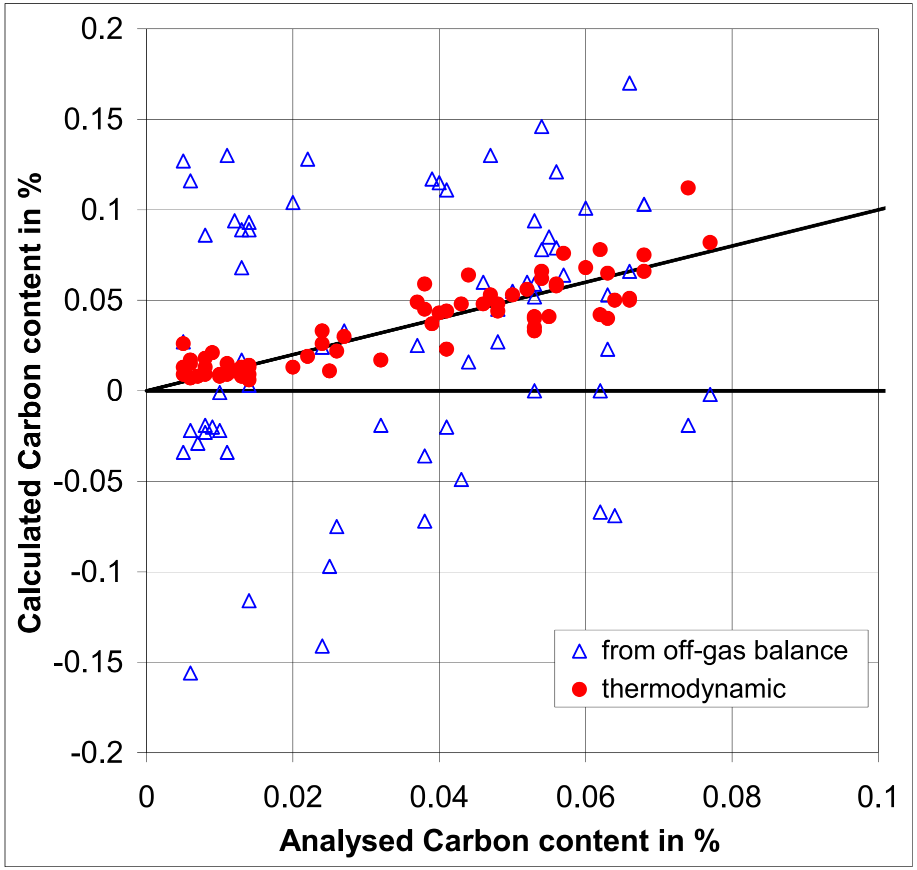
$$F_{CO} = Cr_Q^{2/3} \cdot 10^{(2/3 \cdot \lg f_{Cr} - \lg f_C)} \cdot 10^{(1/3 \cdot \lg K_{Cr} - \lg K_C)} \cdot a_{OX}^{-1/3} \cdot \frac{\%}{bar}$$

P_{CO} lowered from CO dilution by inert gas with flow rate Q_P of effectiveness R_{VQ}:

$$P_{CO} = \frac{Q_{CO}}{Q_{CO} + R_{VQ} \cdot Q_P} \cdot P_A$$

Accuracy of decarburisation calculation for the AOD process

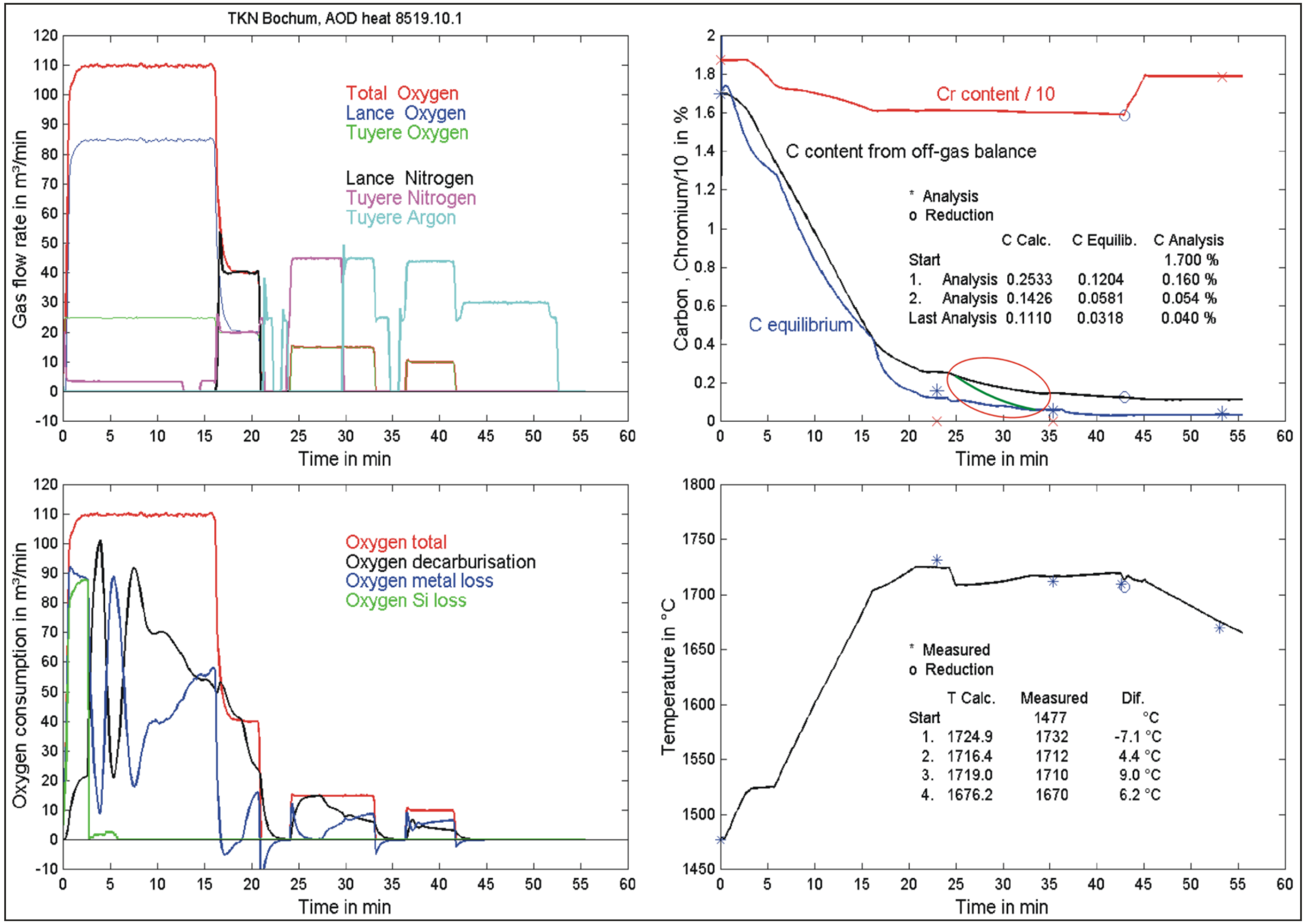




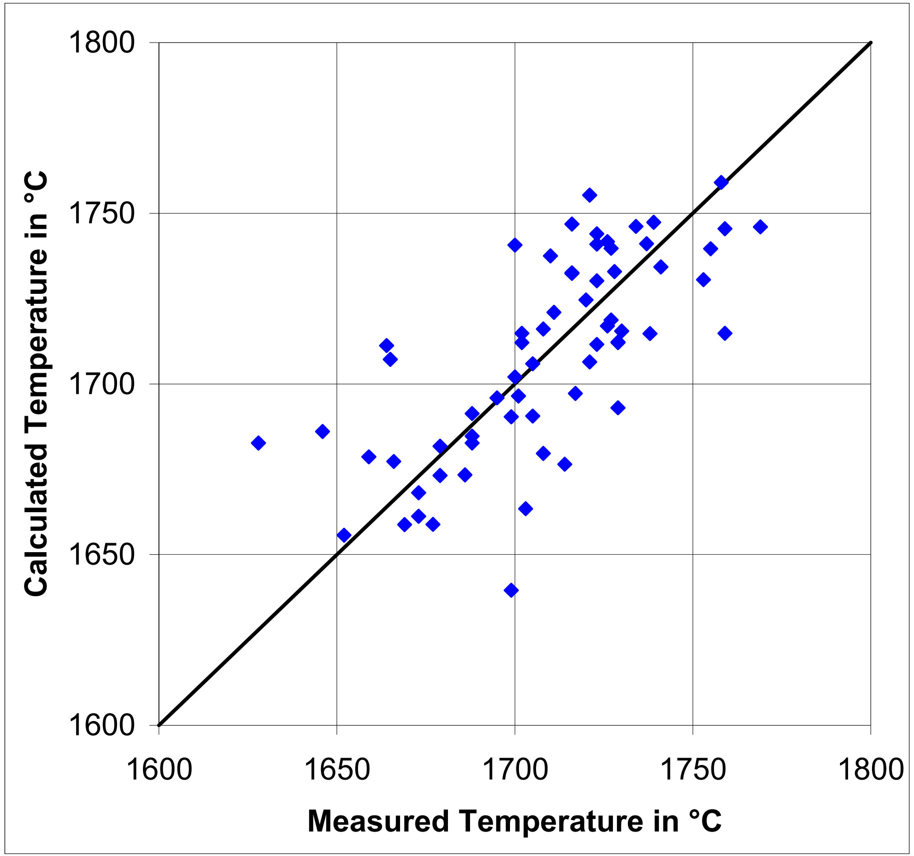
Modelling error	off-gas balance / thermodyn.
Mean value =	-0.001 % / 0.062 %
Standard dev. =	0.070 % / 0.135 %

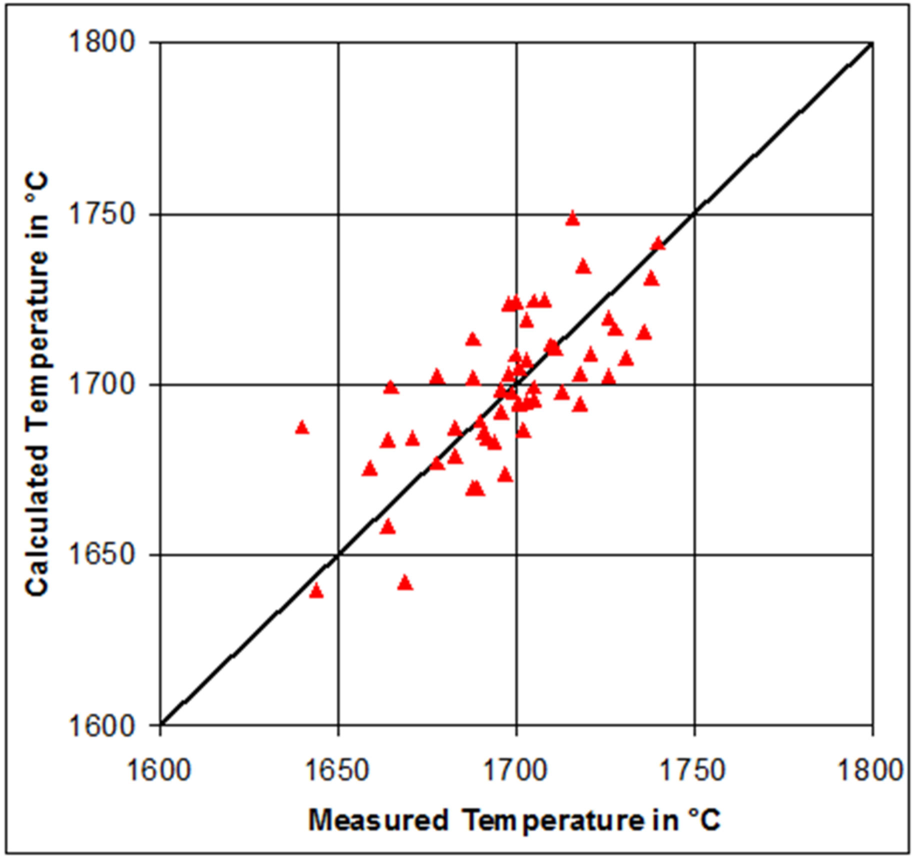
Modelling error	off-gas balance / thermodyn.
Mean value =	-0.002 % / 0.001 %
Standard dev. =	0.072 % / 0.011 %

On-line observation of decarburisation for an AOD example heat



Accuracy of temperature calculation for the AOD process





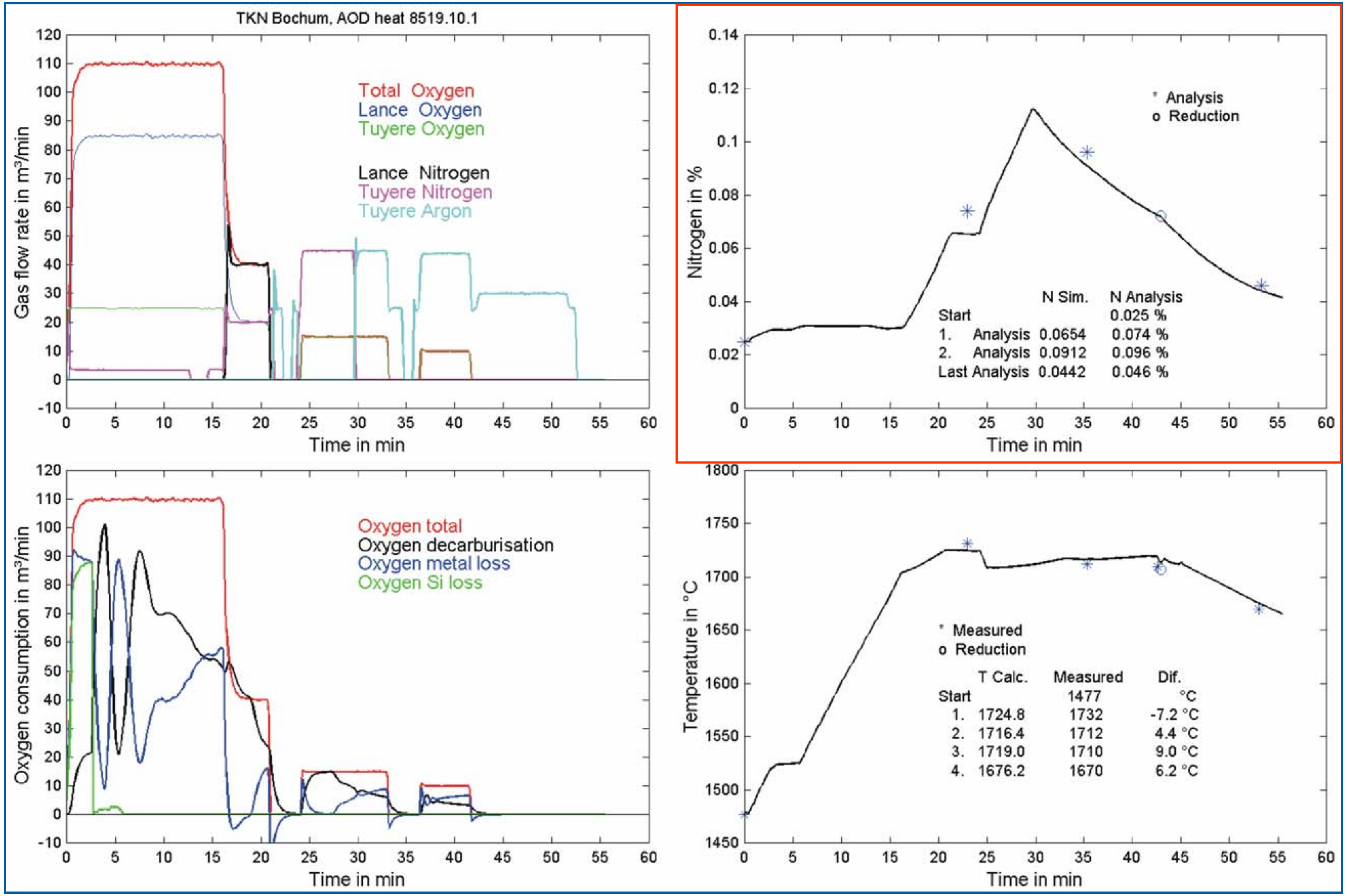
Modelling error of temp. before reduction:

Mean value = -0.2 K
Standard dev. = 16.5 K

Modelling error of final temp. with adaptation to meas. before reduction:

Mean value = 1.0 K
Standard dev. = 16.9 K

On-line observation of Nitrogen content for an AOD example heat

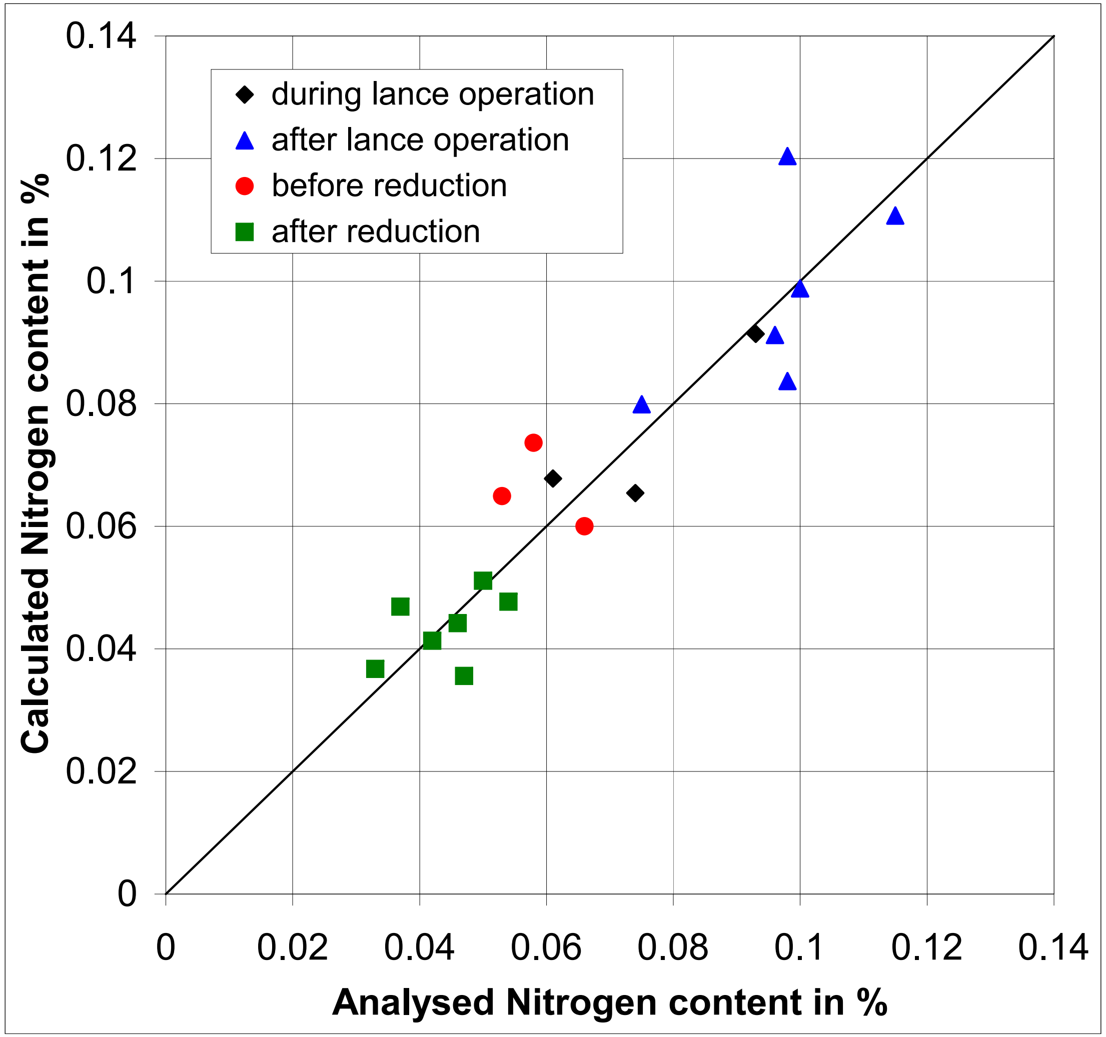


Accuracy of Nitrogen content calculation

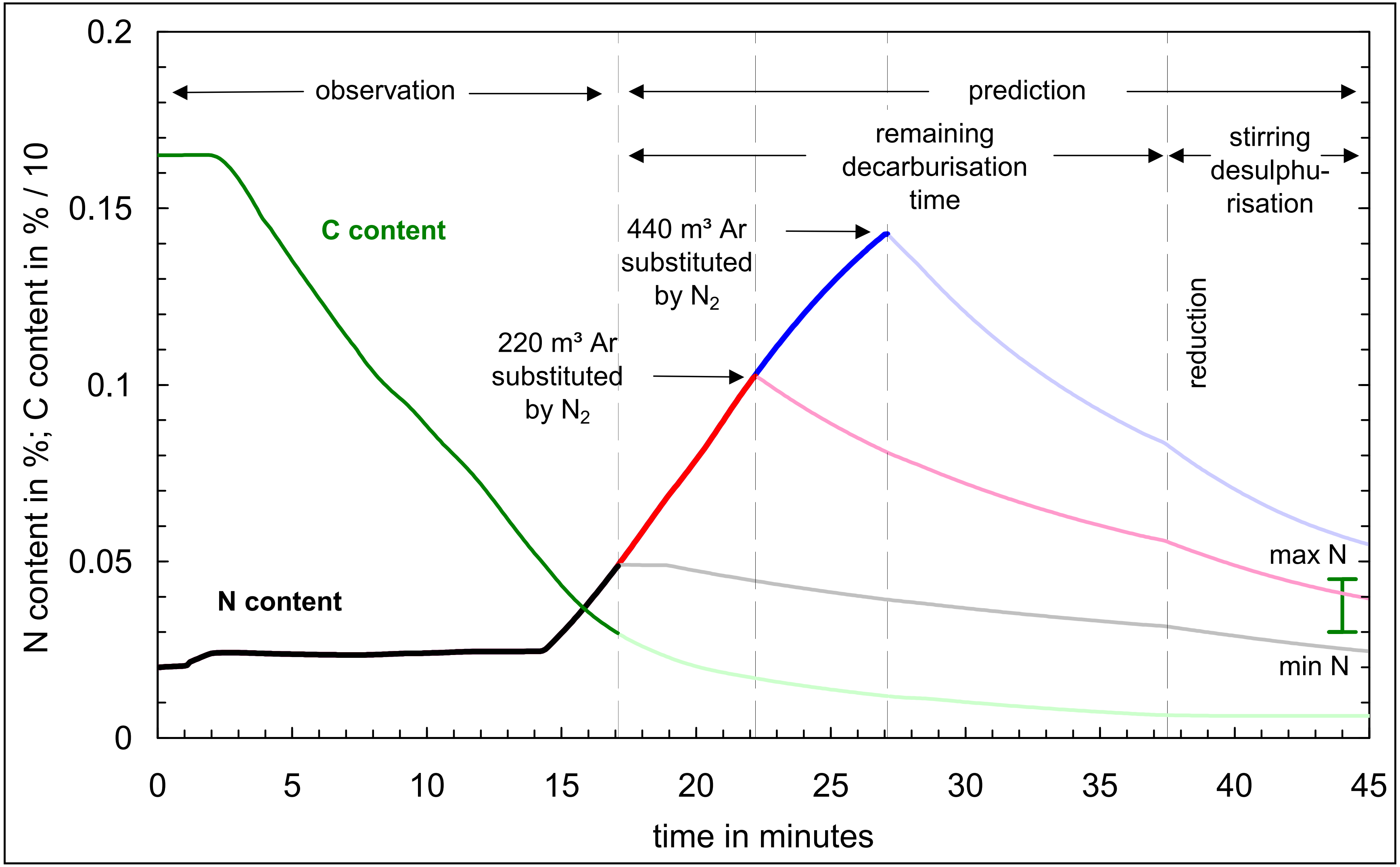
Intermediate sampling for verification of the nitrogen model

Modelling error of the final Nitrogen content:

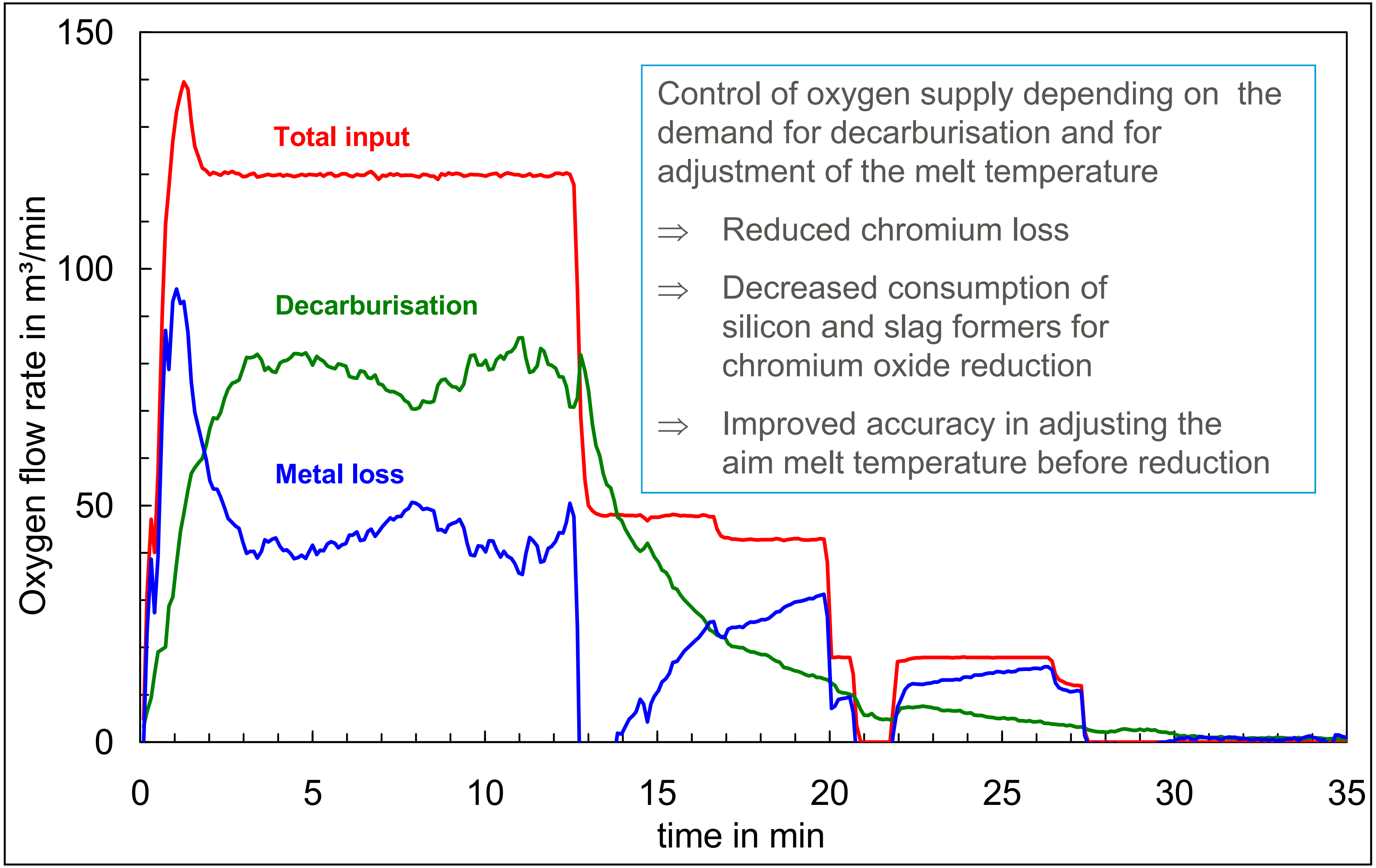
Mean value = 0.001 %
Standard dev. = 0.007 %



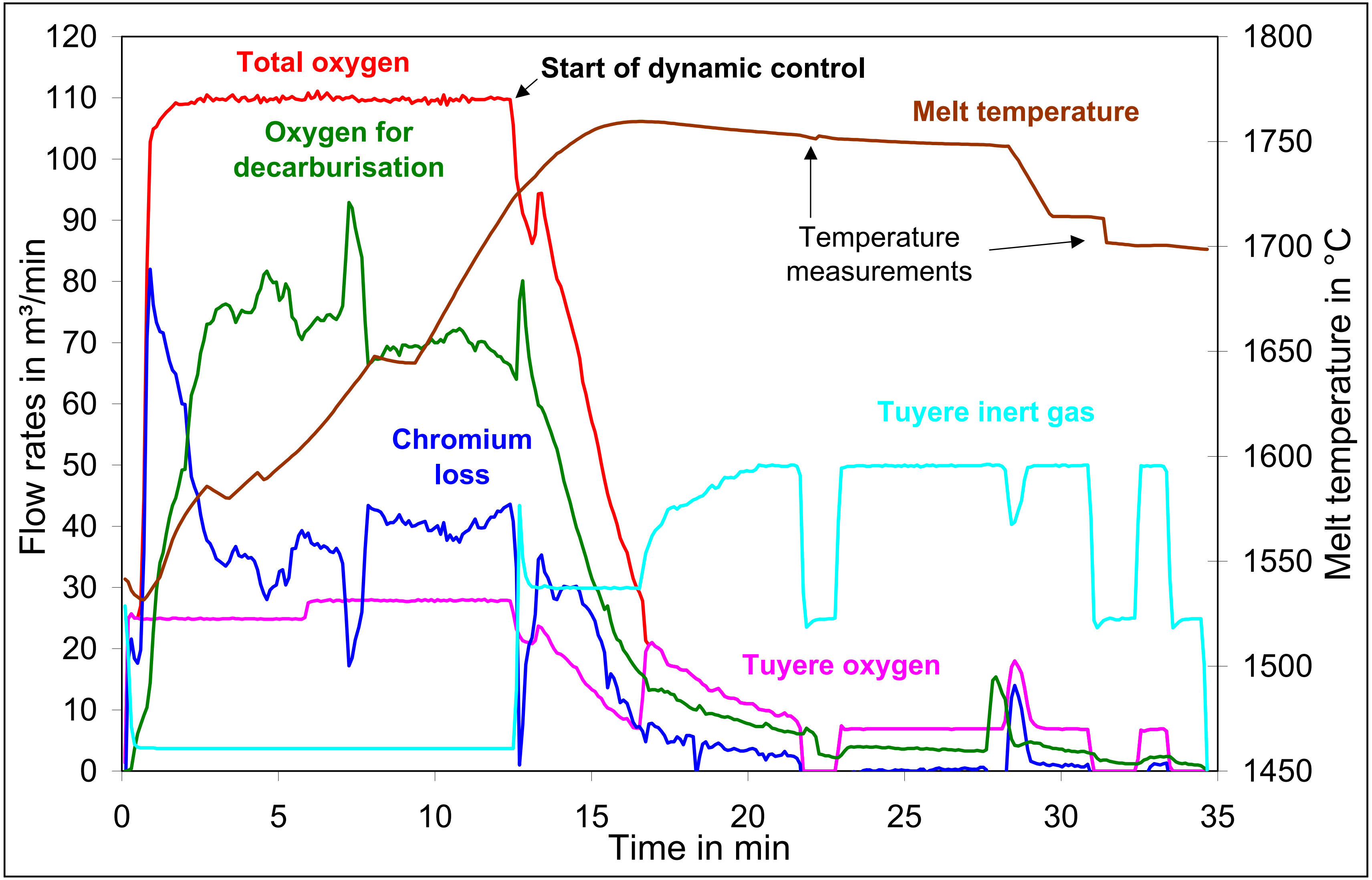
Determination of the optimal switching point from N_2 to Ar inert gas



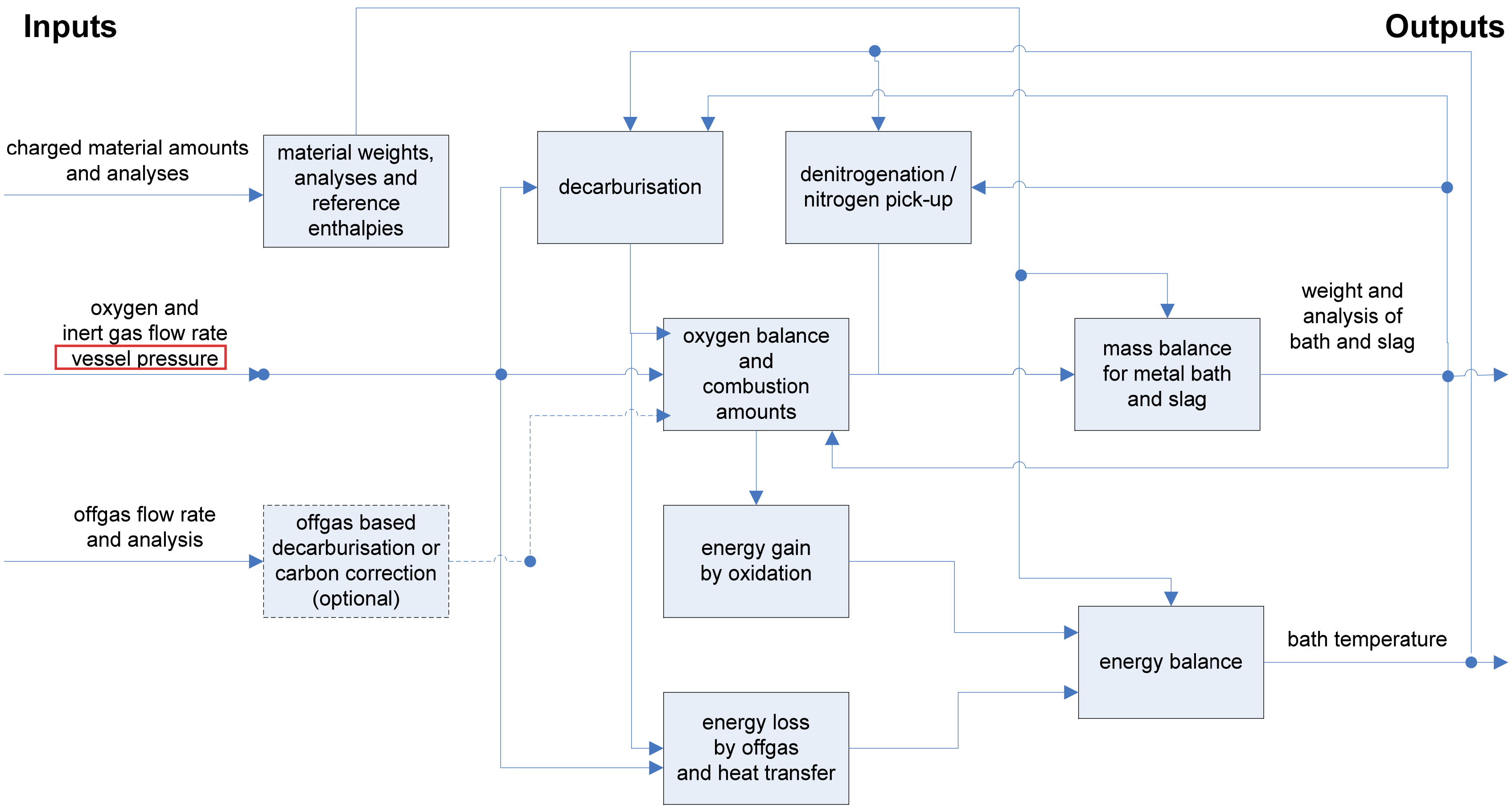
Motivation for dynamic control of oxygen supply: Oxygen balance for a step-wise controlled heat



Example AOD heat with dynamic control of oxygen supply



Structure of dynamic process model for oxidation phase of the VOD process



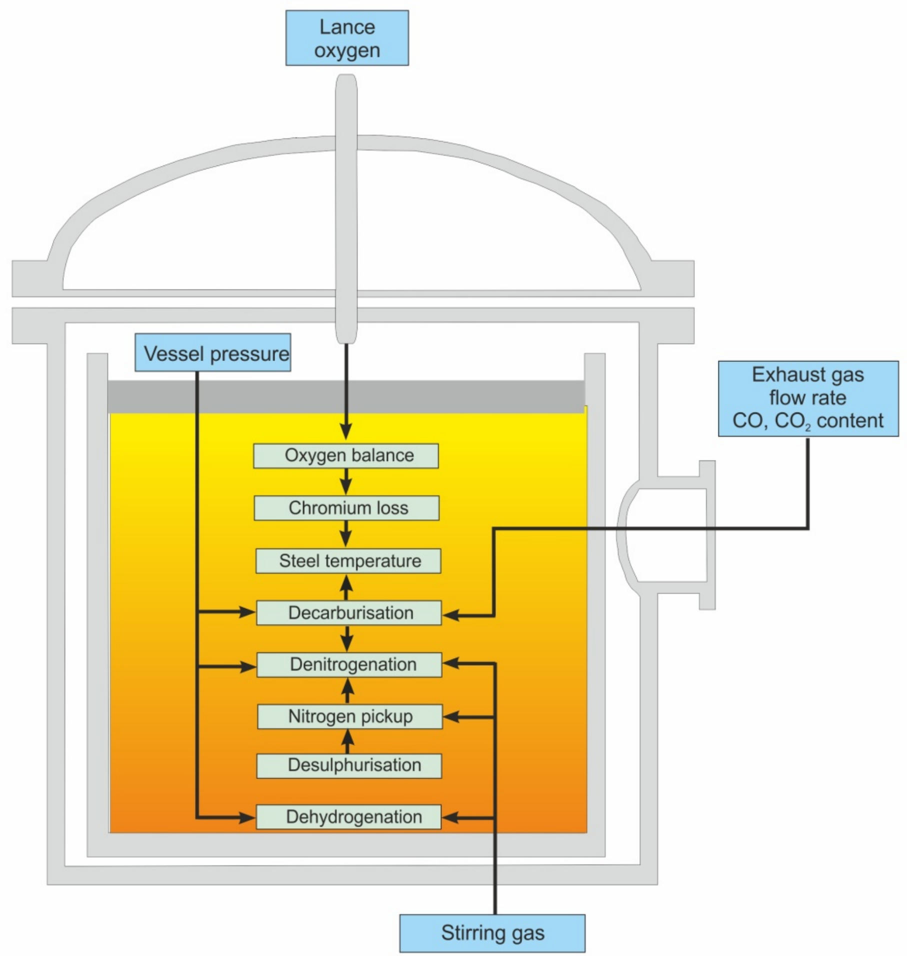
Model-based process control of the VOD plant

Functions of the process model

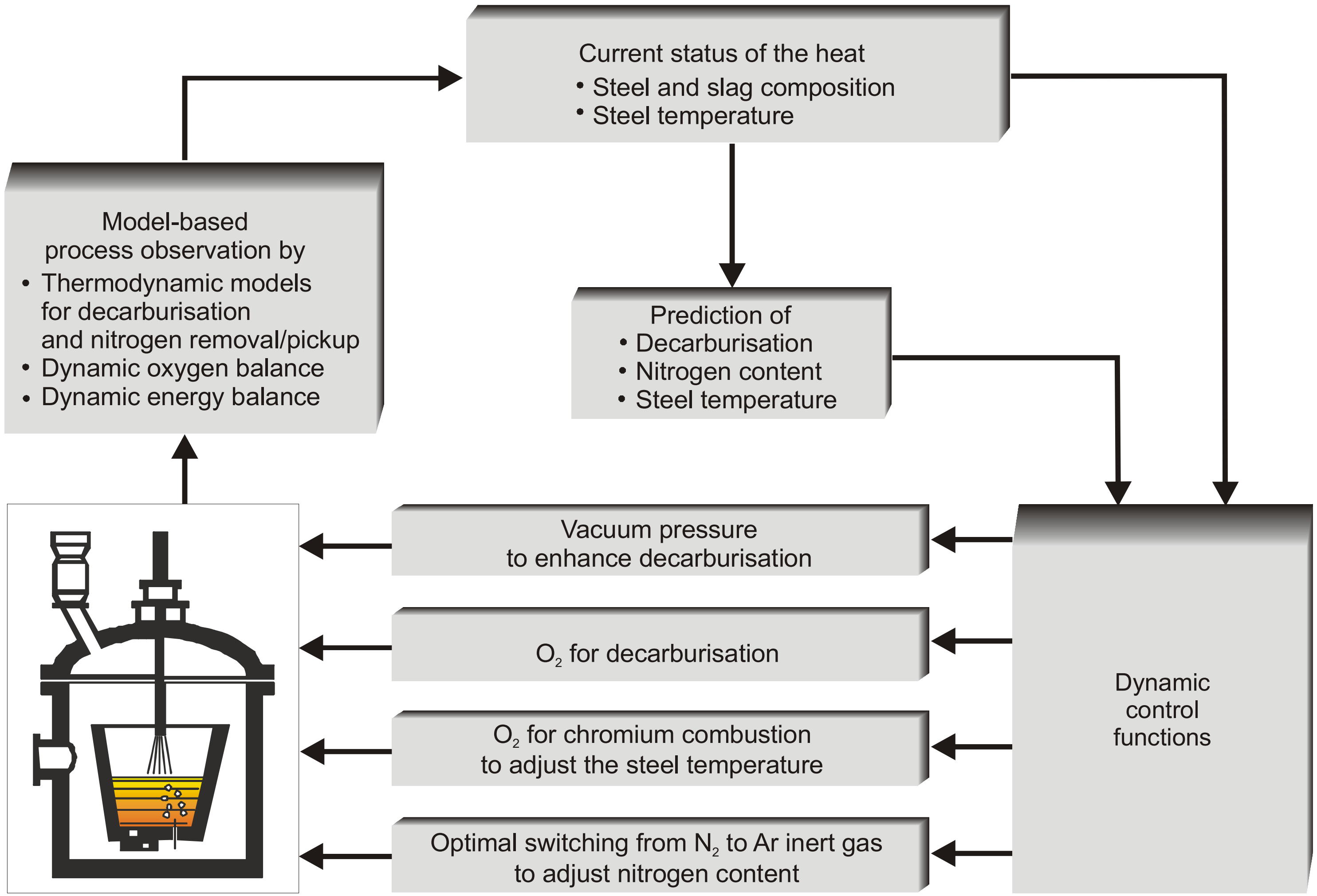
- On-line observation of decarburisation, chromium loss, denitrogenation / nitrogen pick-up, dehydrogenation, desulphurisation and steel temperature
- Dynamic correction of carbon balance based on exhaust gas flow rate and analysis for accurate determination of final carbon content
- Dynamic control of lance oxygen input in the decarburisation phase to minimise the chromium loss

Required input data

- Vessel pressure
- Bottom stirring gas flow rate and type
- Lance oxygen flow rate
- Offgas values for correction of decarburisation rate at critical point
- Weights and types of all charged materials



Concept for comprehensive model based dynamic control for stainless steel refining processes (VOD, AOD)



Results and conclusions regarding model-based control of stainless steel refining (AOD and VOD) processes

- On-line observation of current process state regarding decarburisation, oxidation and metal slagging, nitrogen content and melt temperature
- For VOD additionally: desulphurisation and hydrogen removal

⇘ Accurate end point control of the process

- Determination of the optimal switching point between Nitrogen and Argon inert gas on the basis of a dynamic prediction of the nitrogen content evolution
- Dynamic control of oxygen and inert gas supply for diminished chromium loss and improved melt temperature adjustment

⇘ Accurate and resource-saving adjustment of the melt temperature as well as of carbon and nitrogen content

Selected RFCS research projects dealing with aspects of through-process modelling

	Contract Report	Title	Participants	Date Start / End	Topic regarding modelling and control
Finished	RFCS-CT-2008-00003	Optimized production of low C and N steel grades via the steelmaking route **(LOWCNEAF)**	BFI, AM Olaberria, CRM, Gerdau, PTG, Riva	01.07.2008 to 31.12.2011	**EAF route** Carbon and nitrogen content evolution
	RFSR-CT-2010-00003	Multi-criteria through-process optimisation of liquid steelmaking **(TOTOPTLIS)**	CSM, AME, Lucchini, PTG, BFI	01.07.2010 to 31.12.2013	**BOF route** Temperature model **EAF route** Temperature and metallurgical models
	RFSR-CT-2010-00005	Increased yield and enhanced steel quality by improved deslagging and slag conditioning **(OPTDESLAG)**	Mefos, Saarschmiede, SSAB, BFI	01.07.2010 to 30.06.2013	**EAF route** Slag balance model
	RFSR-CT-2011-00004	Intelligent cleanness control in secondary steelmaking by advanced off-line and on-line process models **(IntCleanCon)**	Tecnalia, Gerdau, DEW, BFI	01.07.2011 to 31.12.2014	**EAF route** Cleanness model
Running	RFSP-CT-2015-00026	Plant wide control of steel bath temperature **(PlantTemp)**	GMH, BFI	01.07.2015 to 30.06.2018	**EAF route** Temperature model

RFCS research projects LowCNEAF and TotOptLiS

Objectives

- Development of a through-process control strategy for reliable achievement of
  - liquid steel quality, especially w.r.t. low carbon, nitrogen, hydrogen and sulphur levels
  - liquid steel temperature
- Optimisation of the operational practices in terms of energy and material costs as well as productivity aspects

Applied methods

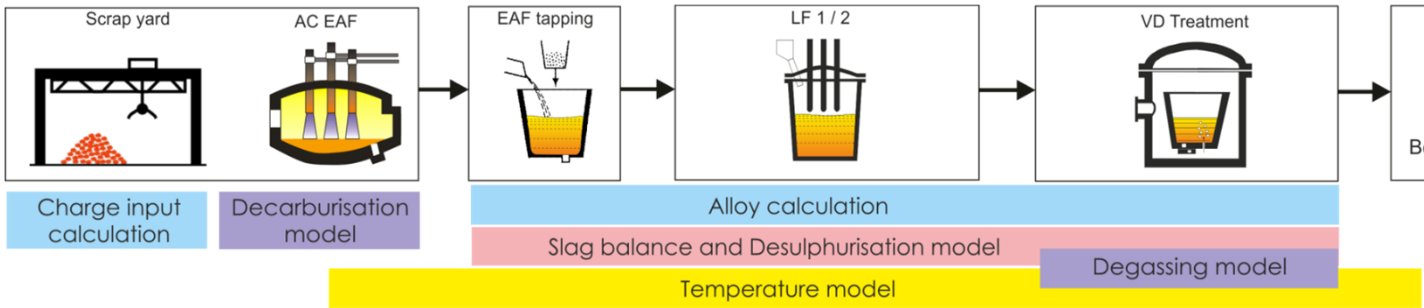
- Integration of process models for
  - steel temperature evolution
  - pick-up and removal of carbon, nitrogen, hydrogen and sulphur

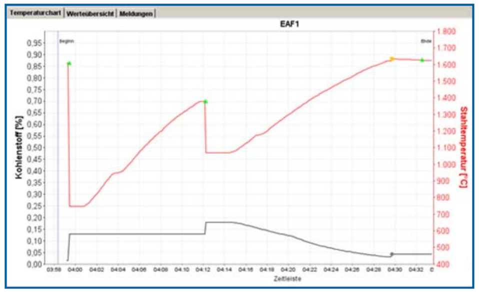
  into a through-process online monitoring and control system for the complete electric steelmaking route (EAF, LF, VD) from scrap yard up to start of casting
- Combination of integrated model calculations with suitable optimisation tools for optimal layout of treatment practices with regard to quality, costs and productivity
- Dynamic adaption of defined set-points of the treatment practices based on predictive model calculations

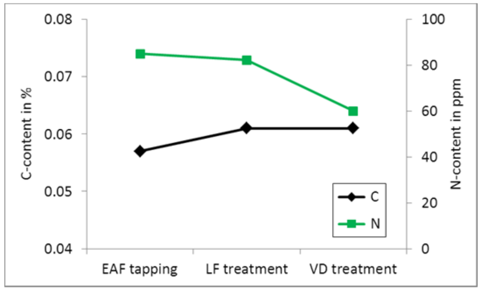
RFCS project LowCNEAF: Through process modelling and control of carbon and nitrogen content

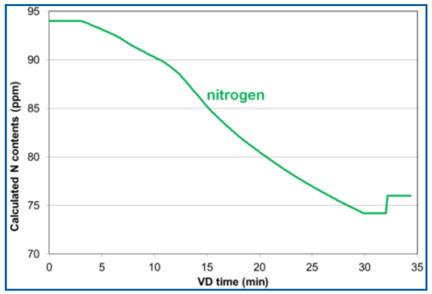
Combination of different dynamic process models and regression / statistical models to a through process control approach for the complete electric steelmaking route

- EAF charge material selection with a cost optimal charge input calculation
- Control of decarburisation in the EAF based on a dynamic carbon balance model down to the required C content at tapping
- Selection of alloys by a cost optimal alloy calculation with restriction of C and N pick-up
- Control of denitrogenation during vacuum degassing with monitoring of the achievement of the required Nitrogen end-point via a dynamic degassing model







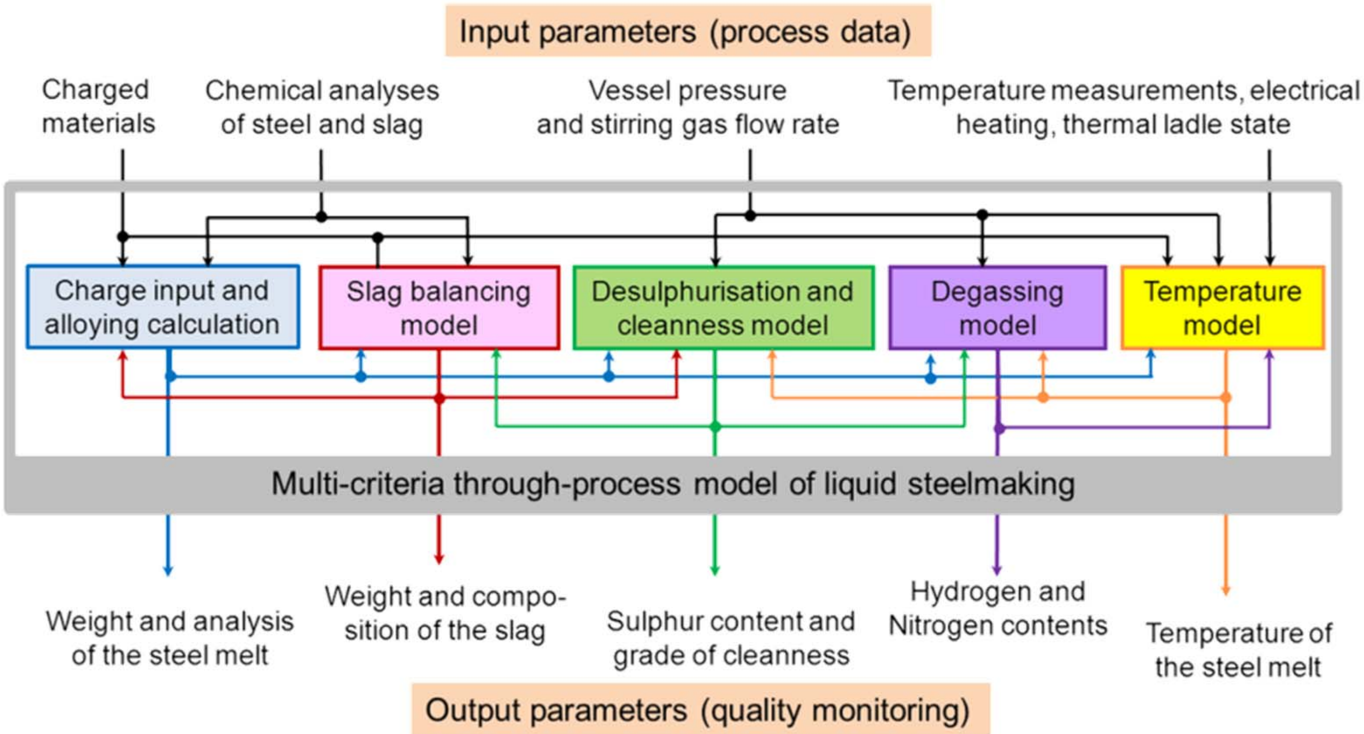


RFCS project TotOptLiS: Through process modelling and control of liquid steel temperature and composition

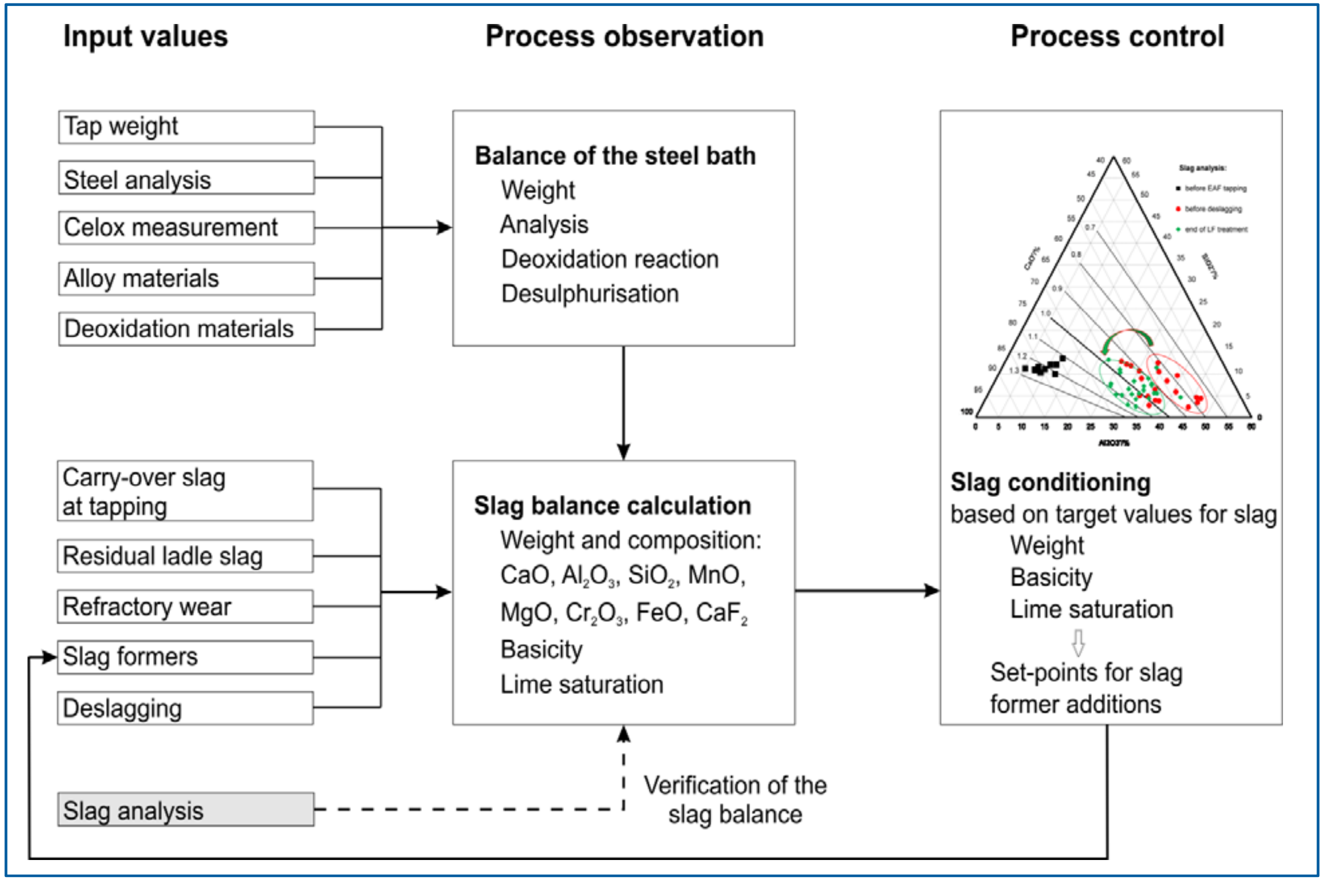
Integration of dynamic models for

- slag balancing and desulphurisation
- vacuum degassing
- through-process temperature evolution

for online monitoring, end-point control and calculation of optimal control set-points

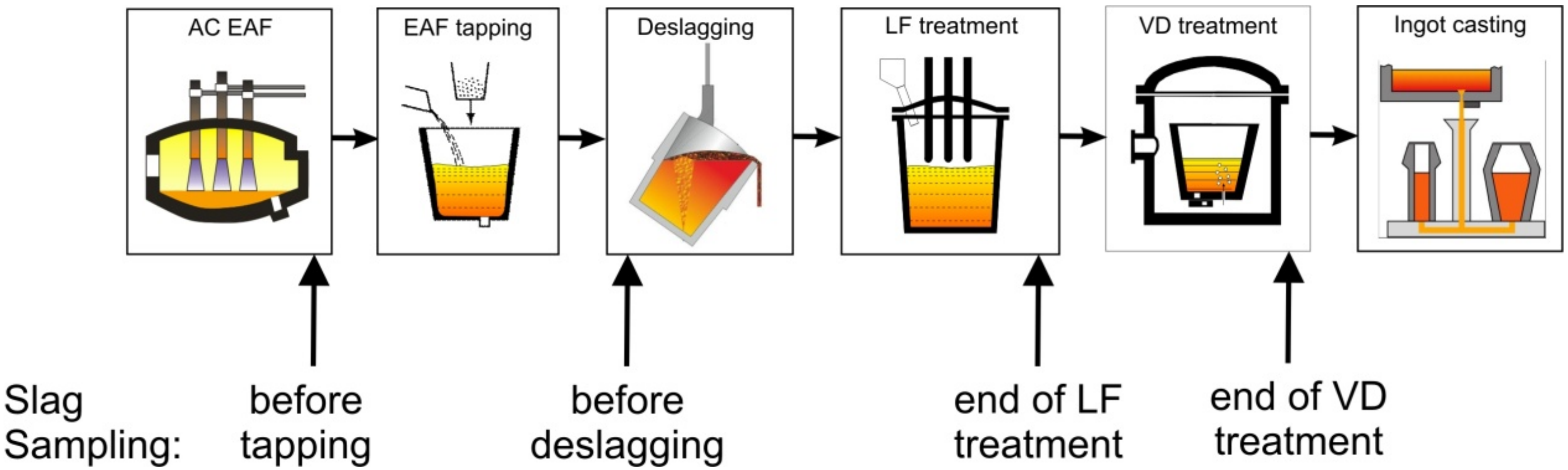


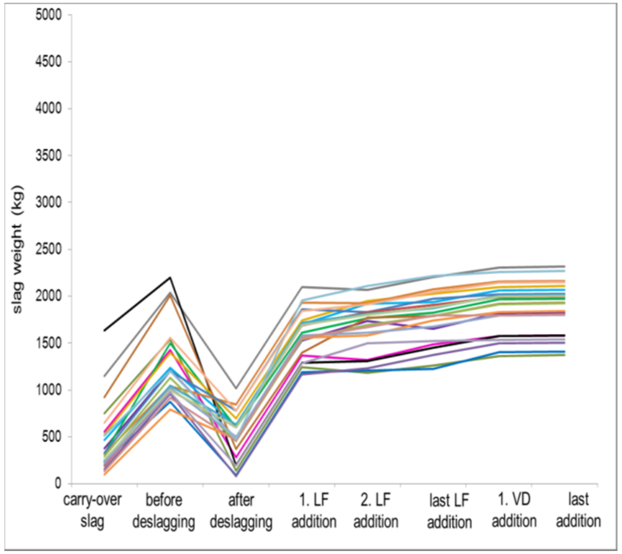
RFCS project OptDeSlag: Ladle slag balance model for optimisation of slag former additions

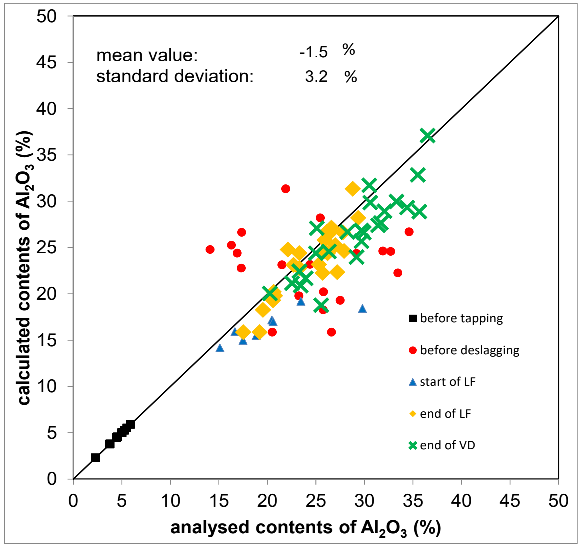


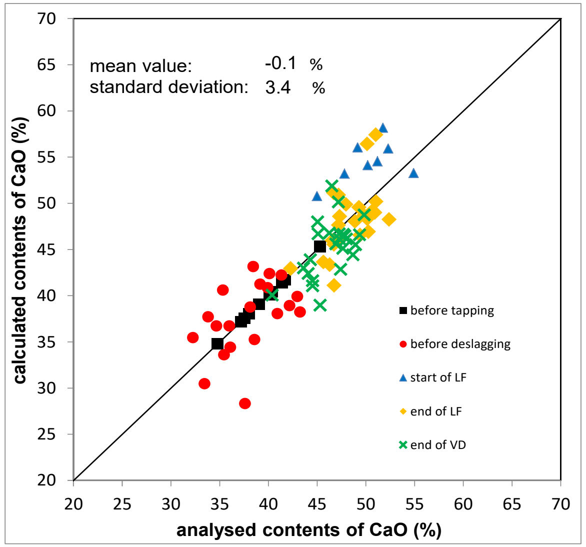
- Model-based balance calculation for on-line monitoring of ladle slag amount and composition
- Determination of amounts of slag former additions for optimal metallurgical operations depending on interaction between steel and slag (desulphurisation, inclusion removal)

RFCS project OptDeSlag: Results of through process slag balance modelling

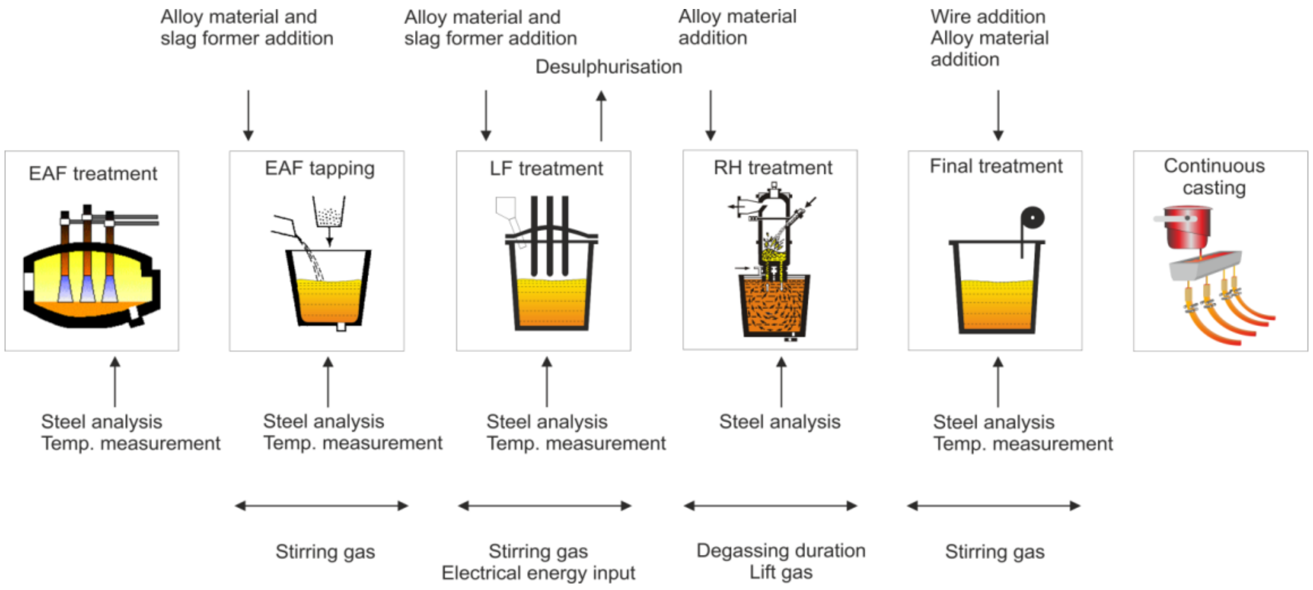








RFCS project IntCleanCon: Through process modelling and prediction of cleanness level



Investigation of two steel grade groups with similar cleanness levels:

- Heat treatable steels

  42CrMo4
  30CrMoV9

- Precipitation hardening steels

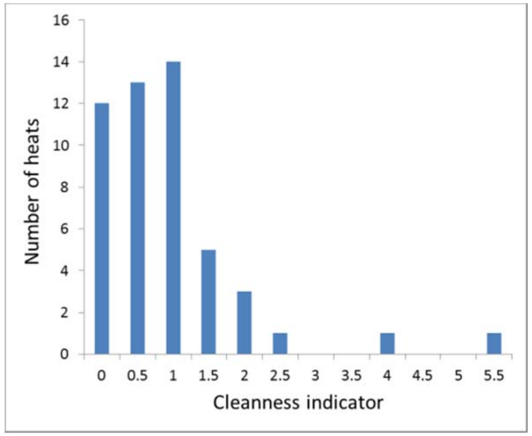
  38MnSiVS6
  44MnSiVS6

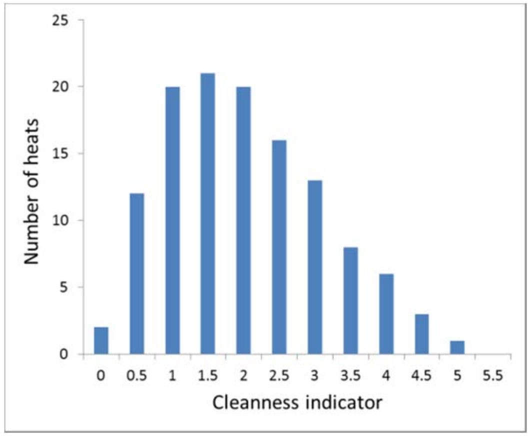
Creation of a through process data base:

- Steel analyses, T measurements and material additions
- Characteristic process parameters regarding stirring, RH degassing and LF electrical heating
- Inclusion density determined by ultrasonic testing of solid strand samples to derive cleanness indicator

RFCS project IntCleanCon: Correlation between process performance of ladle treatment and steel cleanness

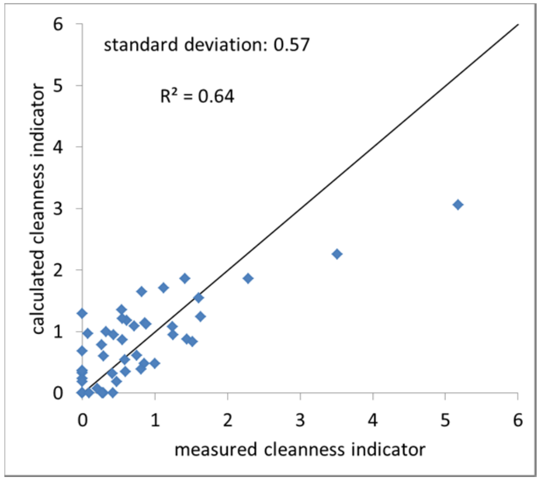
Excellence in Applied Research

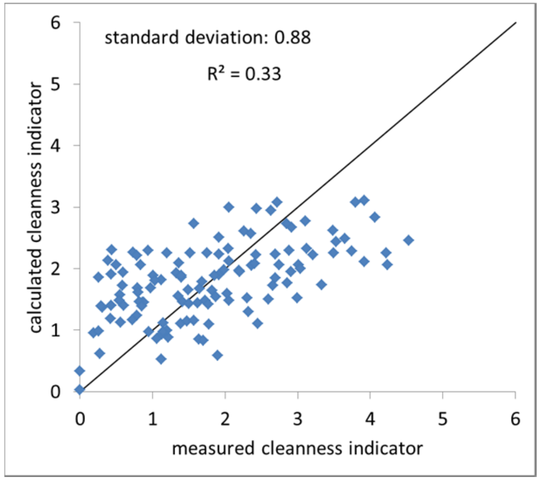




Cleanness indicator Group 1
42CrMo4 and 30CrMoV9

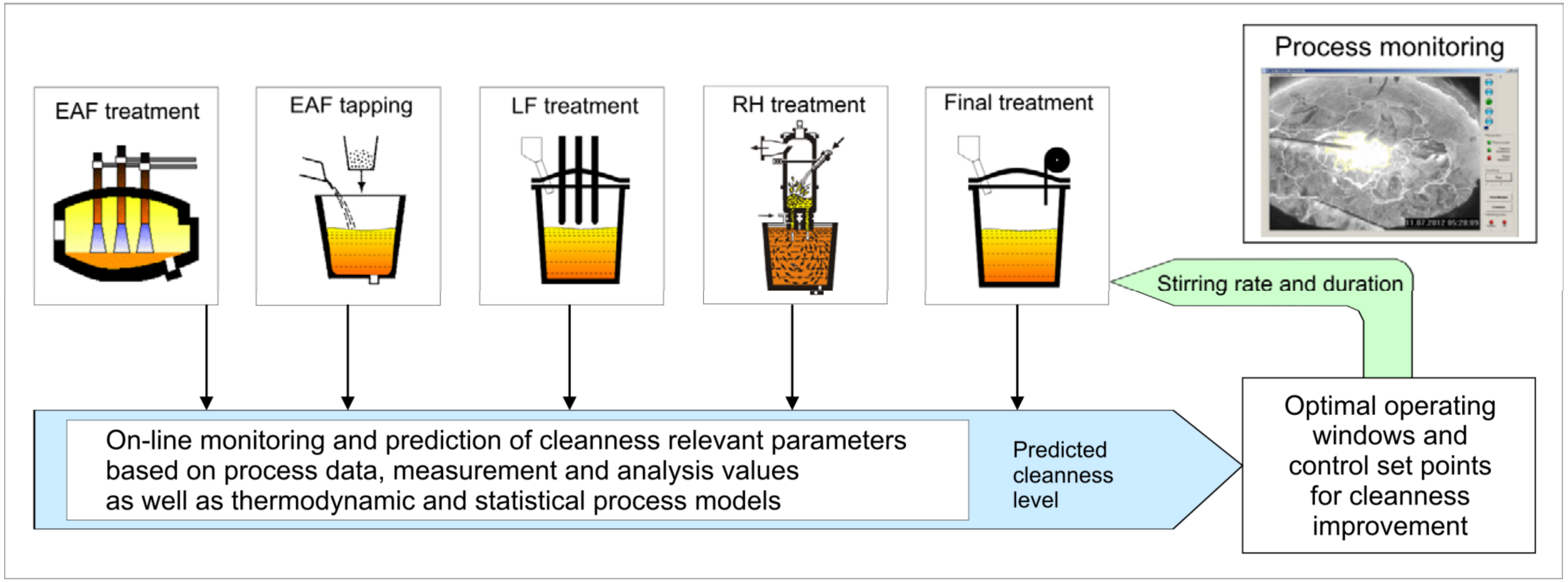
Cleanness indicator Group 2
38MnSiVS6 and 44MnSiVS6

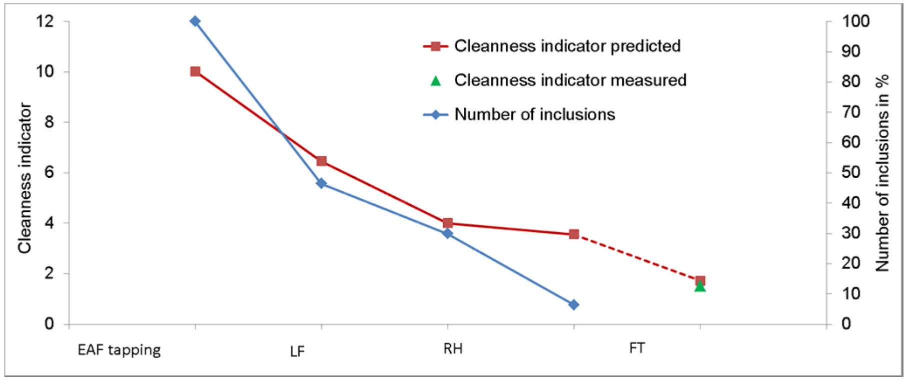




- Multi linear regression to determine the relevant process parameters throughout the process chain of ladle treatment influencing the cleanness level
  - Input of Al, Si, Mn, Cr, Mo, Ca
  - Al, Si and Mn oxide formation
  - Desulphurisation degree
  - LF energy input, T level and treatment duration
  - RH treatment time under different pressure levels
  - LF and FT stirring parameters
- Basis for development of a prediction model for the cleanness indicator

RFCS project „IntCleanCon“: Through process modelling and control of steel cleanness

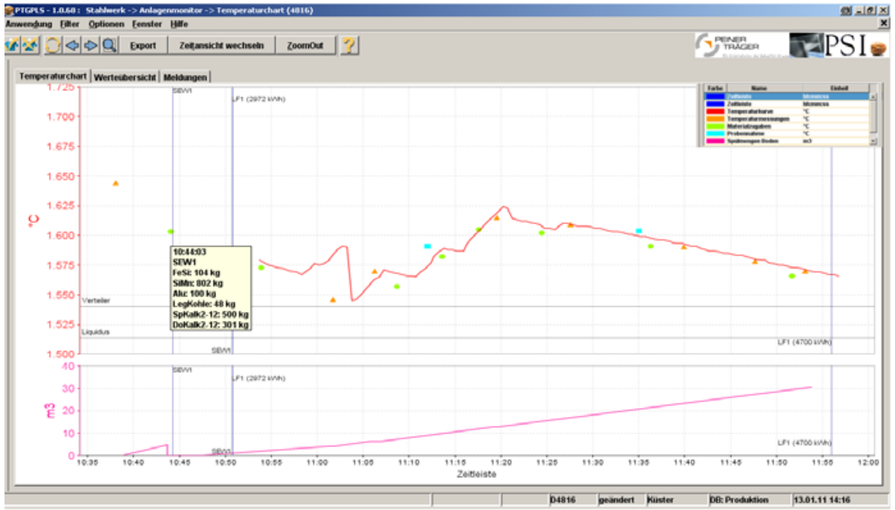


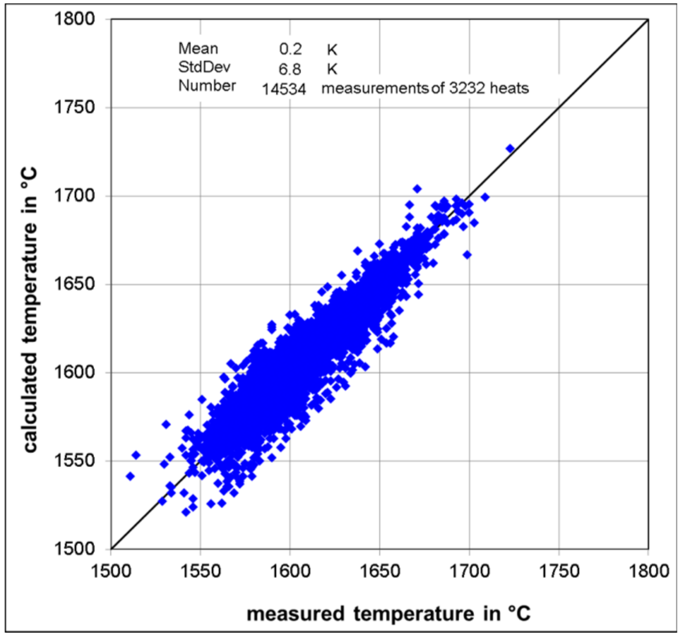


- On-line prediction of evolution of cleanness index based on through-process monitoring of relevant process parameters, with focus on prediction of cleanness indicator before start of final stirring treatment
- Determination of optimal stirring pattern (intensity, duration) based on predicted level of cleanness
- Camera-based monitoring of optimal stirring intensity

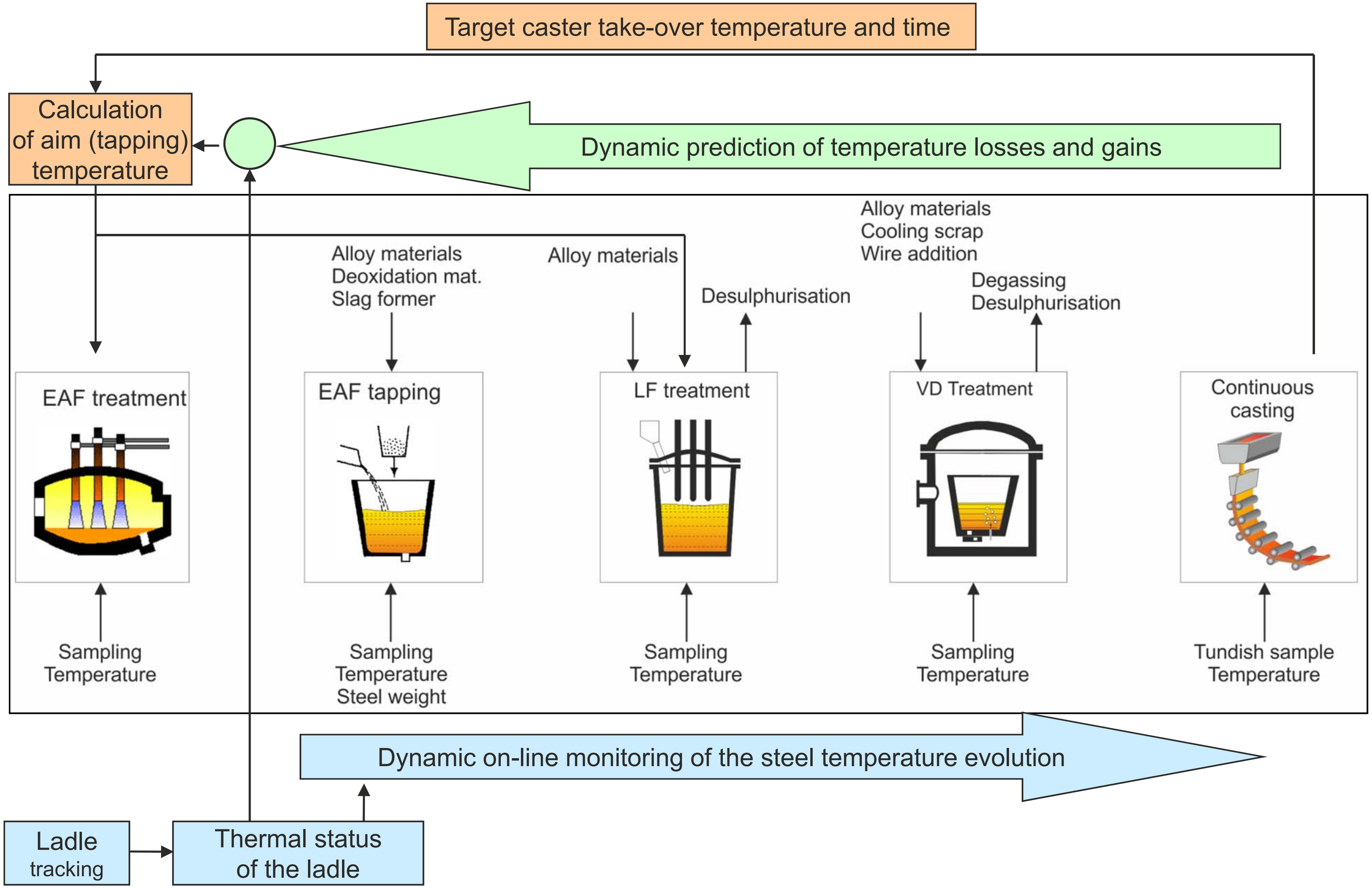
RFCS project PlantTemp: Dynamic modelling of temperature evolution

- The dynamic temperature model considers
  - initial heat state after tapping to be calculated from last steel temperature and analysis in EAF and tapping process with material additions including deoxidation reactions
  - ladle history data (ladle empty time, preheating duration and ladle age) for determination of dynamic temperature loss rate
  - additional temperature losses by inert gas stirring and vacuum treatment
  - cooling effect of alloy material, cooling scrap and slag former additions
  - electrical energy input at LF
  - temperature gain by oxidation reactions

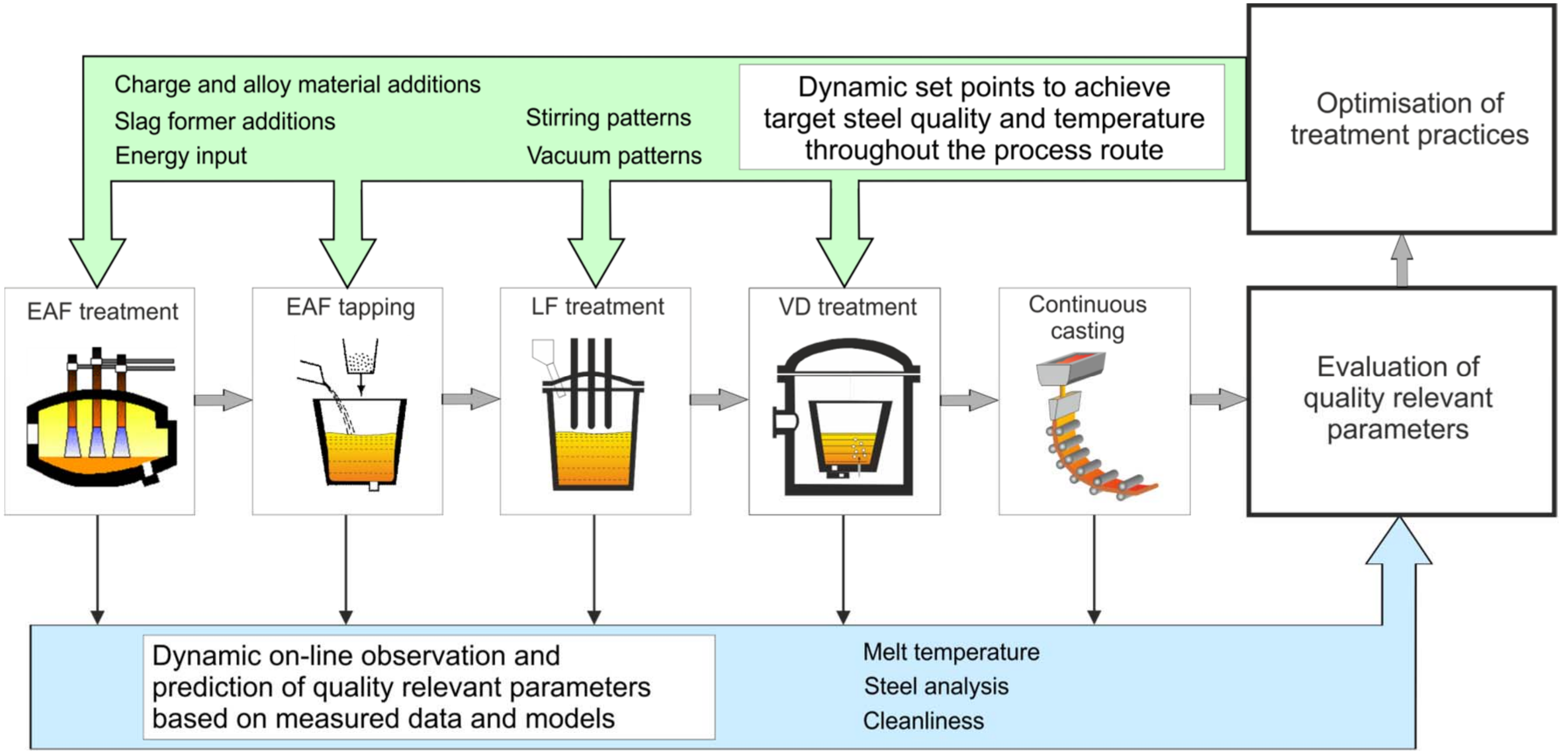




Through-process temperature control for the complete electric steelmaking plant



Through-process temperature and quality control along the electric steelmaking route



› Integration of dynamic process models to monitor and control the heat state evolution throughout the complete process route

› On-line control along the process route by combination of predictive model calculations with optimisation tools for adaption of treatment practices and model-based set-point calculations

↳ Temperature and quality targets can be achieved under minimum material, energy and production costs with maximum productivity

↳ Improved steel quality, less downgrading due to violation of limits for C, N, H or S targets

Thank you very much for your attention !

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