Dynamic on-line monitoring and end-point control of dephosphorisation in the BOF converter process

RFCS Project BOFdePhos

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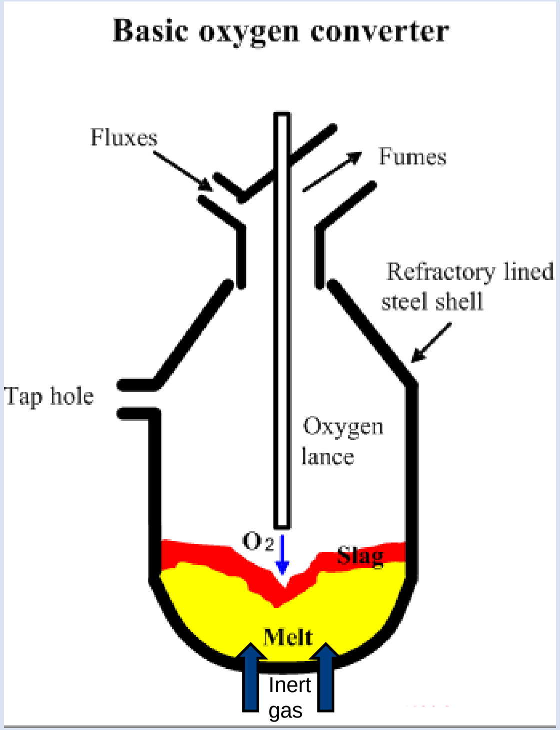
Contents

- Introduction to BOF process
- Objectives of BOFdePhos project
- Main approaches and structure of the project
- Current status of dynamic BOF model of BFI
- Conclusions

Introduction to BOF process (1)

- In Germany roughly 2/3 of the crude steel (ca. 28 Mt/a) are produced via the **blast furnace – BOF converter route**
- In the **BOF process**
  - oxygen is blown via a top-lance into the steel bath (ca. 80% hot metal from blast furnace and 20% scrap)
  - which in many plants additionally is stirred by bottom purging of inert gas (N_2 or Ar)
  - formation of a basic slag on top of the melt is achieved by addition of lime or dolomite
- This is a **highly exothermic**, complex, oxidising-refining process for **removal of hot metal impurities** from iron - especially carbon, silicon and phosphorous - and achievement of an optimal end temperature for further secondary metallurgical treatment of the crude steel



Introduction to BOF process (2)

- An **oxygen supply beyond the demands** for decarburisation and dephosphorisation results in undesired high combustion of iron and manganese and increased oxygen content of steel
  ➯ **losses in metallic yield**
  and increased consumption of deoxidation aluminum
- Process behaviour can be **measured only with interruption** of the oxygen blowing by a sublance or **indirectly**, e.g. via analysis of the off-gas composition
- On-line information on **dephosphorisation** behaviour is not available

➯ Application of complementary **process models** necessary

Main objectives of the BOFdePhos project

Development of a **comprehensive dynamic process model for the BOF**

- which can be used for on-line monitoring and control of the process behaviour
- with focus on dephosphorisation
- taking into account the actual slag conditions and the melt temperature
- based on detailed studies of the thermodynamic and reaction kinetic fundamentals
- application of new sensors measuring the oxygen activity and height of the converter slag
- ➢ determination of the **end-point of the process** with respect to the phosphorus content and the melt temperature with higher accuracy
- application of the model in a predictive mode to calculate **dynamic set-points** for oxygen blowing, slag former and heating or cooling material additions in the final blowing phase
- ➢ achievement of the target values at minimum cost and time with maximum yield

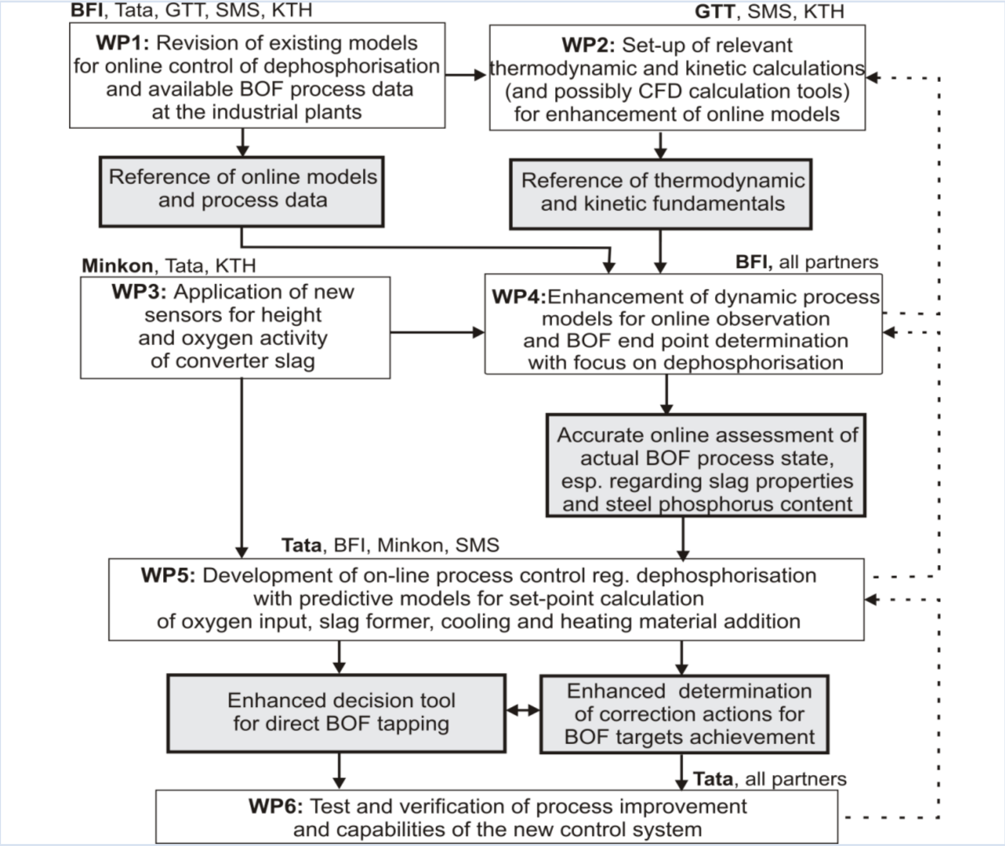
BOFdePhos project partners

- VDEh-Betriebsforschungsinstitut (BFI)
  Private-sector institute for applied research and development in steel technology
- Tata Steel UK (Tata)
  Steelmaking company involved with its BOF plants at Port Talbot and Ijmuiden
- SMS Siemag AG (SMS)
  Supplier for steelmaking and processing plants
- Gesellschaft für Technische Thermochemie und –physik mbH (GTT)
  Supply and consulting with respect to thermochemical databases and related software
- Kungliga Tekniska Hoegskolan (KTH)
  Technical university with wide activities in metallurgical and materials processes
- Minkon GmbH (Minkon)
  Supplier for sampling technology and measuring sensors for metallurgical processes

Main approaches of the BOFdePhos project

- **Enhancement** of existing **dynamic converter models** by
  - fundamental investigations of **thermodynamic equilibrium** conditions for dephosphorisation in BOF based on appropriately extended thermodynamic database using ChemApp or FactSage
  - investigations including laboratory experiments with respect to **lime dissolution**
  - CFD simulations of mass flows determining the **reaction kinetics**
  - parameter studies with enhanced dynamic BOF flow-sheet model coupled to new thermodynamic database and incorporating calculated mass flows between relevant reaction zones
  - trials with special **sublance probes** for determination of the **slag oxygen content**
- Development of **model based dynamic control strategies** for precise determination and optimal adjustment of the process end-point regarding phosphorus content and melt temperature in order to achieve direct tapping after sublance measurement without waiting for steel probe analysis

Structure of the BOFdePhos work programme



Basic principles of dynamic process models

Dynamic process models are

- based on energy and mass balances
- using thermodynamic equilibrium states and reaction kinetic equations
- solved cyclically along the time axis
- taking into account the respective cyclic process input data (like process gas flow rates) as well as acyclic events (e.g. material additions)
- optionally complemented by balances based on off-gas analyses, e.g. regarding decarburisation

Applications of dynamic process models

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 systematically varied operating conditions

On-line applications

- Monitoring of evolution of the current heat state
- Prediction of the further heat state evolution, e.g. for end-point determination
- Calculation of set-points for an optimised process control

On-line installations of thermodynamic BFI converter models

1. AOD model

- TKN Krefeld (2006)

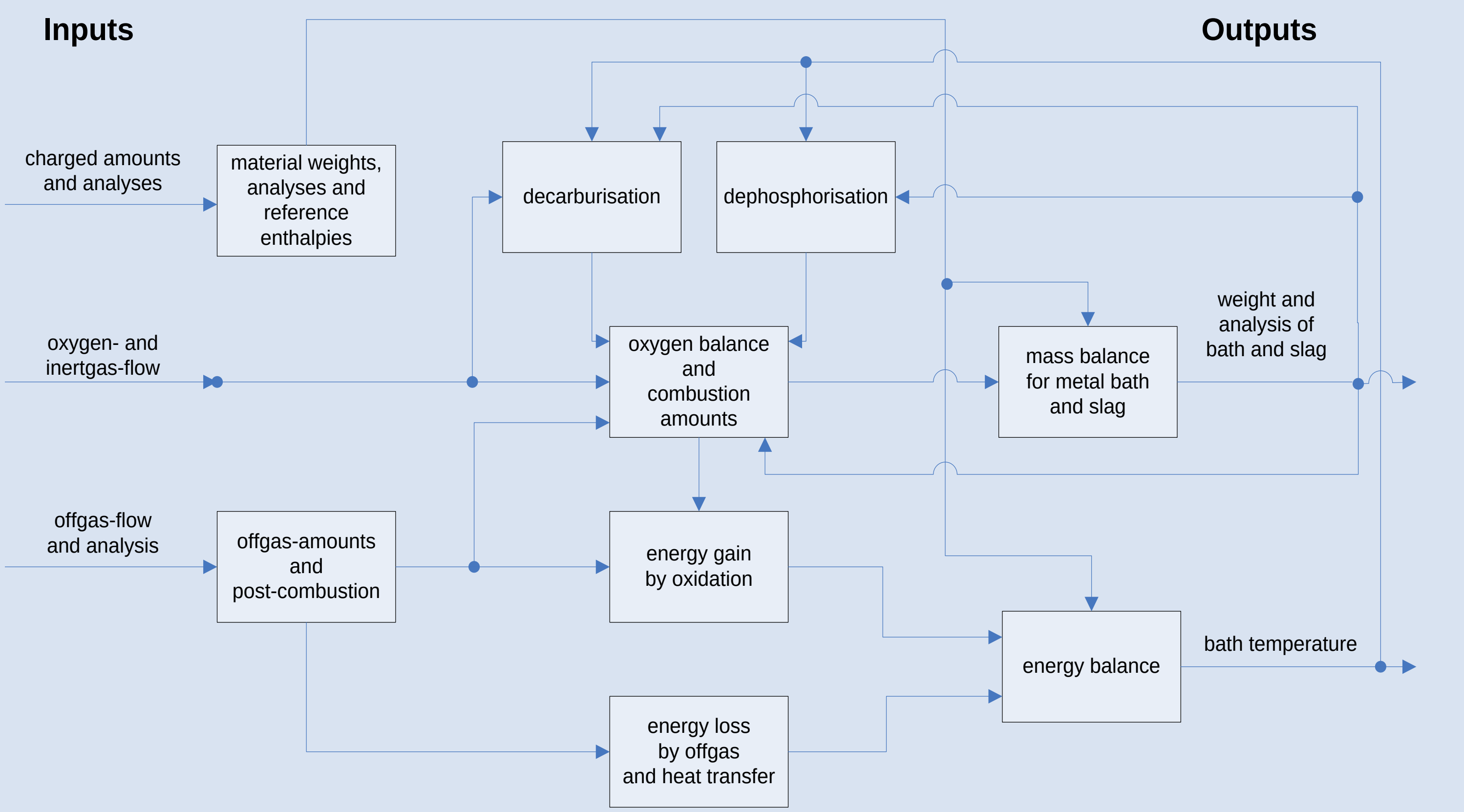
2. VOD model

- Acroni, Jesenice/Slowenien (2009)
- Dörrenberg Edelstahl (2011)
- DEW Siegen (2014)

3. BOF model

- Saarstahl (2009)
- HKM (2012)

Structure of dynamic BFI BOF model



Thermal model for BOF process

Cyclic energy balance

+ **Current** energy content

- initial energy content
- enthalpies of oxidation reactions
  (decarburisation with CO post combustion, dephosphorisation,
  slagging of metallic elements – Al, Si, Mn, Ti, Cr, Fe)
- energy losses by off-gas, iron dust, converter walls & radiation

– **Reference** energy content of charged materials

- hot metal
- scraps
- slag formers
- cooling/heating agents

⇒ **Bath temperature**

Metallurgical model for BOF: basic principle

Cyclic mass balance

+ Input by **charged materials**

- hot metal
- scraps
- slag formers
- cooling/heating agents

– **Combustion reactions** (modelled by dynamic oxygen balance)

- decarburisation → ΔC
- dephosphorisation → ΔP
- slagging of metallic elements
  → ΔAl, ΔSi, ΔMn, ΔTi, ΔCr, ΔFe

⇒ **Composition & weight of steel and slag**

Metallurgical model for BOF: oxygen balance

Effective oxygen input (within a time interval)

- via the top lance
- by reduction of oxidic additions (e.g. from iron ore)

is **distributed with dynamically calculated fractions** to

- decarburisation and dephosphorisation
- post-combustion of CO
- nearly complete combustion of the oxygen affine metallic elements (Al and Si)
- combustion of other non-iron metallic elements (e.g. Mn, Ti, Cr)
- combustion of iron (with distinction between cases of soft and hard blowing, taking into account fixed ratio of bivalent and trivalent iron in the slag)
- increase of oxygen activity of the steel bath

Metallurgical model for BOF: decarburisation (1)

Thermodynamic equilibrium contents **$[C_Q]$ & $[O_Q]$**

- with reactions

$$1/2\{O_2\} = [O]$$

$$[C] + [O] = \{CO\}$$

$$[Fe] + [O] = (FeO)$$

$$(FeO) + [C] = [Fe] + \{CO\}$$

- law of mass action regarding carbon steel grades

⇒ depending on

  - temperature
  - iron oxide activity
  - partial pressure of CO gas

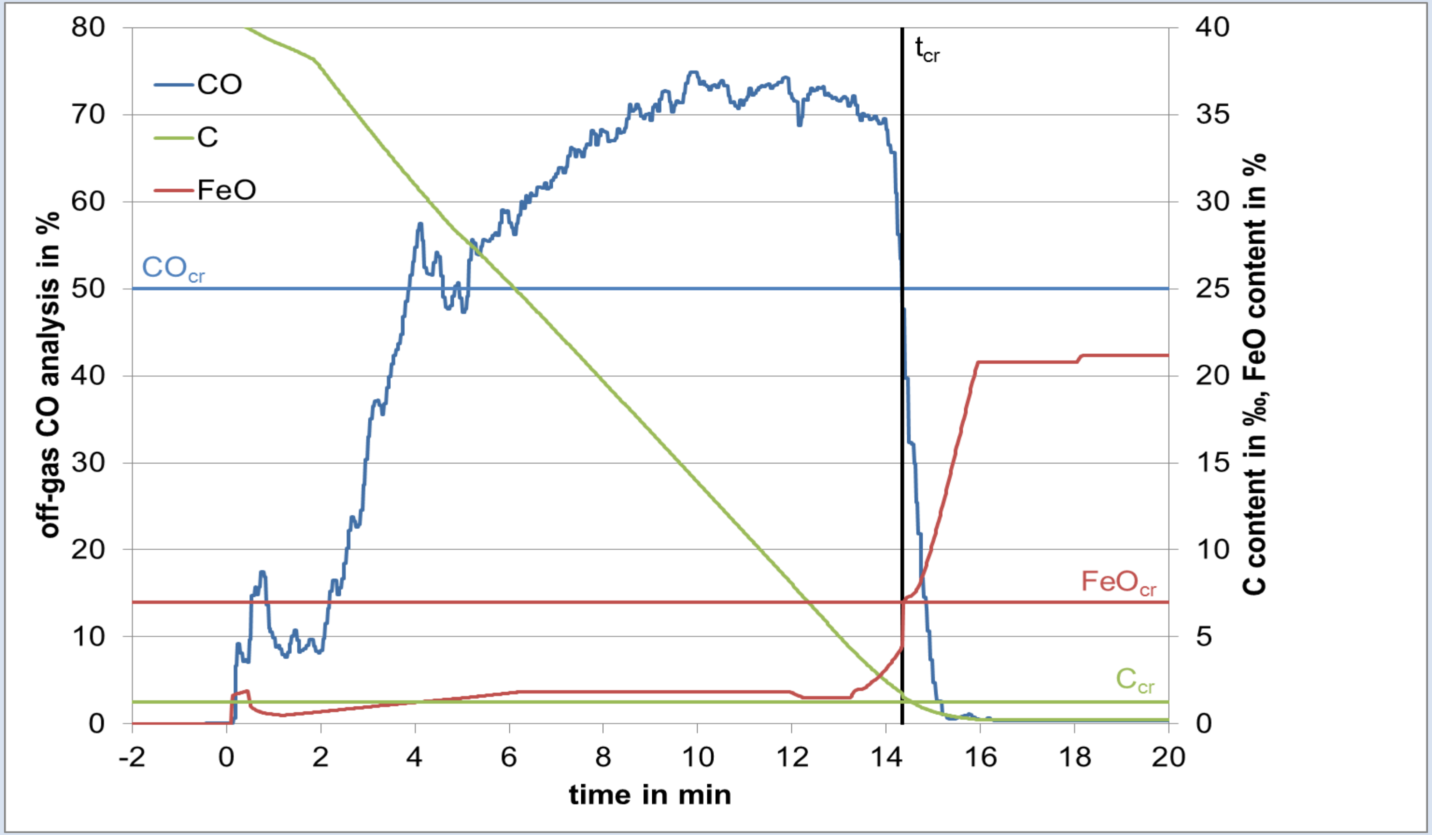
Metallurgical model for BOF: decarburisation (2)

- **ΔC-rate limited by**
  - O_2-flow rate (0th order reaction kinetics)
  - diffusive and convective transport (1st order reaction kinetics)

$$\frac{d[C]}{dt} = -\frac{1}{T_c}([C]\text{-}\ [C_Q])$$

- **Correction** of transition 0th → 1st order by
  - off-gas analysis with drop of CO content at ‘critical point’

Off-gas based model correction at critical point



Metallurgical model for BOF: dephosphorisation (1)

Thermodynamic equilibrium partition L_P of P between slag and steel

- with reaction

  $[P] + 5/2[O] + 3/2(O^{2-}) = (PO_4^{3-})$

- law of mass action regarding lime saturated slag conditions
- plant trials with (P_2O_5) contents up to 2.6 %

$$\Rightarrow \log L_P = \log \frac{(P_Q)}{[P_Q]} = -11.8 + \frac{23306}{T} + 2.5 \cdot \log(Fe) + \left(0.06404 - \frac{267.8}{T}\right) \cdot (Fe) - \left(0.0005347 - \frac{1.959}{T}\right) \cdot (Fe)^2 + \left(16.09 - \frac{32941}{T}\right) \cdot [Mn]$$

$$\Rightarrow [P_Q] = \frac{[P_0] \cdot m_{B0} + 100 \cdot m_P}{m_B + L_P \cdot m_S}$$

Metallurgical model for BOF: dephosphorisation (2)

- **Deviation from lime saturation** by

$$D(CaO) = 68.1 - 0.3328\,(FeO)' - 0.0024\,(FeO)'^2 - (CaO)' > 0$$

$$\Rightarrow [P_Q] \rightarrow [P_Q] + a_S + b_S \cdot D(CaO)$$

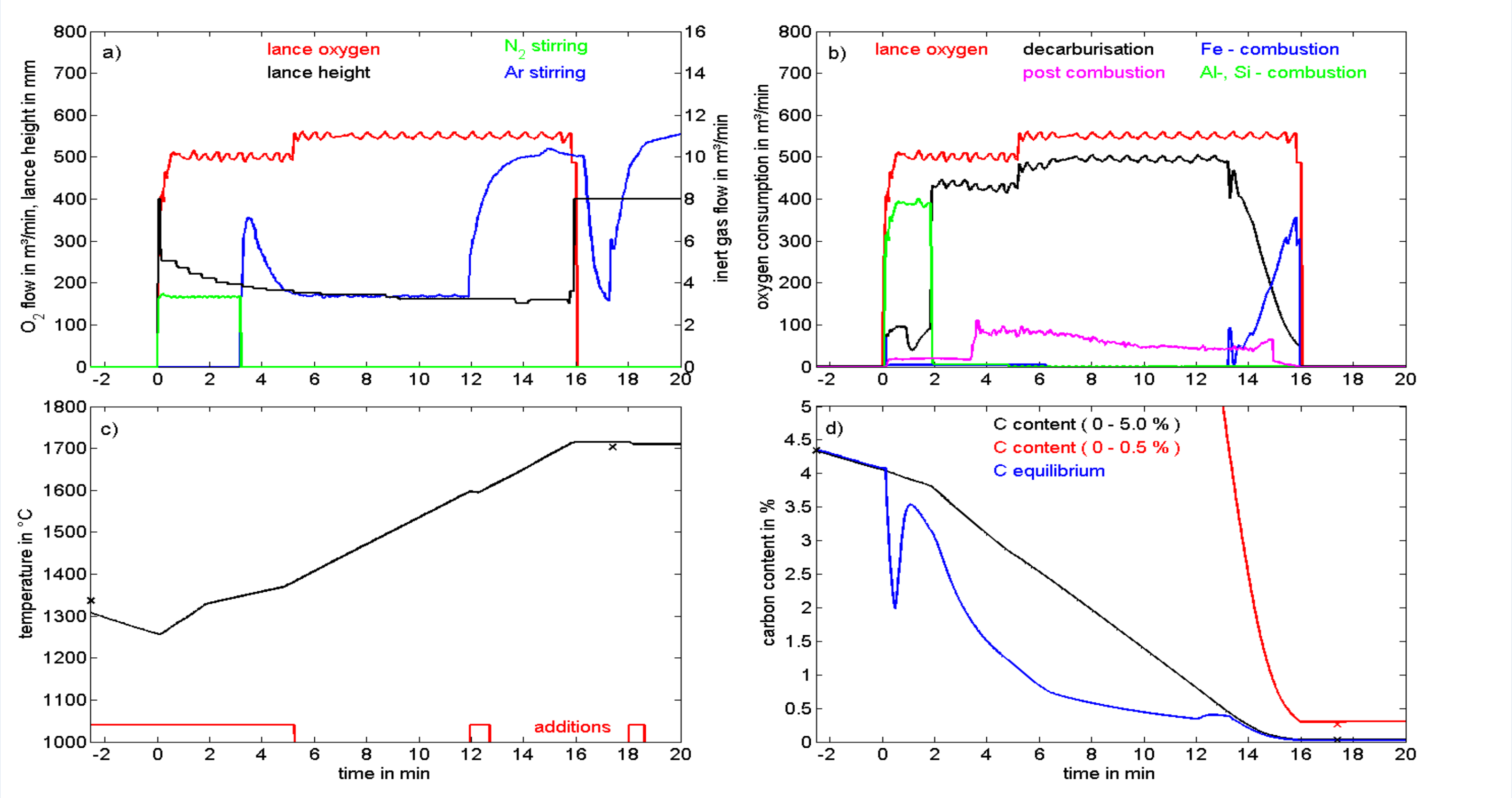
with model parameters a_S, b_S, which have to be adapted to the slag operation practice of the respective BOF process

- **ΔP-rate limited by**
  - diffusive and convective transport (1st order reaction kinetics)

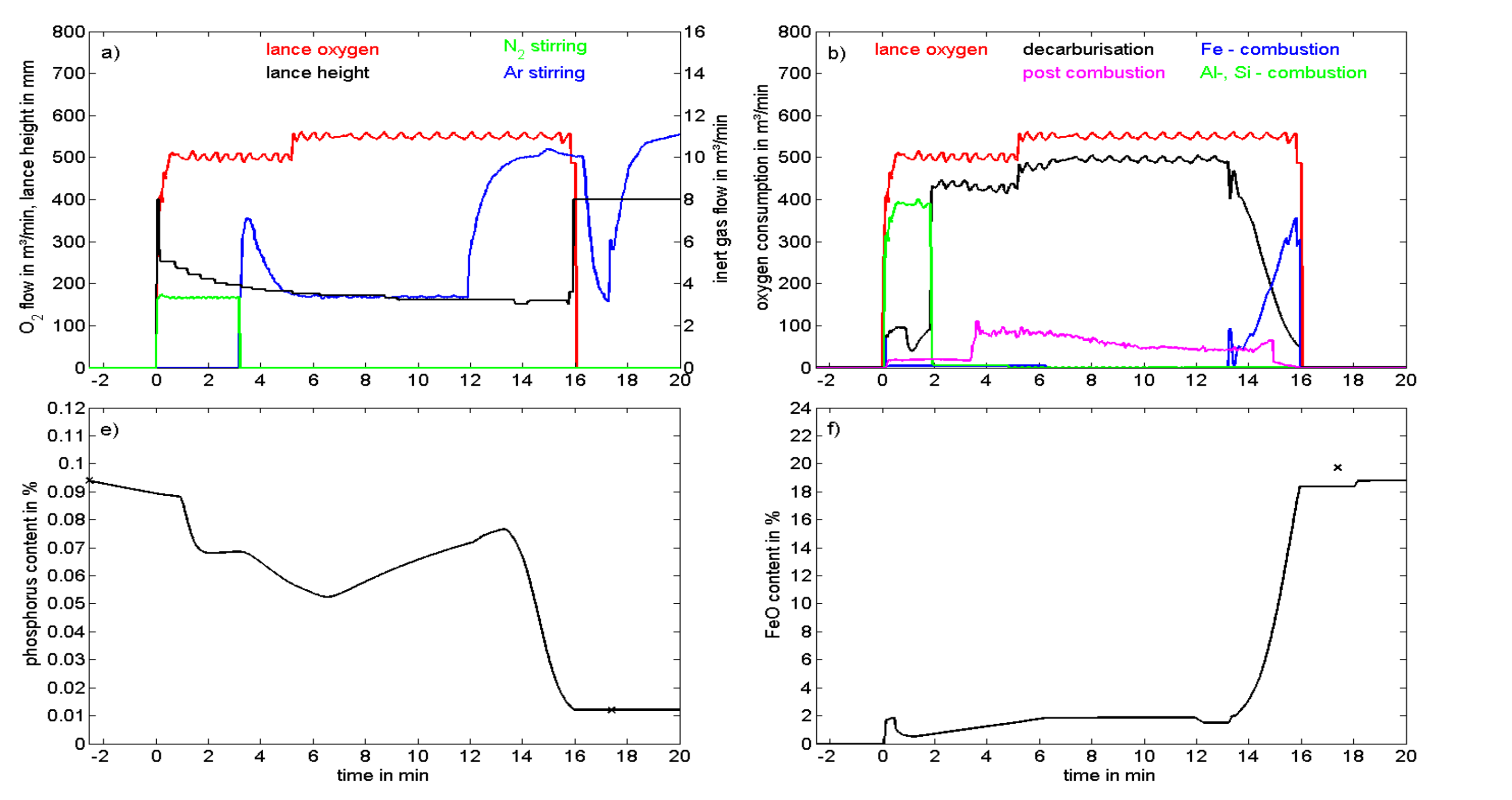
$$\frac{d[P]}{dt} = -\frac{1}{T_P(QI)}([P] - [P_Q])$$

  - where time parameter T_P decreases with increasing inert gas flow rate Q_I

Heat state evolution for BOF example heat (1)

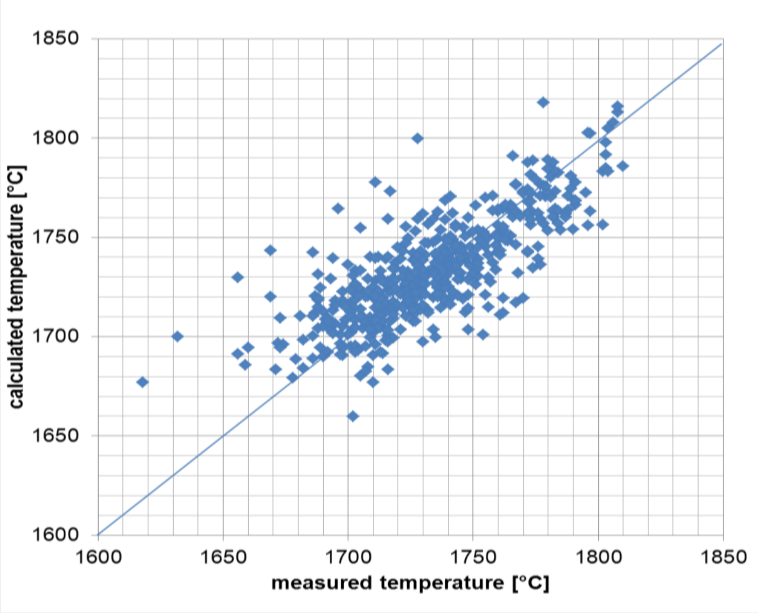


Heat state evolution for BOF example heat (2)



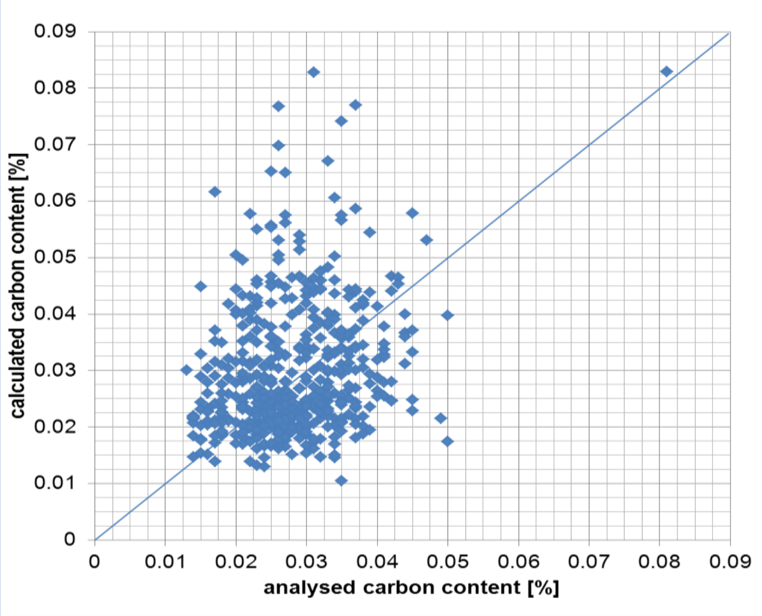
BOF model accuracies: temperature and carbon

Temperature



Number of Heats: 508
Mean Value: 0.3 K
Standard Deviation: 19.5 K

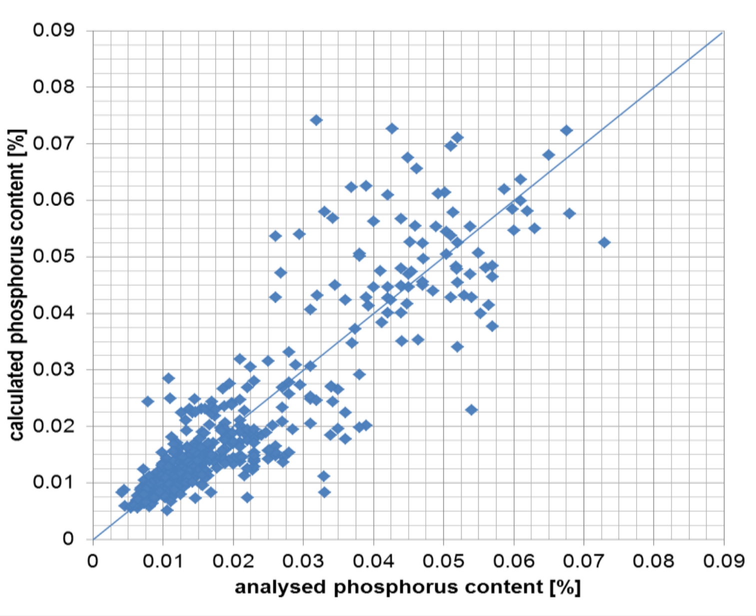
Carbon content



Number of Heats: 508
Mean Value: 18 ppm
Standard Deviation: 128 ppm

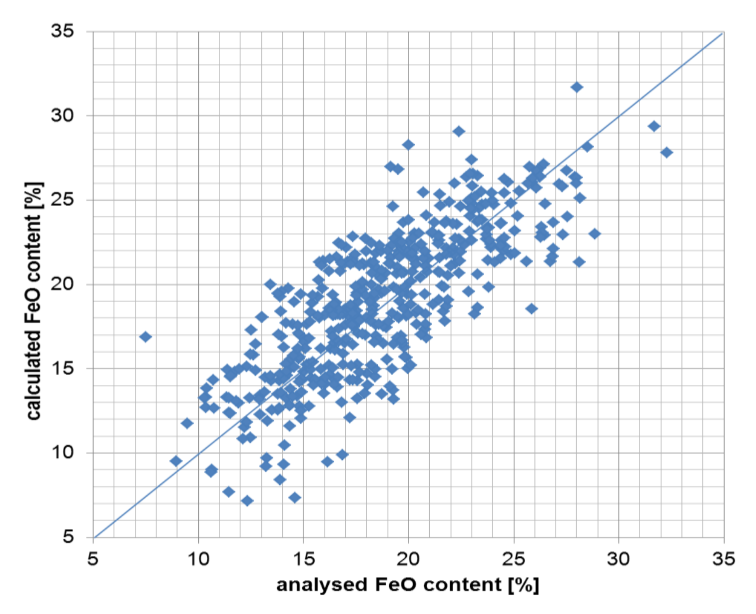
BOF model accuracies: phosphorus and iron oxide

Phosphorus content



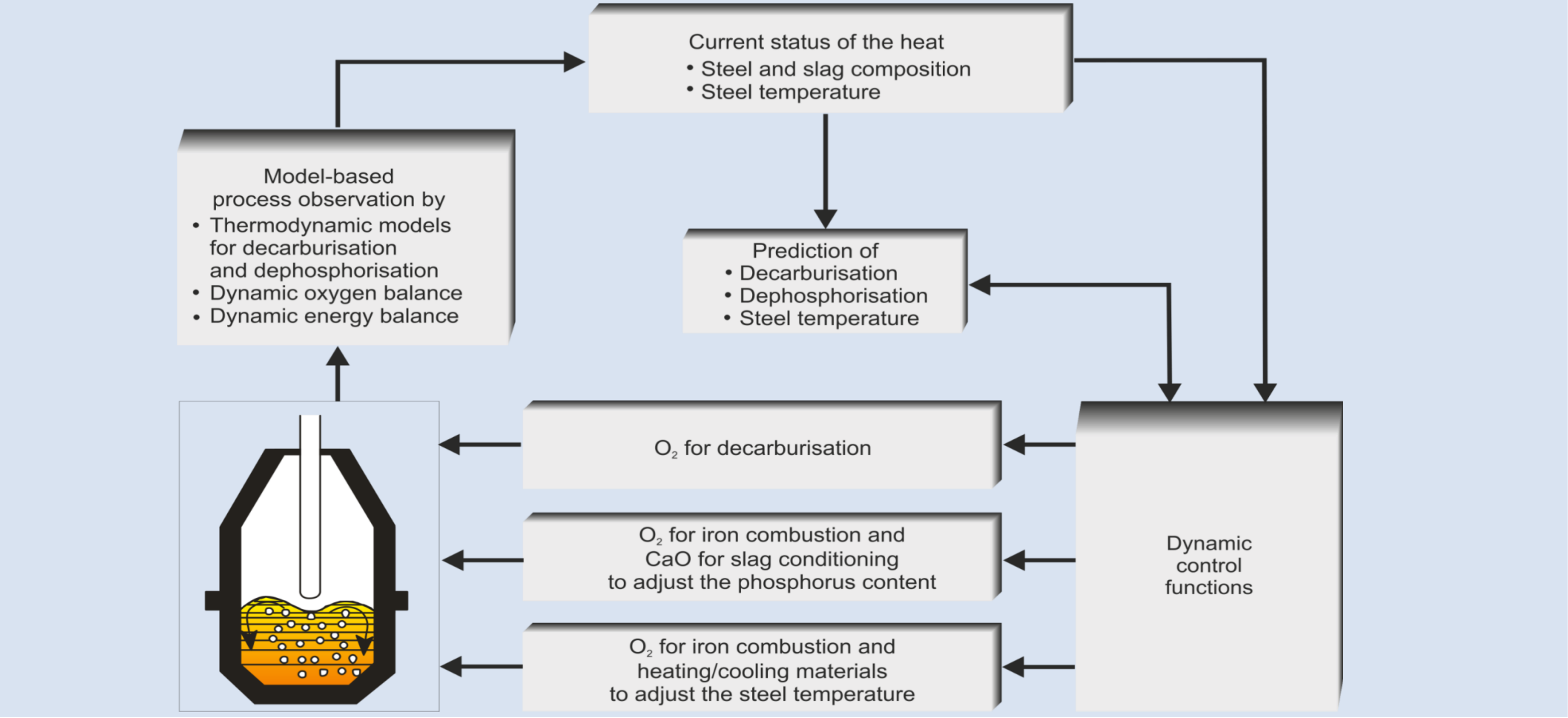
Number of Heats: 508
Mean Value: -3 ppm
Standard Deviation: 69 ppm

Slag FeO content



Number of Heats: 486
Mean Value: 0.31 %
Standard Deviation: 2.76 %

Comprehensive optimised BOF process control



Conclusions

Dynamic BOF process model of BFI

- is based on cyclically solved thermodynamic and reaction kinetic equations
- **monitors** the current heat state
- **predicts** its further evolution, e.g. for end-point control and calculation of **optimal set-points** regarding oxygen blowing, lime addition, addition of heating or cooling materials
- shall be improved regarding modelling of dephosphorisation (equilibrium P-partition, process kinetics, lime dissolution) within **BOFdePhos** research project