Development of a Comprehensive Model for Oxygen Steelmaking

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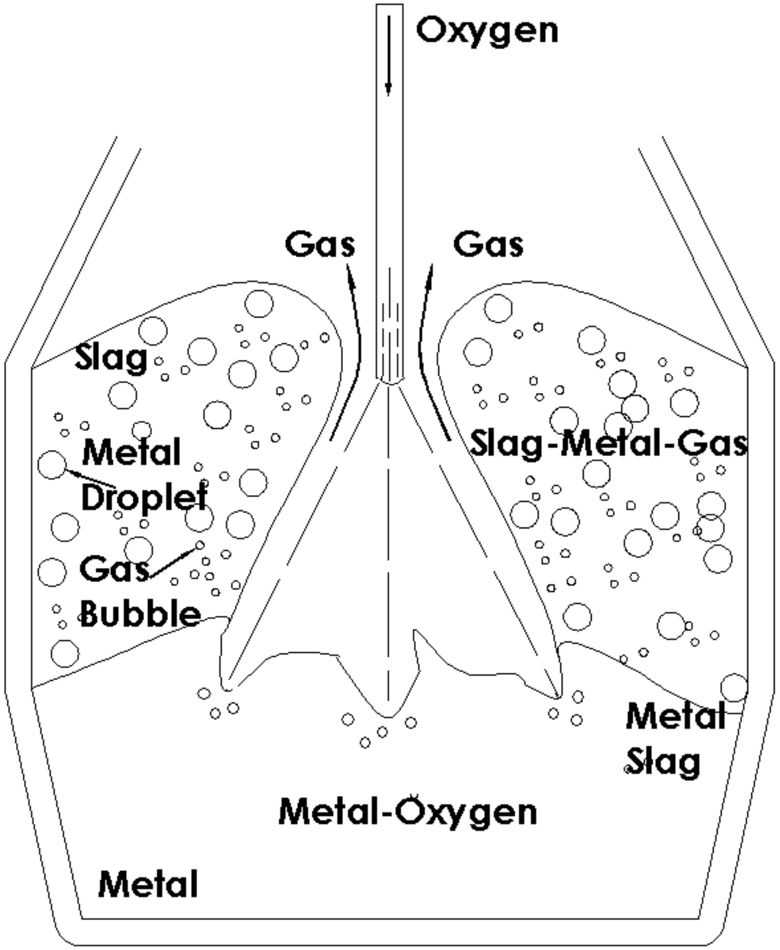
Presentation Outline

- Introduction
- Model Development of Oxygen Steelmaking
    1. Decarburization Kinetics in Bath Zone
    2. Decarburization Kinetics in Emulsion Zone
- Results
- Conclusion

Oxygen steelmaking process



Hot Zone

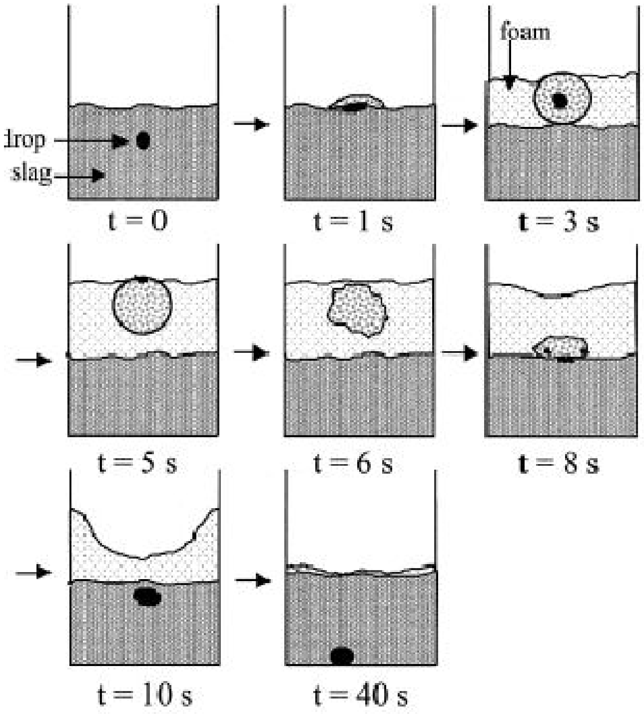
$O_2(g) = 2\underline{O}$

$\underline{O} + \underline{C} = CO(g)$

Emulsion

$(FeO) + \underline{C} = Fe + CO(g)$

“Bloated” droplet theory

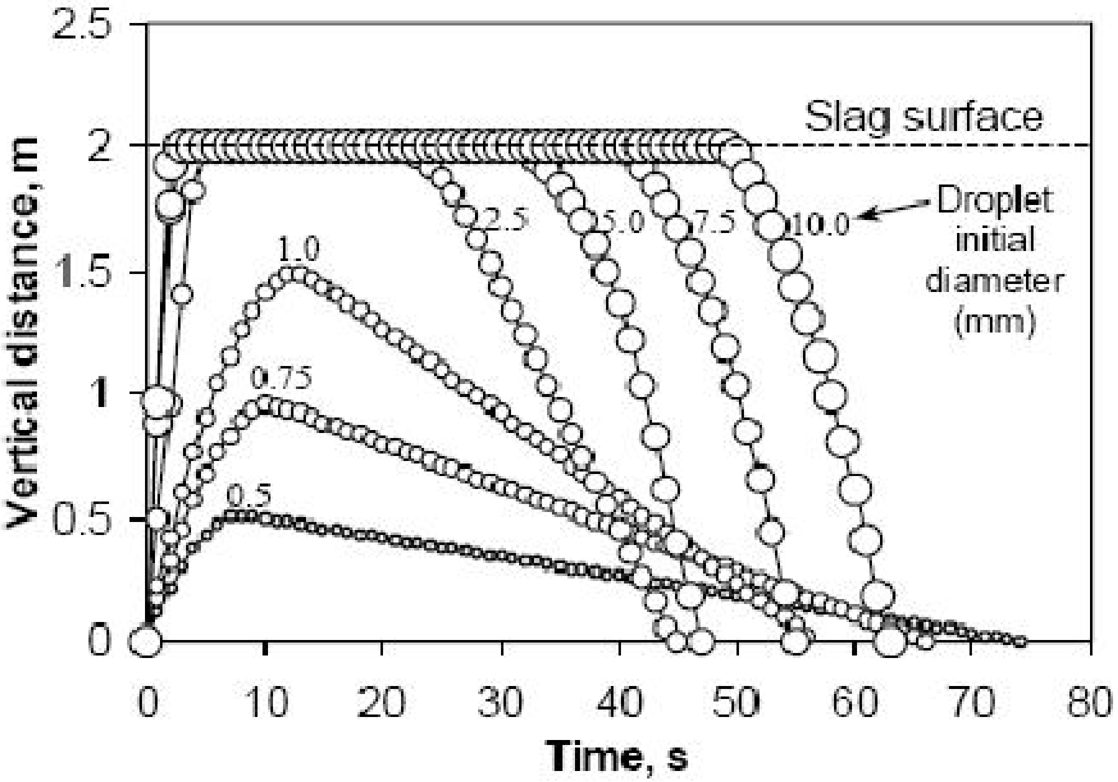


$$(\mathrm{FeO}) + \underline{\mathrm{C}} = \mathrm{Fe} + \mathrm{CO(g)}$$

X-ray fluoroscopy of an Fe-C drop in a slag

Molloseau and Fruehan, Met. Matl. Trans. B, 2002

Residence time of droplets



(i) dense droplets

(ii) bloated droplets

Brooks, Pan, Subagyo and Coley, Met. Matl. Trans. B, 2005

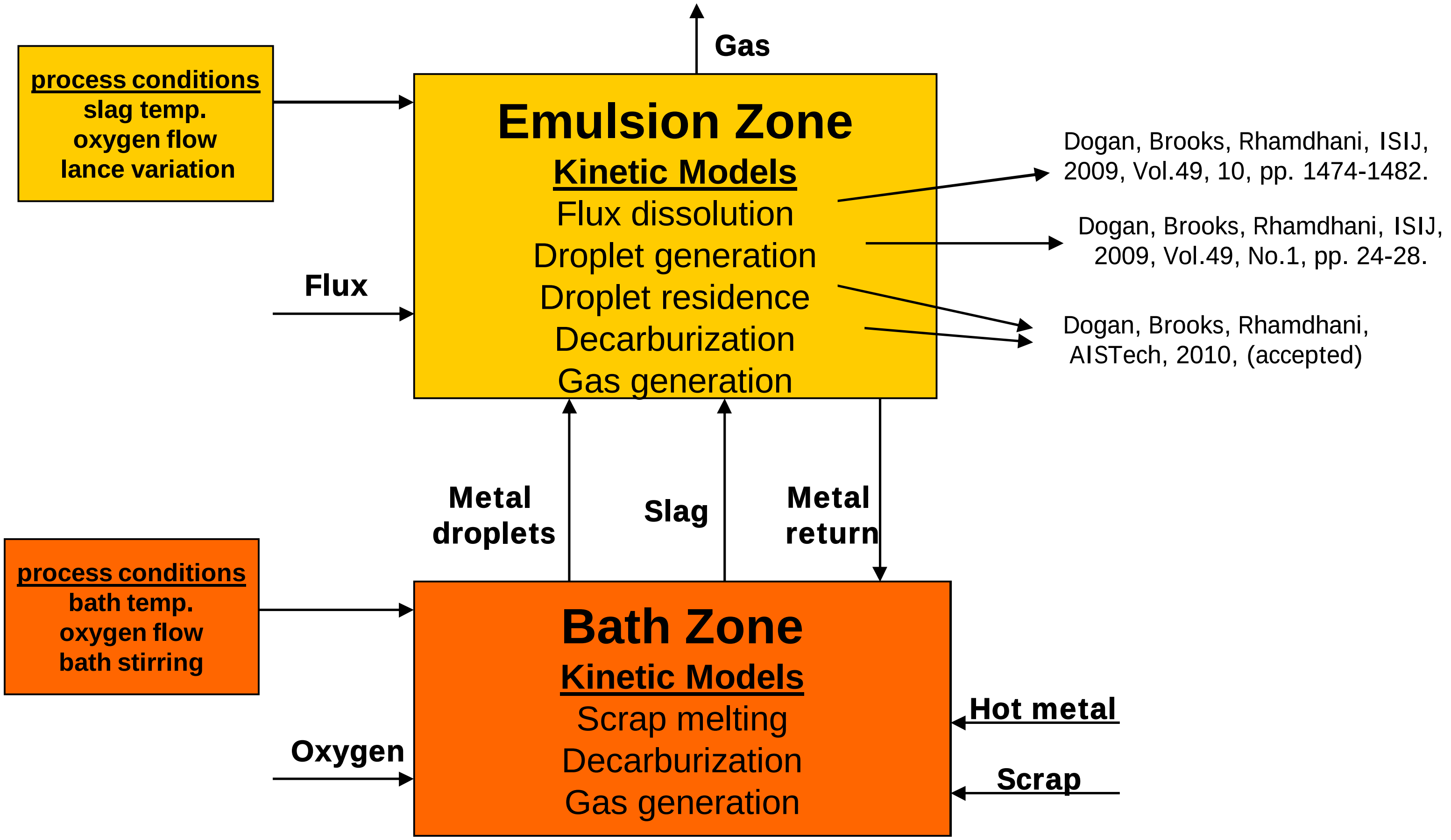
Aims of the project

1. Development of mathematical models of oxygen steelmaking coupled with bloated droplet theory

2. Validation of the results of the model against data from industrial systems

3. Evaluation of the repercussions of the model on the operation of oxygen steelmaking

Conceptual model



process conditions
slag temp.
oxygen flow
lance variation

Flux

Gas

Emulsion Zone

Kinetic Models
Flux dissolution
Droplet generation
Droplet residence
Decarburization
Gas generation

Dogan, Brooks, Rhamdhani, ISIJ, 2009, Vol.49, 10, pp. 1474-1482.

Dogan, Brooks, Rhamdhani, ISIJ, 2009, Vol.49, No.1, pp. 24-28.

Dogan, Brooks, Rhamdhani, AISTech, 2010, (accepted)

Metal droplets

Slag

Metal return

process conditions
bath temp.
oxygen flow
bath stirring

Oxygen

Bath Zone

Kinetic Models
Scrap melting
Decarburization
Gas generation

Hot metal

Scrap

1. Decarburization in bath zone

$$[\mathrm{C}] + 1/2\mathrm{O}_{2(g)} = \mathrm{CO}_{(g)}$$

$$[\mathrm{C}] + \mathrm{CO}_{2(g)} = 2\mathrm{CO}_{(g)}$$

at high carbon concentrations:

$$\frac{-dC}{dt} = \frac{1200A}{\rho V}\left(\frac{k_g^0 k_r}{k_g^0 + k_r}\right) P_{CO_2}^b \qquad \frac{-dC}{dt} = \frac{2400A}{\rho V} k_g \ln\left(1 + P_{O_2}^b\right)$$

at low carbon concentrations:

$$\frac{dC}{dt} = k_m \frac{A}{V}\left(C_b - C_{eq}\right)$$

Sain & Belton, Met Trans,B 1976
Mannion and Fruehan, Met Trans B. 1989

Model assumptions

- Interfacial area is assumed to the summation of individual impact areas.
- Mass transfer in gas boundary layer

$$\mathrm{Sh} = 0.026\,\mathrm{Re}^{1.06}\,\mathrm{Sc}^{0.53}\left(\frac{\mathrm{h}}{\mathrm{d}_{\mathrm{t}}}\right)^{-0.09}$$

- Reaction rate constant

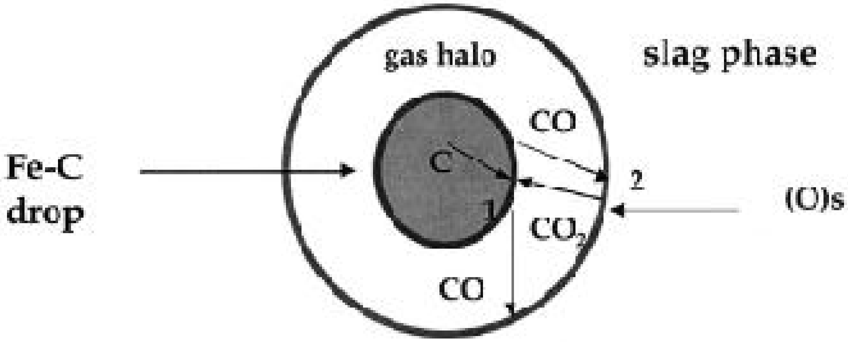
$$k_t = \frac{k_f}{1 + K_s \gamma_s (mass\%S)} + k_r$$

- Mass transfer correlation for low carbon concentrations:

$$k_m = \beta\left(\frac{D_C \cdot V_G}{A}\right)^{1/2}$$

F. Oeters, “Metallurgy of Steelmaking” 1994
Sain & Belton, Met Trans,B 1976, Mannion and Fruehan, Met Trans B. 1989

2. Decarburization in emulsion



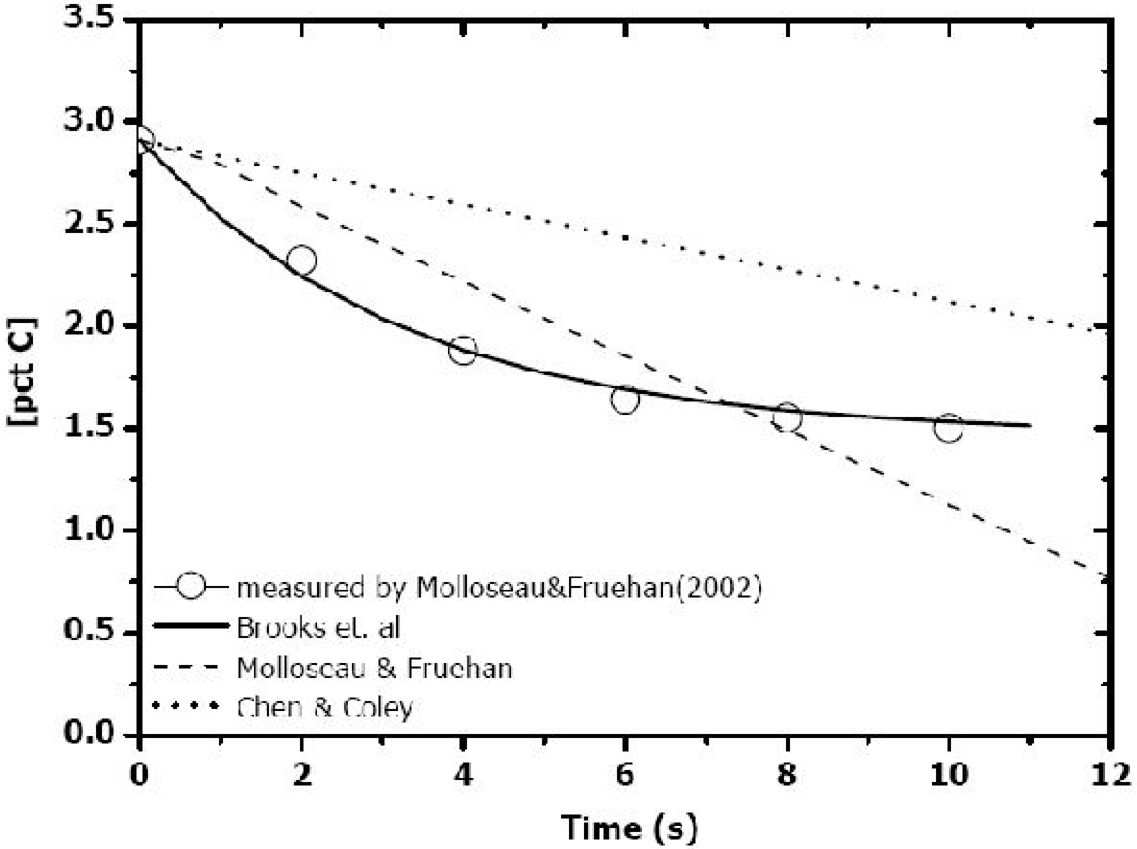
$$CO_{(g)} + (FeO) = Fe + CO_{2(g)}$$

$$CO_{2(g)} + [C] = 2CO_{(g)}$$

$$(FeO) + [C] = Fe + CO_{(g)}$$

Studies	Rate Equation	Reaction Mechanism
Molloseau & Fruehan (2002)	$\text{Rate}\left(\frac{\text{moles}}{\text{s}}\right) = \frac{k_s A \rho_s}{100 mw_{FeO}} (\text{mass\%FeO})$	mass transfer of FeO through slag phase
Brooks et al. (2005)	$\text{Rate}\left(\frac{\text{mass\%}}{\text{s}}\right) = k_{eff} \frac{A_{app}}{V_{app}} (C_b - C_{eq})$	mass transfer of carbon through metal phase
Chen & Coley (2009)	$\text{Rate}\left(\frac{\text{moles}}{\text{s}}\right) = J_s \frac{n_e}{N_A} (V_0)$	chemical reaction of C and O in the metal droplet

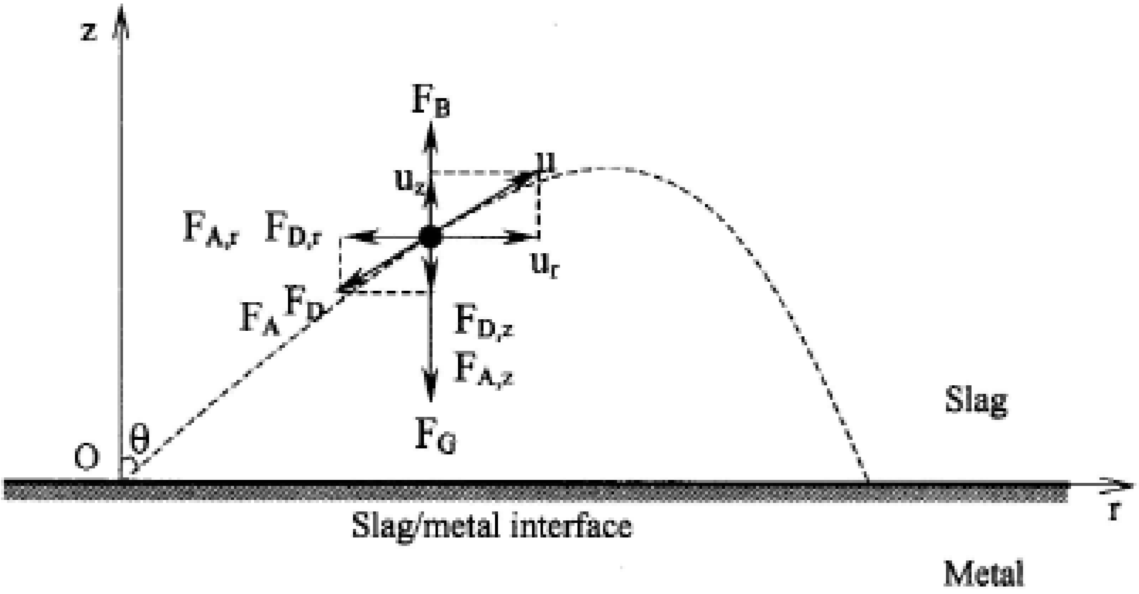
Comparison of kinetic models



Molloseau and Fruehan, Met. Matl. Trans. B, 2002

Droplet Residence Model

Based on the force balance affecting droplet motion



Brooks, Pan, Subagyo, Coley, Met. and Matl. Trans. B, 2005

Kinetic equation

$$r_c = -\frac{d[\%C]}{dt} = k_{eff}\frac{A_{app}}{V_{app}}\left([\%C]-[\%C]_e\right)$$

Notations:

k_{eff}: effective rate constant
D_c: effective diffusivity of carbon in liquid iron
$D_{d,app}$: apparent diameter of droplet
u_d: overall velocity of droplet

Higbie Penetration Theory for Mass Transfer:

$$k_{eff} = 2\sqrt{D_c u_d/(\pi D_{d,app})}$$

$$M_e\frac{dC}{dt} = \frac{\sum_{i=1}^{n}\frac{m_i}{100}\left(C_i^{t+\Delta t} - C_i^{t}\right)}{\Delta t}$$

n=number of droplets in the emulsion phase
mi = weight of a single droplet (kg)
C = carbon content of droplet (mass%)

Brooks, Pan, Subagyo, Coley, Met. and Matl. Trans. B, 2005

Model assumptions

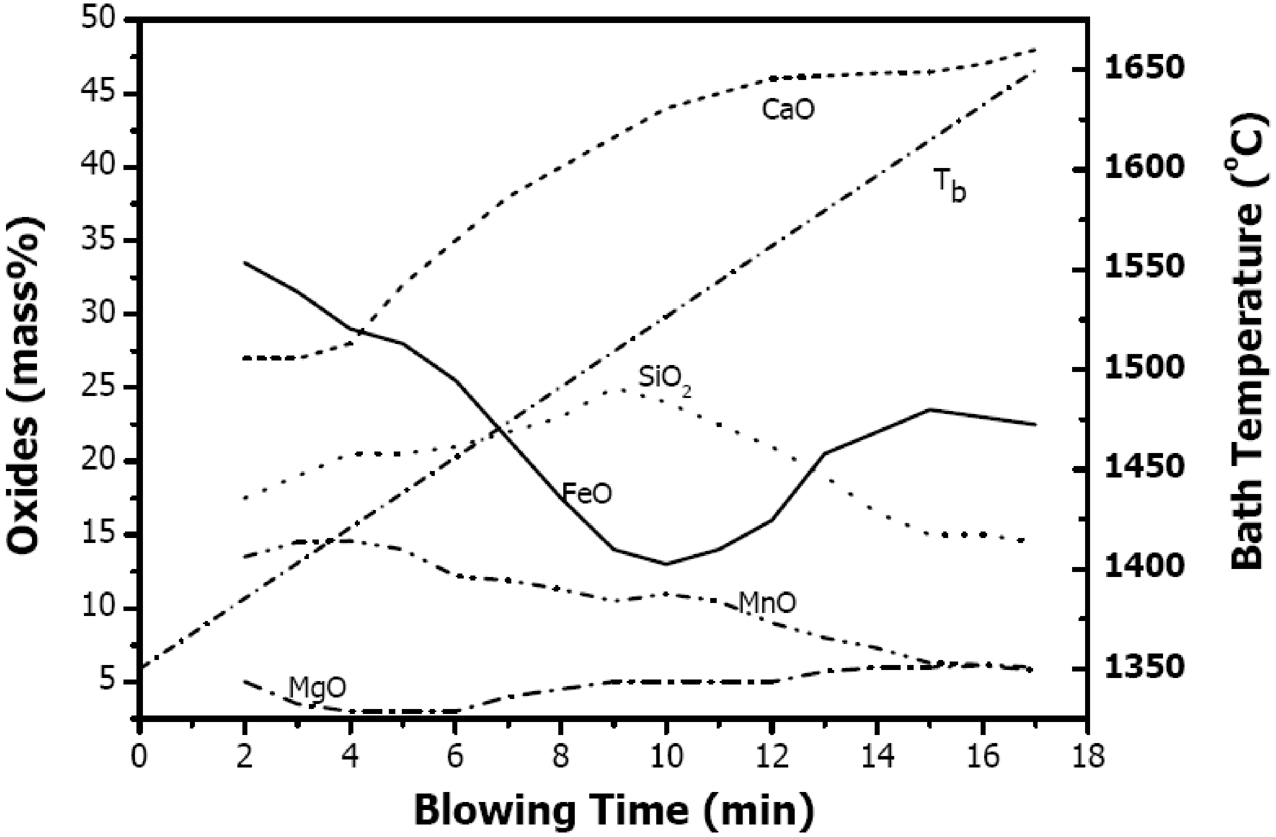
- Diameter of a metal droplet ejected is assumed to be 2.5 mm.
- Ejection angle of droplets is assumed to be 60º.
- Carbon content of metal droplet ejected = carbon content in the liquid bath.
- Bulk carbon content is calculated using mass balance, which includes scrap melting, the decarburization reaction rates.

Data used for calculations

Amount of hot metal charged	170000 kg
Amount of scrap charged	30000 kg
Inclination angle	17.5°
Exit diameter of nozzle	45 mm
Throat diameter of nozzle	33 mm
Supply pressure	10 atm
Initial hot metal temperature	1350°C
Tapping temperature	1650°C
Oxygen blow	620 m^3/min, 6 hole lance
Inert gas (Ar/N_2)	150-500 m^3/h through the bottom
Lance height	2.5m/ 2.2m/ 1.8m
Sulphur content	0.015 mass%

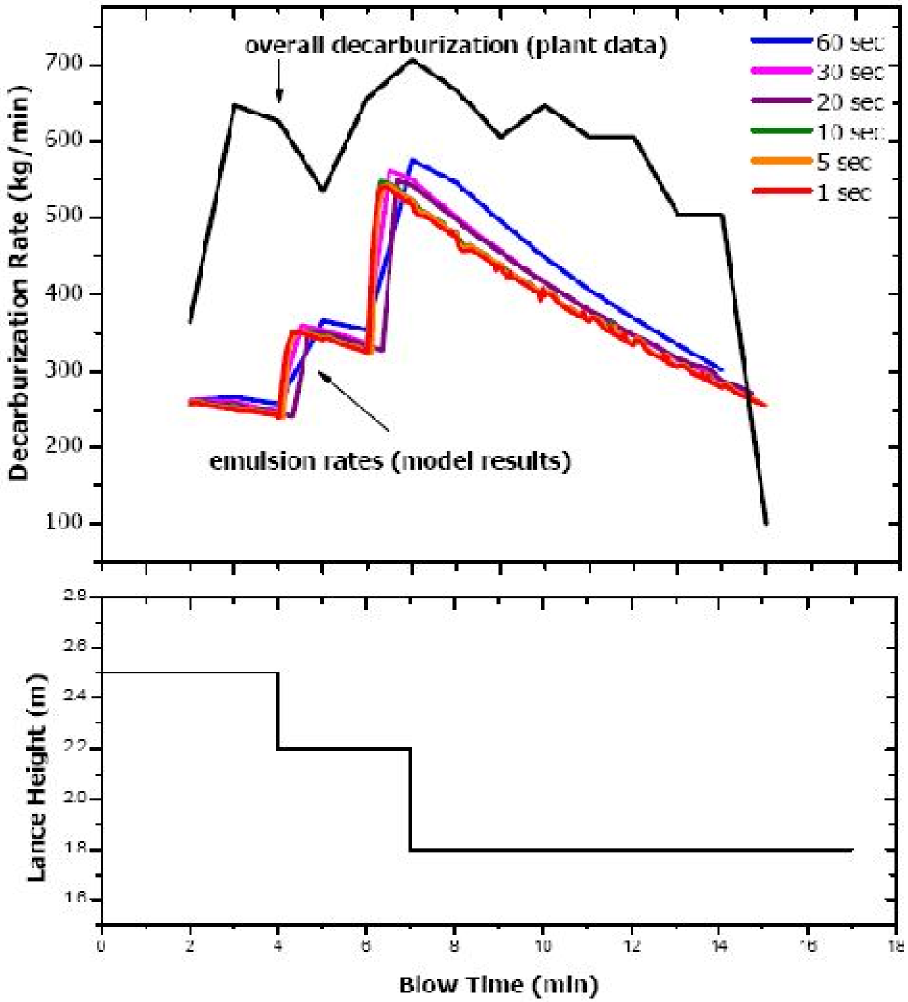
Cicutti, Valdez, Perez, Donayo and Petroni, Latin Am. App. Res., 2002

Data used for calculations



Cicutti, Valdez, Perez, Donayo and Petroni, Latin Am. App. Res., 2002

Decarburization rate for various time-steps

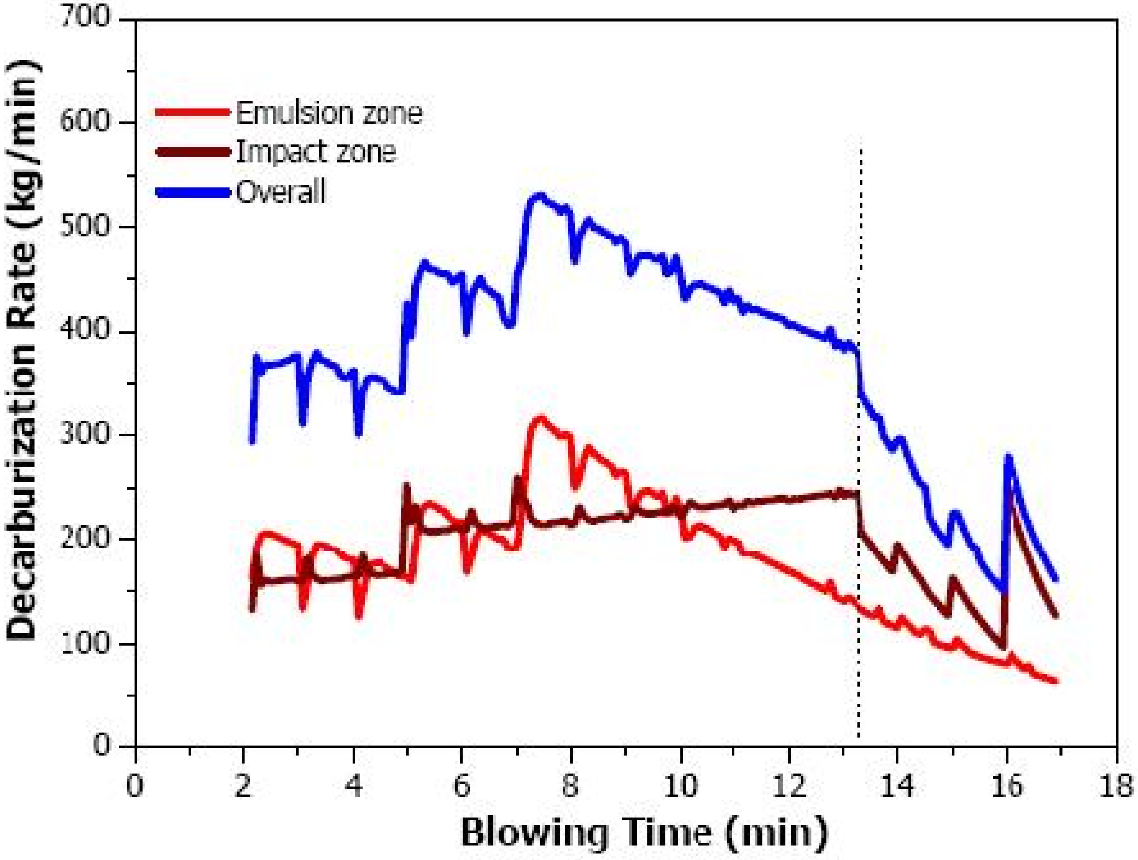


Numerical calculations

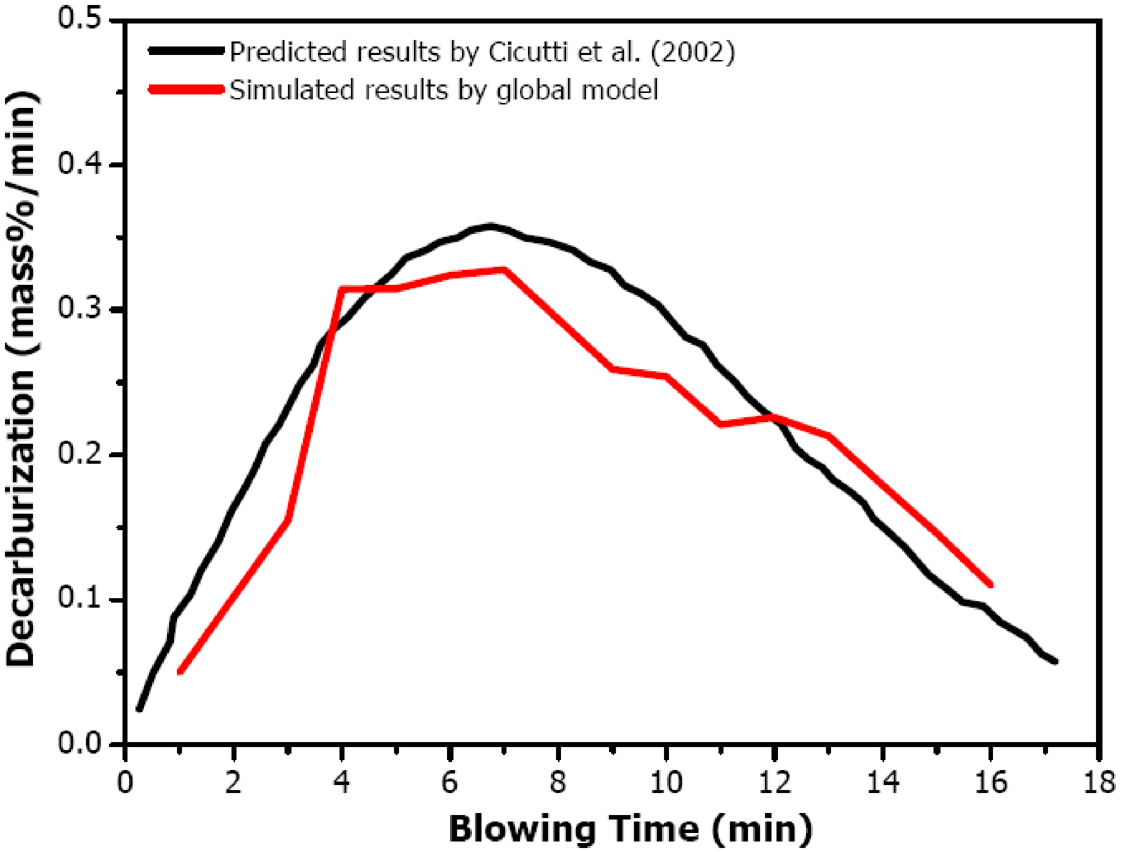
Cicutti, Valdez, Perez, Donayo and Petroni, Latin Am. App. Res., 2002

Decarburization rates in the furnace

Model results

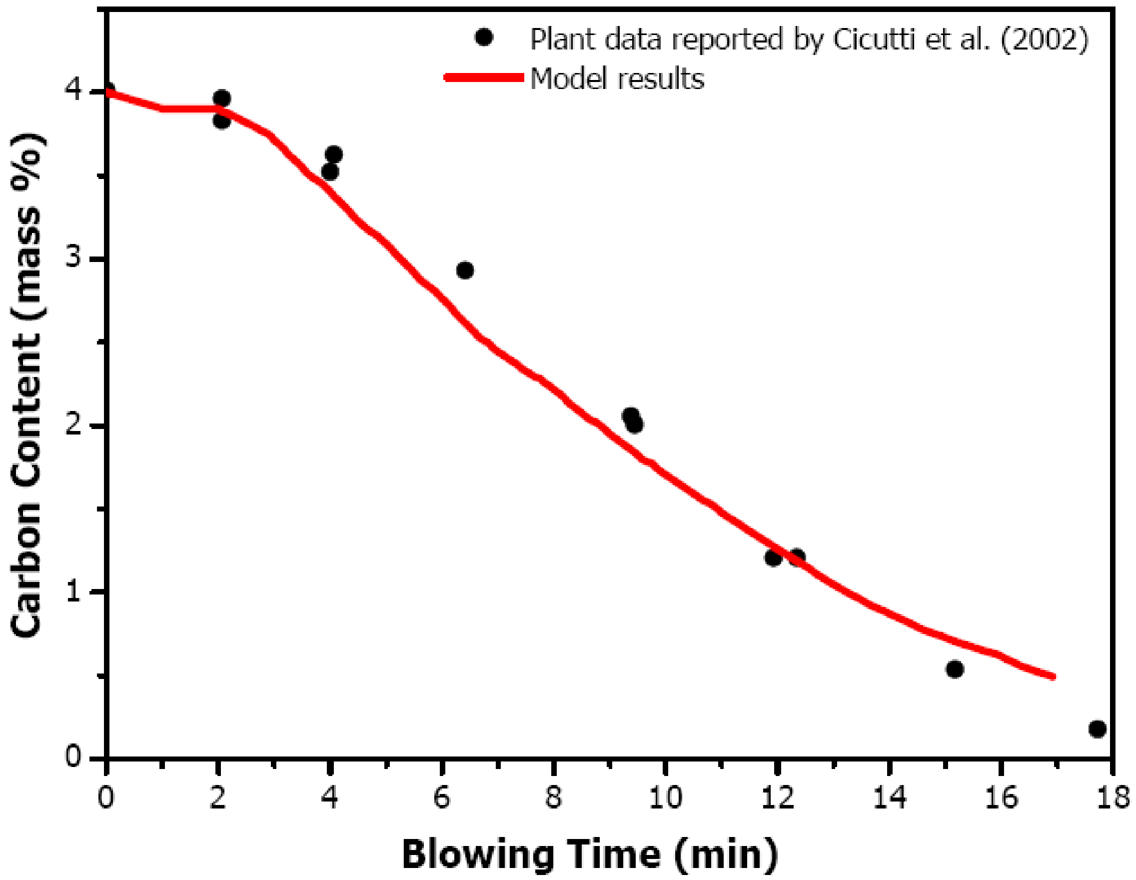


Decarburization rates comparison



Cicutti, Valdez, Perez, Donayo and Petroni, Latin Am. App. Res., 2002

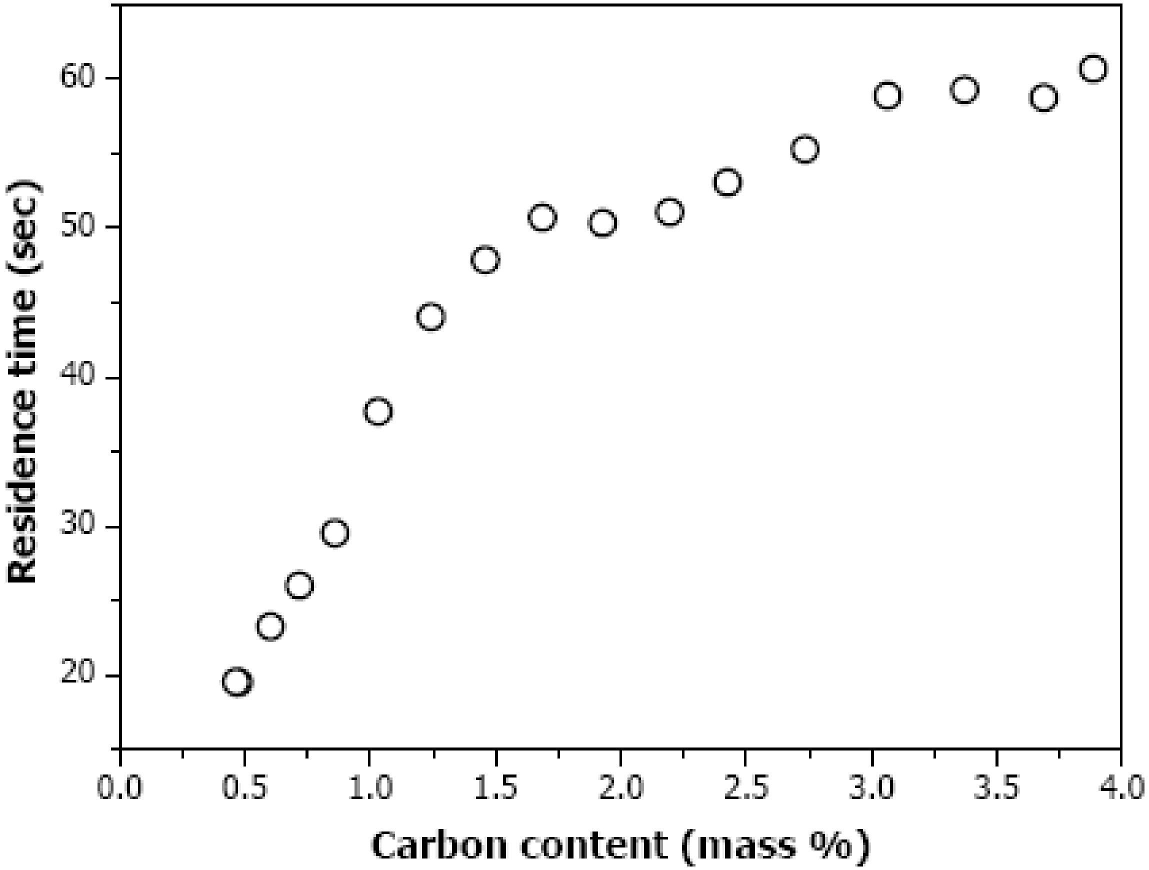
Carbon content of liquid iron



Cicutti, Valdez, Perez, Donayo and Petroni, Latin Am. App. Res., 2002

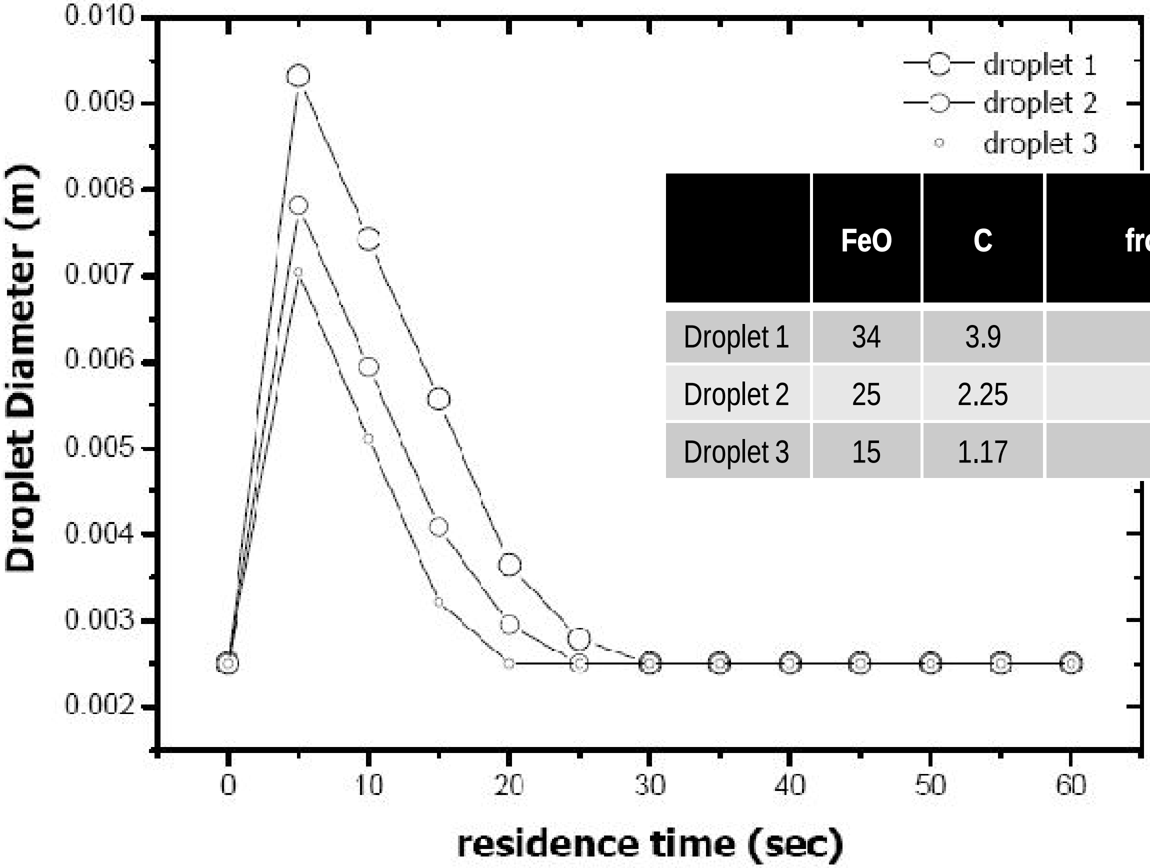
Residence time of droplets

Model results



Behaviour of droplets at different times

Model results



	FeO	C	Ejection time from start of the blow min sec
Droplet 1	34	3.9	2 00
Droplet 2	25	2.25	7 00
Droplet 3	15	1.17	12 00

Industrial repercussions

- Global model including the bloated droplet theory can predict decarburization rates of individual droplets under full-scale operating conditions for oxygen steelmaking process.
- Required computational time is getting increased significantly as the time-scale is reduced.
- This model can be used for advancing our knowledge and designing for new technology.
- More robust understanding of how slag composition varies during the blow is important to improve current model.

Conclusion

- Model suggests that decarburization reaches 60% in the emulsion during the main blow.
- Decarburization rate is strongly dependent on residence time of droplets.
- Model predicts that residence time of droplets varies from 20 to 60 seconds.

Future work

- Droplet residence model will be further studied using dense droplet approach.
- Evaluate influences of various process variables on the kinetics of the process
- Further validation against industrial data

Acknowledgement

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Thank you

Any Questions??