Modelling entrained-flow slagging gasification of solid fuels: assessment of near-wall particle segregation

Maurizio Troiano[1]*, Roberto Solimene[2], Fabio Montagnaro[3], Piero Salatino[1]

1 Dipartimento di Ingegneria Chimica, dei Materiali e della Produzione Industriale, Università degli Studi di Napoli Federico II, Piazzale V. Tecchio 80, 80125 Napoli (Italy); 2 Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, Piazzale V. Tecchio 80, 80125 Napoli (Italy); 3 Dipartimento di Scienze Chimiche, Università degli Studi di Napoli Federico II, Complesso Universitario di Monte Sant'Angelo, 80126 Napoli (Italy)

**Corresponding author: maurizio.troiano@unina.it*

Highlights

- The fate of carbon particles during entrained-flow slagging gasification is analyzed.
- Wall adhesion and rebound mechanisms dictate near-wall particle segregation.
- The establishment of a dense-dispersed phase is beneficial to carbon conversion.

1. Introduction

Gasification offers a variety of routes for the thermochemical conversion of solid fuels to produce chemicals, fuels and electricity [1]. Most of the entrained-flow gasifiers (EFGs) operate in slagging conditions: the combustible fraction of the particles is converted into the gas phase while the mineral matter is converted into molten ash. The performance of slagging EFG is critically affected by the slag formation and flow as well as by the fate of char/ash particles as they interact with the wall slag layer [1,2]. Mass, momentum and energy exchange between the wall and the lean particle-laden phase must consider particle deposition and the development of near-wall multiphase flow structures. Critical parameters are particle and wall temperatures, solid/molten status of the particles and of the wall layer, degree of carbon conversion in char particles, dynamical patterns of particle-wall interaction [1,2]. This study addresses the fate of carbon particles during entrained-flow gasification of coal in the slagging regime. The dynamical patterns of fuel particles in the near-wall region of the gasifier are analyzed on the basis of previous theoretical and experimental investigations [2,3]. Particle segregation is analyzed considering migration toward the wall, interaction upon the impact with the wall ash layer, coverage of the slag layer by refractory carbon particles, accumulation of carbon particles in the near-wall region of the gasifier and particle heterogeneous reactions.

2. Methods

The 1.5D model of the entrained-flow gasifier is based on the conceptual framework outlined in Figure 1a). The entrained-flow gasifier is operated under slagging, co-current and autothermal conditions. Mass balances are written for both the solid and gaseous phases. Figure 1a) highlights distinctively different stages of the interaction between the particle-laden mainstream and the wall, ultimately leading to extensive particle segregation. In **stage 1** (**dry wall**) the particle-laden flow (lean-dispersed phase) interacts with the wall as it is not yet covered (or sparsely covered) by the slag layer. At this stage, char and molten ash transferred toward the gasifier walls undergo either adhesion or inelastic rebound. Permanent adhesion of molten ash and char particles onto the reactor walls gives rise to the formation of a "slag phase". Instead, ash and char particles rebounding with small values of the restitution coefficient give rise to a "dense-dispersed phase", which progressively builds up as a "curtain" of molten ash and char particles in the near-wall region of the gasifier. Stage 1 extends to the point when the thickness of the slag layer (δ^{slag}) exceeds a critical value ($\delta^{slag,*}$). Beyond this point, the interaction pattern modifies into **stage 2** (**wet wall/pre-coverage**): now particles reaching the wall impinge onto a fully established slag layer, and rebound is unlikely for both ash and char particles. Molten ash impinging the slag layer are fully incorporated and contribute to its build-up. Carbon-rich char particles impinging the slag layer are all trapped but not incorporated (due to interfacial forces, see ref. 2), so that they gradually form a carbon-rich refractory coverage of the slag layer. As particle rebound is prevented, no particle input to the dense-dispersed phase is considered during stage 2. When full coverage of the slag layer with refractory carbon-rich particles is approached, transition to **stage 3 (wet wall/post-coverage)** occurs. In this stage, particles approaching the char-covered slag layer will either rebound (accumulating in the dense-dispersed phase) or adhere onto the slag phase. In stage 3, the dense-dispersed phase grows again, as a consequence of the input from low-kinetic energy rebounds of impinging particles. Growth of the dense-dispersed phase may lead to the point when the wall is fully sheltered by a curtain of particles, hence a transition to **stage 4 (fully developed dense-dispersed phase)** occurs. The transition criterion is based on the comparison of the actual thickness of the dense-dispersed phase (δ^{dense}) with a critical thickness ($\delta^{dense,*}$) beyond which particle travelling across the dense dispersed phase is unlikely. In stage 4, all particles reaching the wall lose their momentum in the dense-dispersed phase and are trapped therein, whereas particle input to the slag phase is very limited.

The model of the gasifier incorporates detailed description of particle-wall interaction and formation of the segregated phases, and accounts for gasification reactions progressing in all phases. Partitioning of char/ash among the three phases (lean-dispersed, dense-dispersed and slag) is relevant to the gasifier performance.

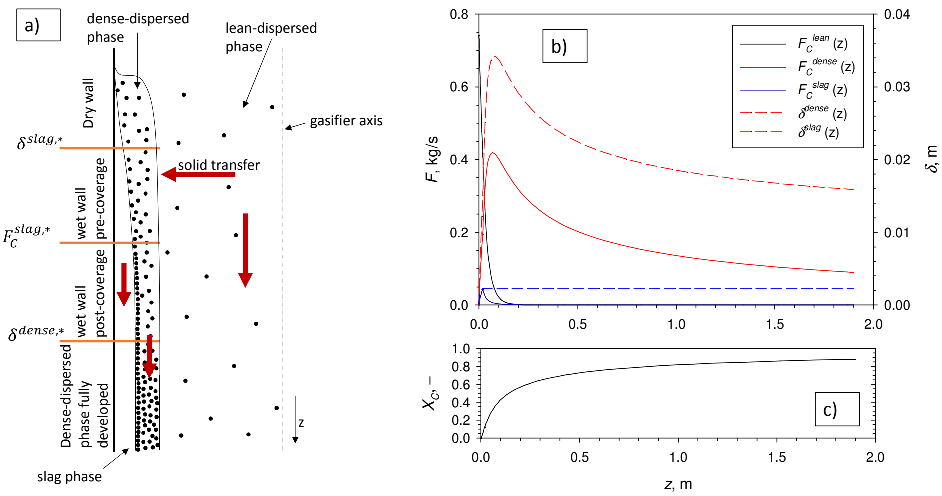

Figure 1. Sketch of the entrained-flow gasifier, with indication of the four possible scenarios (a). Mass flow rates profiles in the three phases and thickness profile for the dense-dispersed phase and the slag phase (b). Carbon conversion profile (c).

3. Results and discussion

The axial profiles of the mass flow rates of carbon in the three phases are reported in Figure 1b). A fast decrease of F_C^{lean} is observed, related to the combined effects of gasification and carbon transfer to the slag and dense-dispersed phases. F_C^{dense} reaches a maximum at about z = 0.07 m, to decrease henceforth, due to competing effects of carbon migration from the lean- to the dense-dispersed phase and of carbon gasification in the dense-dispersed phase. F_C^{slag} increases until z = 0.02 m, to decrease henceforth, confirming that stages 1, 2 and 3 are active only in the proximity of the fuel feeding point. Early establishment of a dense-dispersed phase is predicted, as a consequence of the particle-to wall transfer and micromechanical interaction patterns described in the previous section. The thickness δ of the dense and slag phases is also reported in Figure 1b). δ^{dense} mirrors F_C^{lean}, as expected. δ^{slag} gradually approaches a constant value of around 3 mm (in agreement with the literature [1]), confirming the establishment of a stable slag layer covered by particles and the formation of an extended dense-dispersed phase. Figure 1c) reports that the overall carbon conversion degree approaches 90%, a figure that is largely dependent on the partitioning of char among the three phases.

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Keywords
Slagging; particle-to-wall transfer; gasification; deposition and segregation.

Maurizio Troiano

Address Via Piave, 136, 80126 Napoli, Italy

Date of Birth 20th December 1986

Nationality Italian

Home Phone +39 081 640121
Mobile Phone +39 3337159246
Email
maurizio.troiano@unina.it

WORK AND RESEARCH EXPERIENCE

Sept 2015 – Present **Postdoctoral Researcher, Department of Chemical, Materials and Industrial Production Engineering, Università degli Studi di Napoli Federico II**

The research activity deals with the thermo-chemical conversion processes of solid fuels. The main objective of the research is the assessment of particle behaviour in entrained-flow gasifiers operated in slagging conditions. The role of particle-wall interaction patterns and segregation phenomena on the fate of reacting particles has been experimentally investigated under low and high temperature conditions. Modelling entrained-flow slagging gasification incorporating detailed description of particle-wall interaction and formation of the segregated phases is currently addressed.

2015 **Term contract, CRDC Tecnologie SCARL, Napoli**
From 30th March to 30th June.

The research activity dealt with the development of an experimental apparatus for the assessment of particle-wall interactions, relevant to entrained-flow slagging gasifiers. The apparatus was designed to investigate the impact-deposition-rebound patterns during the collision of particles with a flat wall at high temperature (up to 1500°C).

EDUCATION

2012 – 2015 **Università degli Studi di Napoli Federico II**
PhD in Chemical Engineering (XXVII Cycle)
Thesis Title: Physical modelling of near-wall phenomena in entrained-flow coal gasifiers
Supervisors: Prof. Piero Salatino, Prof. Pier Luca Maffettone, Prof. Fabio Montagnaro, Dr. Roberto Solimene, Prof. Kevin J Whitty.

2012 Passed the state exam for habilitation to the profession of engineer.

2009 – 2011 **Università degli Studi di Napoli Federico II**
Master's Degree in Chemical Engineering (110/110 cum laude)
Thesis Title: Comminution phenomena of a lignite during fluidized bed gasification
Supervisors: Prof. Piero Salatino, Prof. Fabrizio Scala, Dr. Paola Ammendola

2005 – 2009 **Università degli Studi di Napoli Federico II**
Degree in Chemical Engineering
Thesis Title: BTEX and Trimethylbenzene analysis in Tunnel
Supervisor: Prof. Fabio Murena.

2000 – 2005 **Adolfo Pansini High School, Napoli**
Diploma in Classical Lyceum (100/100)

AWARDS, HONOURS AND SCIENTIFIC ACKNOWLEDGMENTS

2017 Mobility grant from University of Naples Federico II to spend a period at IFPEN (Lyon, France) starting from 2nd November 2017

2017 Best oral presentation award at the *40th Meeting of the Italian Section of the Combustion Institute*, Rome (Italy), June 7 - 9, 2017

2014	Mobility grant from University of Naples Federico II within the program "Reti di Eccellenza" (P.O.R. Campania FSE 2007-2013, Asse IV, Rete di Eccellenza: POLIGRID) to spend a period as a scientist visitor at the Department of Chemical Engineering at the Utah University (USA).
2015 – Present	Reviewer for the International Scientific Journals: Fuel, Fuel Processing Technology, Industrial & Engineering Chemistry Research, International Journal of Heat and Mass Transfer, Solar Energy
2012 – Present	Member of the Italian Section of the Combustion Institute.

PUBLICATIONS

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An experimental investigation on near-wall particle segregation in entrained-flow slagging coal gasifiers, XXXVI Meeting of the Italian Section of the Combustion Institute, June 13-15, 2013, Procida (Italy).

Physical Modelling of entrained-flow slagging coal gasifiers, XXXV Meeting of the Italian Section of the Combustion Institute, October 10-12, 2012, Milano (Italy).

ACADEMIC TEACHING EXPERIENCE

2012 – Present	Teaching assistant for the Course of Chemical Engineering Reactions (Chemical Engineering Course) at Università degli Studi di Napoli Federico II
2012 – Present	Tutor/co-supervisor for Degree and Master's Degree Theses in Industrial Chemistry and Chemical Engineering:
	"Esercizio di un reattore modello per l'indagine di fenomeni di interazione char–slag in parete, di interesse in gassificatori slagging a flusso trascinato", Eduardo Gais, Degree in Industrial Chemistry (academic year 2012/2013);
	"Modellistica fisica delle interazioni in parete di flussi trascinati bifasici", Laura Pirro, Master's Degree in Chemical Engineering (academic year 2013/2014);
	"Analisi dei fenomeni di interazione particella–parete in gassificatori a flusso trascinato", Fabrizio Pucci, Degree in Chemical Engineering (academic year 2014/2015);
	"Fenomeni di segregazione nella gassificazione di combustibili solidi in letto trascinato", Luigi Marra, Degree in Chemical Engineering (academic year 2015/2016);
	"Interazioni particella–parete nella gassificazione a letto trascinato di combustibili solidi", Tommaso Santagata, Master's Degree in Chemical Engineering (academic year 2015/2016).
	"Effetto del confinamento di sospensioni solido-gas nella gassificazione a letto trascinato di biomassa", Sara Asprone, Master's Degree in Chemical Engineering (academic year 2016/2017).

OTHER TRAINING AND CERTIFICATES

2013	Ansys Summer School CFD/DEM, Università degli Studi di Napoli Federico II (24-26/09).
2012	International Summer School on Advanced concepts and process schemes for CO_2-free fluidized and entrained-bed co-gasification of coal, biomass and waste, FECUNDUS Project, Ciemat (Madrid) (3-6/07).
2011	English Course (30 hours), Trinity Point, B2.3 Level.
2001	Certificate of Spoken English for Speakers of Other Languages, Grade 8, Trinity College.

LANGUAGES

Italian – Mother tongue

English – Proficient

French – Basic user