PHYSICAL MODELLING OF ENTRAINED-FLOW SLAGGING COAL GASIFIERS

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Abstract
This paper reports a theoretical and experimental study which aims to give a contribution in the development of a phenomenological model of the fate of coal/ash particles which considers the establishment of a particle segregated phase in the near-wall region of the gasifier. Mechanistic understanding of particle-wall interaction patterns in entrained-flow gasifiers has been carried out using the tool of the physical modelling, implemented by rational downscaling of the real system into a lab-scale cold entrained-flow reactor. Hydrodynamics of sticky wall-sticky particle regime has been characterized by partitioning measurements between simulated segregated phases and by visual observation of wall-layer phase.

1. Introduction

Modern entrained-flow coal gasifiers are characterized by operating conditions that promote ash migration/deposition onto the reactor walls whence the molten ash is drained and quenched at the bottom of the gasifier as a vitrified slag [1-3]. The recent literature has addressed the fate of char particles as they impinge on the wall slag layer [3-5]. This research group has contributed [6-8] to develop a phenomenological model of the fate of coal/ash particles which considers the establishment of a particle segregated phase in the near-wall region of the gasifier. This configuration can lead to an extensive coverage of the slag layer with carbon particles (segregation and coverage regime) beneficial to carbon conversion, as it gives rise to a longer mean residence time of carbon particles belonging to this segregated phase [6]. The phenomenological model has received some qualitative validation from analysis of the properties of ash streams generated in a full-scale entrained-flow gasification plant [7]. Moreover, the complex phenomenology associated with interaction of a particle-laden turbulent flow with the inelastic slag-covered wall of the gasifier has been the subject of numerical simulations [8], that confirmed both a possible near-wall accumulation of particles and the relevance of such phenomenon on the performance of entrained-flow gasifiers.

In the gasification chamber, coal particles are fed in such a way to form a lean-dispersed particle-laden gas flow. This stream is characterized by inertia and turbulence, due to the centrifugal forces associated to the swirl or tangential flow and to the 'turbophoretic' transport near the reactor walls, respectively [6]. Other authors [5] described different particle-wall interaction patterns on the basis of the stickiness of both impinging particles and wall:

i) Sticky Wall-Sticky Particle (SW-SP), in which char particles with high carbon conversion impinge on the slag layer (Fig. 1a);

ii) Sticky Wall-No Sticky Particle (SW-NSP), for particles with a low carbon conversion impinging on the slag layer [3,6] (Fig. 1b);

iii) No Sticky Wall-Sticky Particle (NSW-SP), when high carbon conversion char particles impinge on either dry wall or a carbon-covered ash layer (Fig. 1c);

iv) No Sticky Wall-No Sticky Particle (NSW-NSP), referring to low carbon conversion char particles impinging on either dry wall or a carbon-covered ash layer (Fig. 1d).

The particle or the wall is considered sticky when both the particle carbon conversion is above a certain critical (threshold) value (as explained by Li et al. [4], who set this value around 88%) and the temperature is above the ash melting point.

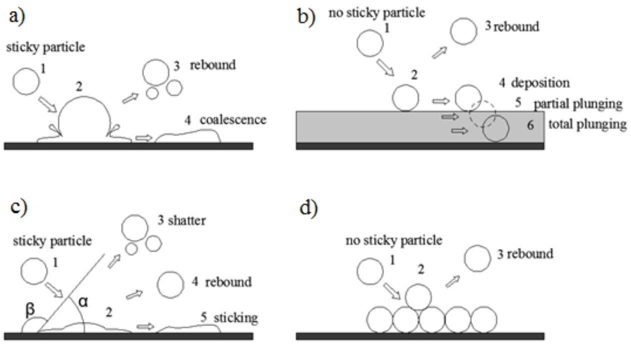

Figure 1. Micromechanical interaction patterns: a) SW-SP; b) SW-NSP; c) NSW-SP; d) NSW-NSP. (1) pre-impact, (2) impact, (3-6) post-impact.

This study aims at implementing a physical modelling by rational downscaling of the real gasifier into a lab-scale cold entrained-flow reactor. The operation of the downscaled reactor ensures the formation of two phases: a dispersed phase and a near-wall layer to reproduce and characterize the four micromechanical interaction patterns depicted in Fig. 1. The present work, in particular, is focused on the study of the first regime (SW-SP) for which, after the droplets impact on the liquid layer, it is possible to have rebound and/or coalescence of droplets, as shown in Fig. 1a.

2. Downscaled cold flow model reactor and experimental features

A downscaled lab-scale cold flow model reactor has been designed, built-up and developed in order both to avoid the difficulties related to the 'hard' operating conditions of entrained-flow slagging gasifiers in terms of pressure and temperature and to ensure the optical accessibility of the reactor walls. The design regarded the choice of a suitable material to simulate, at atmospheric conditions and at low temperature, the slag phase behavior of an actual entrained-flow gasifier. In this respect, the use of melted wax (1-hexadecanol) has been reported by Shimizu et al. [9], even if for a different application. Following this path, Waradur E© wax has been selected (Vöelpker, Germany) (Table 1) after a comparison of the properties of different waxes with those typical of slag [2,3]. Choice criteria were inspired to have: i) similar wax-vs.-slag kinematic viscosity to ensure laminar flow of the melted phase along the wall; ii) peculiar wax properties, such as the plunging and overlayering criteria are not satisfied, as it is expected during particle-slag interaction in entrained-flow gasifiers [6].

Table 1. Comparison between wax and slag properties (viscosity, density, kinematic viscosity).

	Wax	*Slag*
μ (Pa s)	0.02-0.1 (at 130°C-90°C)	0.05-1 (at about 1200-1500°C)
ρ (kg m^{-3})	1000	2500-3000
ν (m^2 s^{-1})	2×10^{-5}-10^{-4}	1.7×10^{-5}-3.3×10^{-4}

The operating conditions have been set on the basis of the ratio between the reactor volume and the fuel inlet mass flow rate commonly found for industrial gasifiers. This ratio is around 5 m^3 s kg^{-1}. Assuming as lab-scale model reactor a cylindrical tube of 0.04 m ID and 1 m high, the fuel inlet mass flow rate is around 0.3 g s^{-1}. The inlet wax and air mass flow rates are 0.2 g s^{-1} and 1 m^3 h^{-1} (at 298 K), respectively. To simulate char particles in a slagging gasifier, the wax has been fed with a mean particle size of about 50–100 µm. The nozzle was chosen to give a full cone spray that ensures the formation of two phases: a dispersed phase and a wax layer on the internal wall of the reactor. The schematic representation of the experimental apparatus is reported in Fig. 2. Once the wax, collected in a storage vessel, is heated to the liquid state, a three-way valve is opened to convey it to the atomizer. The atomization section provides for two inlet air streams: an atomization air stream (0.3 m^3 h^{-1}) and a main air stream (0.7 m^3 h^{-1}). A 0.04 m ID Pyrex tube has been utilized as experimental reactor, to ensure the optical accessibility. The atomization air stream is fed to the nozzle, while the main air stream is uniformly conveyed, sideways to the nozzle after passing through a distribution plate, to the Pyrex tube.

In order to correctly operate the lab-scale reactor, three different temperatures have to be taken in account: the atomization temperature, i.e. the nozzle exit temperature, the main stream temperature, the wall temperature. The first one has to be set in such a way to ensure the complete liquid state of the wax droplets at the Pyrex tube inlet. Different aggregation states and viscosity values of wax in the dispersed phase can be reached by varying the main stream temperature. The wall temperature can be varied to assure the desired aggregation state and viscosity value of the wall-layer wax. Thus, by tuning these three temperatures, it is possible to obtain the different micromechanical interaction patterns above discussed.

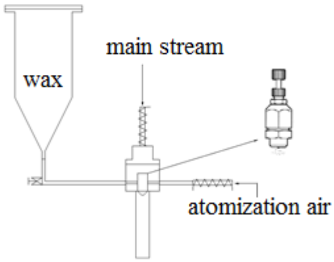

Figure 2. Experimental apparatus with a zoom of the atomization nozzle.

An experimental campaign has been carried out setting these temperatures to obtain the Sticky Wall-Sticky Particle (SW-SP) regime. Hydrodynamics has been characterized by partitioning measurements of the wax droplets into a dilute-dispersed phase, a dense-dispersed phase and the layered material on the wall at the exhaust and by visual observation of wall-layer phase at Pyrex tube exit. Partitioning measurements were carried out by measuring the mass fractions of wax exiting the reactor in the dispersed phase and in the wall-layer phase. To this end, the apparatus was equipped with a system (consisting by a vacuum flask, a trap, a filter and a pump) for the two phases wax collection at the bottom of the Pyrex tube. The dispersed phase wax mass fraction y^{lean} was used to evaluate a bulk-to-wall flux, thus, the mean bulk-to-wall mass-transfer coefficient k_m:

$$k_m = -\frac{1}{\tau} ln \frac{W_{WAX}^{lean}(z=L)}{W_{WAX}^{lean}(z=0)} = -\frac{1}{\tau} ln\left(1 - \frac{W_s}{W_{WAX}^{lean}(z=0)}\right) = -\frac{1}{\tau} ln(y^{lean}) \quad (1)$$

where τ is the mean gas residence time, while $W_{wax}{}^{lean}$ and W_s are the wax mass flow rates in the lean phase and in the wall-layer phase, respectively. Furthermore, a CCD camera (Pulnix, 120 fps) equipped with a magnifying zoom lens was positioned at the bottom of the Pyrex tube to acquire images to estimate, by an image analysis technique, the mean velocity of the near-wall liquid layer. The experiments have been characterized by varying the atomization temperature, the atomization air flow rate, and Pyrex tube length.

3. Results and discussion

Partitioning measurements: Figure 3 reports the dilute dispersed phase fraction measured at the exhaust (wax droplets) and the mean bulk-to-wall mass transfer coefficient as functions of the atomization air flow rate (Q_a), the atomization temperature (T_a) and the Pyrex tube length (L).

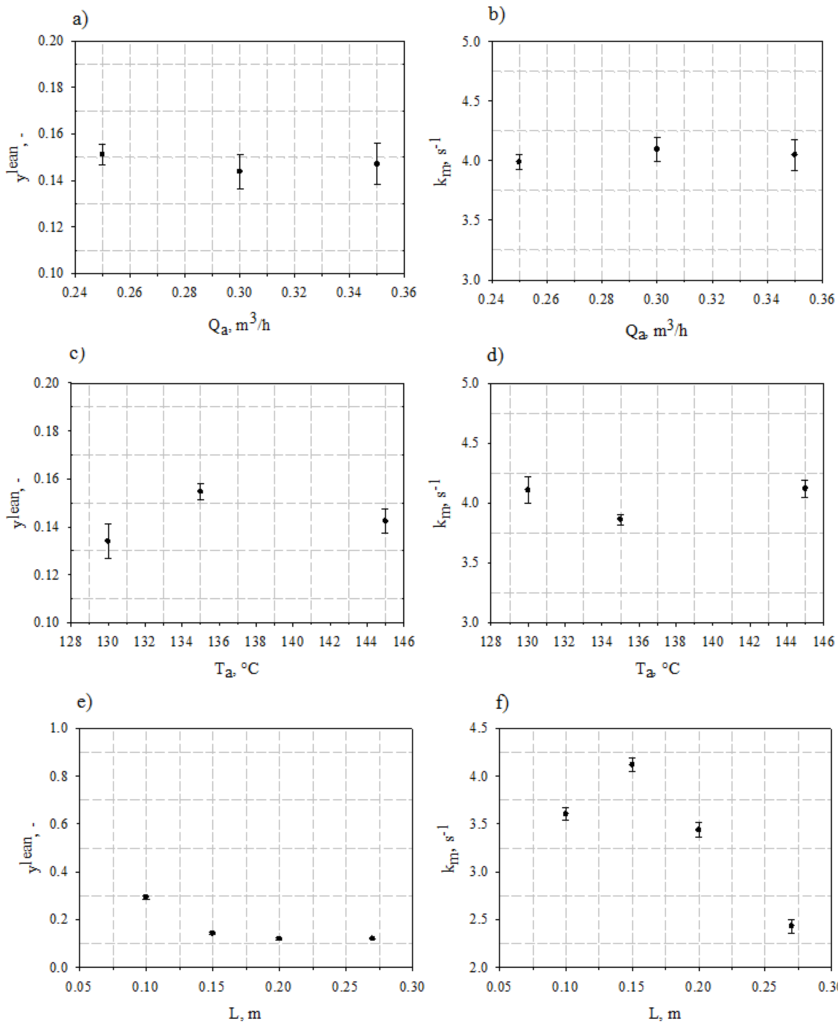

Figure 3. Effect of the atomization air flow rate Q_a, the atomization temperature T_a and the tube length L on: (a)-(c)-(e) the wax lean phase fraction and (b)-(d)-(f) the average mass transfer coefficient.

It can be observed that: i) Q_a slightly influences y^{lean} and k_m (Figs. 3a and 3b) at fixed τ, T_a and L (0.474 s, 145°C and 0.15 m, respectively); ii) y^{lean} and k_m (Figs. 3c and 3d) do not significantly vary with the atomization temperature (Q_a=0.3 m^3 h^{-1}, L=0.15 m). It is noteworthy that the wax viscosity at 145°C is about twice than that at 130°C; thus, at least for the range exploited, viscosity variations do not significantly affect the partitioning results. For these operating conditions, y^{lean} and k_m results to be in the order of 0.15 and 4s^{-1}, respectively. As regards the effect of tube length, the experiments were carried out at four different Pyrex tube lengths and the results are reported in Fig. 3e and 3f. The y^{lean}-vs.-L curve shows a strong decay of y^{lean} with tube length, until it reaches a nearly constant value of about 0.12 at 0.2 m. Figure 3f shows the k_m-vs.-L curve: it is characterized by a non-monotonous trend, confirming what described by Montagnaro and Salatino [6]. Altogether, taking into account the whole set of experimental runs, y^{lean} varied between 0.3 and 0.12, and k_m between 2.3 and 4.2 s^{-1}.

Visual observations: Figure 4 shows a sequence of snapshots of wall liquid layer captured nearby the tube exit by the CCD camera at frame rate of 120fps. The analysis of the snapshots highlights the presence of micron-sized air bubbles entrapped in the wall melted wax layer and descending along vertical streamlines. Assuming that air bubbles behave as seeding “particles”, the wall liquid layer is characterized by laminar flow as expected. Beside following the air bubbles trajectory in the wall layer, it is possible to estimate a descending velocity of wall melted-wax layer in the order of 3-6 mm s^{-1} for each tube length. Further investigations are necessary to determine the velocity profile and the wall layer thickness.

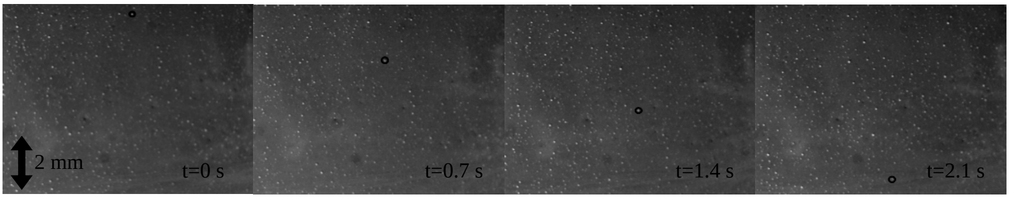

Figure 4. Images sequence captured by CCD camera. Open circle: a descending air bubble entrapped in the wall melted-wax layer.

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