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Design of an indirect heat rotary kiln gasifier

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ABSTRACT

A non-ordinary type of solid fuel gasification reactor, which was under development for the few past decades and it is briefly described as indirect heat rotary kiln gasifier, seems to be capable of sufficiently satisfying the incorporated gasification needs in the most challenging contemporary power technologies using solid fuels, like IGCC and CLC combustion. The design of such a gasifier emerges in this work, while the focus is mostly on the presentation of the relevant theoretical model. Moreover, model predictions are compared and optimized with respect to experimental data that were acquired in a pilot scale gasification unit including the suggested type of gasifier. Comparisons showed successful predictions of such a marginal error that could be characterized as quite sufficient for a primary model validation. However, the model flexibility to a wide variety of different solid fuels, rotary kiln configurations and operating conditions has to be verified by assessment of further experimental results.

1. Introduction

The exploitation of coal resources for power generation seems to be the only worldwide promising method for sufficient cover of the continuously increasing demand, in the short and medium terms at least. Moreover, it is quite sure that the path to sustainable economic development passes through the availability of abundant and affordable electric power, which is combined with the maximum possible environmental protection.

The current level of new coal technologies for electric power and/or heat generation has reached the high standards for pollution abatement, that guarantee the minimization of local and global environmental hazards through the inherent diminishment of emitted local pollutants and the availability being offered for Carbon Capture and Storage (CCS), respectively.

The most promising zero emission coal technologies, either commercially applied (IGCC [1–4]), or under development (solid fuels CLC [5–10]), include gasification as a necessary intermediate process, since it seems to be the only assured method that combines the high efficiency in power generation with the inherent production of clean carbon dioxide to be stored or sequestrated, while the gasifier performance has been proven to be the core issue of such a plant entire operation.

Evaluation of a gasification reactor has not been proven to be a one-way route, but rather a difficult compromise between controversial advantages and drawbacks. Additionally, information about operational availability is in most of the cases either cloudy, or ambiguous, since it is acquired only with gained experience from prolonged operation of the gasifier, under the specified conditions it is intended to perform. Eventually, a reliable evaluation of such a reactor demands exhaustive experimental runs in a pilot or a demonstration scale plant combined with computational runs of theoretical models that predict gasifier performance. Such a theoretical model exploits experimental data of operation, material properties and equipment characteristics to predict reactor operation variables, or to simulate the entire process, for the wider possible reliable range of conditions.

Indirect heat rotary kiln is a type of reactor that meets successfully a bundle of standard gasifier specifications [11], especially for gasifying moist low rank coals. Particular emphasis is given on the heating mode, since rotary kiln is suitable for indirect heat (allo-thermal) gasification, which offers better synthesis gas quality, or under certain conditions gas product rich in hydrogen. Additionally, rotary kiln design and construction is relatively simple and the pertinent technology is established and reliable with industrial applications in the cement and metallurgical industry. However, it has to be mentioned that the current commercial status of rotary kiln technology could offer only an atmospheric indirect heat gasifier operating at temperature below 1000 °C.

The present work aims at the development of a complete theoretical model that can be used for the design or the performance simulation of an indirect heat rotary kiln gasifier, which processes low heating value solid fuels and especially low rank coals (e.g., moist lignite) for the production of medium heating value synthesis gas. The focus is mostly on the presentation of model in the directly utilizable

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form of an integrated tool for chemical reactor design. Furthermore, it is provided validation of the model with experimental data acquired in a pilot-scale gasification unit including an indirect heat rotary tube gasifier. The model utilizes kinetic correlations from literature for solid fuel pyrolysis [12] and gasification [13], while it introduces: (i) mass and enthalpy balances regarding the evolved processes in the specific reactor type, (ii) proper configuration of kinetics for incorporation in balances and (iii) specific solid fuel data for application of kinetic correlations. Selection of kinetic models was based on the sufficient simultaneous satisfaction of the following criteria: (i) validity for a wide range of conditions, (ii) facilitation, with some proper configuration, of a wide variety of different solid fuels, (iii) admission of the most acceptable relevant theories, (iv) restriction of empirical simplicity in isolated terms depending on properties of treated material and/or process equipment and (v) explicit computational algorithm.

Apart from the kinetic correlations, thermodynamic analysis is also a valid method for gasification system approaching. Relevant publications elucidate the various thermodynamic aspects of gasification systems, where various solid fuels are involved [14,15]. In the present work, predictions of kinetics are improved with contribution from those of thermodynamic analysis, while relevant experimental data are exploited for this purpose.

2. Model development

2.1. Description of theoretical model

This work presents a full account of a theoretical model simulating an indirect heat rotary kiln gasifier operation for the chemical conversion of a solid fuel feedstock. The author has originally developed the concept of the theoretical model as part of his PhD thesis ([16], Chapter 4), while only a verbal outline with some first results has been published in [11].

The current work presents the mathematical formulation of the model, which is accompanied with validation from various relevant experimental data. Regarding the physical and chemical patterns, the outline in [11] is completed with the following two supplementary provisions:

(i) The possible reversing of Boudouard reaction creates carbon black suspended particulates that are gasified independently and in accord to the tar gasification reaction scheme.
(ii) The mineral matter of the solid fuel is divided into ash and CO_2. The latter is produced from carbonate salt decomposition, after high temperature heating. The included carbonate salts in solid fuel mineral matter are mostly represented by calcite ($CaCO_3$), thus the thermal decomposition (i.e. calcination) occurs at higher temperature than ~840 °C, while the produced CO_2 is added into the gas product mixture. Moreover, model exploits the reverse calcination reaction (i.e. carbonation) to predict gasifier performance in the case of CO_2 sorbent co-feeding with raw solid fuel.

The gasifier model provides for a general scheme of four parallel processes (drying, pyrolysis, gasification and carbonation/calcination). In actual fact it turns out that the four processes progress according to a series-parallel scheme as the solids move along the reactor length and they gradually enter higher temperature regions of the kiln. The updated process scheme is schematically illustrated in Fig. 1, where the partial overlapping between successive processes is pictorially represented.

The mathematical model simulates a steady state rotary gasifier operation and encompasses mass and enthalpy balances over a Differential Control Volume (DCV). The gasifier is considered as a non-isothermal plug flow reactor with separate local axial velocities, but with common local temperature, between the solid and gas phases of the reactant mixture.

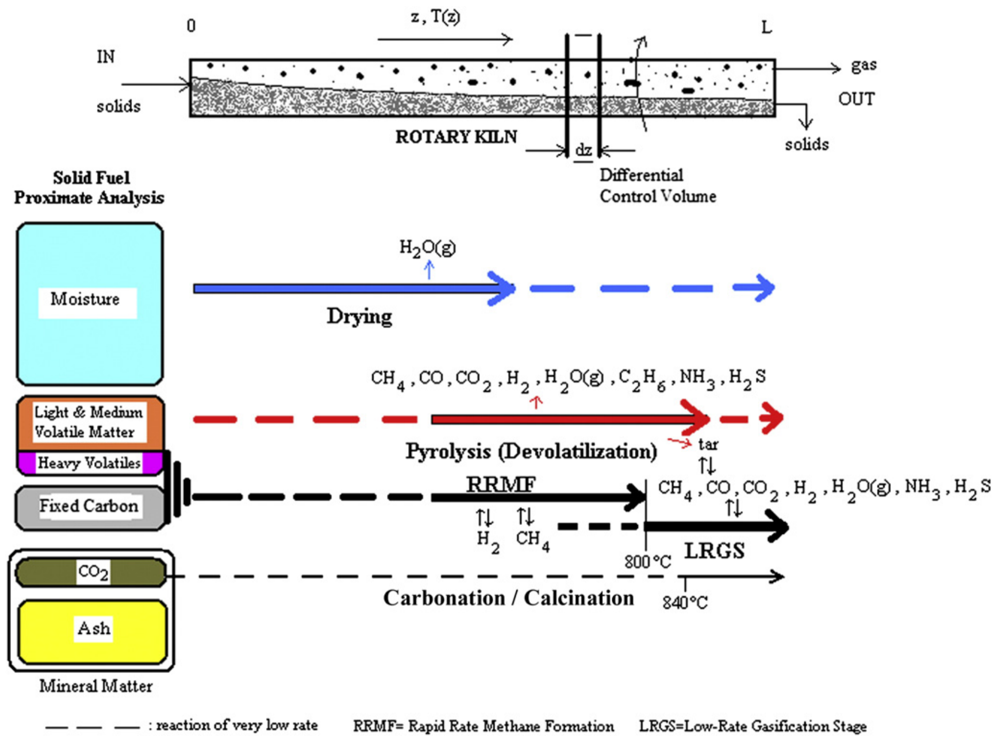

Fig. 1. Schematic representation of processes progress in an indirect heat rotary kiln gasifier.