



## Full Length Article

## Modelling oxy-pyrolysis of sewage sludge in a rotary kiln reactor

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## ABSTRACT

A mathematical model of a rotary kiln oxy-pyrolyser of sewage sludge is presented. The specific feature of the model is the consideration of the effect of axial staging of oxygen feeding to the reactor as one important key to the quality and productivity of the syngas, with a focus on the fate of tar and generation of soot. The gaseous oxidiser is fed to the reactor at multiple locations along its axis in a way that reproduces the paradigm of the Zwietering reactor. The fate of gaseous components and tar is followed using a simplified lumped-kinetic mechanism that was purposely developed. The model implements submodels for heat transfer among the phases and with the wall which embody radiative, convective and conductive terms. Homogeneous reactions in gas phase are modelled with a kinetic submodel that considers the generation of primary tars from devolatilisation of fuel and subsequent formation of secondary tars and soot by thermal cracking. The model validity has been confirmed by critical comparison with experimental literature data referring to a similar case. The steady operation of the oxy-pyrolyser is analysed in terms of fluxes of solid fuel and gaseous species, extent of fuel devolatilisation, temperature profiles of solid and gas phases along the reactor. The performance of the reactor is characterised in terms of process rate and chemical composition of the produced syngas, along with its heating value and thermal power. The influence of the distributed feeding is assessed by comparison with a benchmark case consisting of conventional non-distributed feeding.

## 1. Introduction

The thermal conversion of waste-derived fuels (e.g., municipal solid waste, sewage sludge, agricultural residues, automotive shredder residues) is gaining a clear role in the general frame of the circular economy (opposed to a linear approach where the resource is extracted, used and then disposed of) as one pathway to close the recycle loop when a material/chemical recycle is impossible or economically unfeasible [1–4]. Even though the calorific value of these materials can be lower than that of fossil fuels, and the amount of pollutants (e.g., based on sulphur, chlorine, nitrogen) possibly larger, their thermal conversion may mitigate disposal problems or respond to specific environmental legislations. Since a significant fractional content of waste-derived fuels has a biogenic nature, their use in energy generation can contribute to the net reduction of CO<sub>2</sub> emissions to the atmosphere. Depending on the physico-chemical properties of the alternative fuel, the technical and economic feasibility of thermochemical processing of waste-derived fuels may be improved by co-processing with fossil fuels [5,6].

Sewage sludge derived from the treatment of urban wastewaters is

currently facing rapidly increasing production volumes and severe restrictions of the conventional disposal options. Three disposal methods are used at present: recycling in agriculture, landfilling and combustion. Agricultural utilisation is hindered by the presence of heavy metals and organic micro-pollutants and, as a consequence, this kind of recycling is rapidly losing acceptance [7–9]. Landfilling is not considered anymore as an environmentally sustainable option due to liquid and gaseous emissions in soil, water and air, and is hardly compatible with the perspective of a circular economy as previously highlighted. Thermal conversion stems out as the most viable strategy to dispose sewage sludge, entailing large reduction of sludge volume and thermal destruction of the toxic organic constituents. In the frame of thermochemical conversion, sewage sludge can be classified in three different groups: dry sludge (> 80 wt% d.m.), semi-dried sludge (30–55 wt% d.m.) and mechanically dewatered sludge (20–40 wt% d.m.). In general dry sludge is not considered for single-fuel combustion, whereas semi-dried sludge is preferred to the wet one as the process does not need supplementary fuel.

Concerning thermochemical processing of waste-derived fuels,

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pyrolysis/gasification presents several advantages over the direct waste-to-energy combustion path. This is mostly related to the generation of syngas and condensable species which can be easily transported, burned or even exploited in gas-to-liquid fuel or chemical processes. These advantages may be somewhat counterbalanced by additional complexity and capital cost. Rotary kiln (RK) and fluidised bed (FB) reactors are frequently considered in the thermochemical processing of waste-derived fuels. FB converters ensure intimate mixing of solids and excellent thermal uniformity/stability which enable better control of thermochemical paths and reduce the occurrence of undesired side reactions [10–12]. For these reasons, combustion [13–16] and gasification [17–19] processes of alternative fuels in FB reactors are widely investigated. The favourable features of FB converters may be partly offset by the need for a better control of fuel size and composition, which may require fuel pre-treatment. Under this respect, the RK converters are less sensitive to the fuel nature and indeed able to accommodate large variations in fuel size, shape and composition, as well as calorific value, with minimal or no pre-treatment [20]. As a consequence, RK reactors are largely exploited in combustion [21,22], pyrolysis [23–25] and gasification [26–29] processes of both conventional and alternative fuels.

The present study addresses the development of a process for oxy-pyrolysis of sewage sludge in a rotary kiln converter. The aim of the process is the production of syngas from devolatilisation of a waste-derived fuel, with oxygen playing the role of promoting autothermal operation of the pyrolyser by controlled oxidation of volatile compounds. The analysis of literature dealing with thermal conversion of sewage sludge highlights a lack of understanding about the possible effect related to the way of oxygen feeding on the properties of the produced syngas. Therefore, after a section concerning the validation of the model by critical comparison with experimental literature data, the specific concern of the study will be the assessment of the effectiveness of staged oxygen feeding, as opposed to localised feeding at the reactor inlet, as a tool to selectively promote desired secondary reactions occurring in gas phase, like partial oxidation of tars [30]. The converter consists of a RK in which the oxidiser (O<sub>2</sub>-enriched air) is fed at multiple coordinates along the reactor axis, so as to obtain a reactant contacting pattern resembling that of a Zwietering reactor [31]. The reactor is modelled at the steady state using a 1.5D approach. Material and energy balances are set up considering a semi-lumped kinetic mechanism that was purposely developed to represent the complex chemical pathways of solid fuel, gaseous compounds, different tar components and soot. The model results are analysed with a focus on the effect of axial staging of the oxidiser on the quality of the produced gas and on the reactor performance.

## 2. The model

### 2.1. The reactor

The oxy-pyrolysis reactor is a rotary kiln equipped with a manifold for distributed feeding of the oxidiser (O<sub>2</sub>-enriched air), as schematically represented in Fig. 1. The reactor has been modelled in a 1.5D domain by considering the axial motion of solid phase (consisting of fuel and ballast inert material) and gases, with material and energy transfers between the two streams. The geometric/dimensional features of the system reproduce those of a pilot-scale reactor developed by Centro Sviluppo Materiali [32] in the frame of a joint research project aimed at the production of syngas by thermal processing of solid residues. The kiln is 2.64 m long, 0.9 m ID, inclined by 1° with respect to the horizontal plane and operated at atmospheric pressure. The oxidiser (O<sub>2</sub>-enriched air) is fed through a manifold with 7 nozzles equally distributed along a reactor length of 1.4 m (which represents nearly 50% of the total length). A bed of inert material is present as thermal ballast to moderate temperature non-uniformities. The ballast (which is assumed to be calcined bauxite) is loaded batchwise in the RK prior to

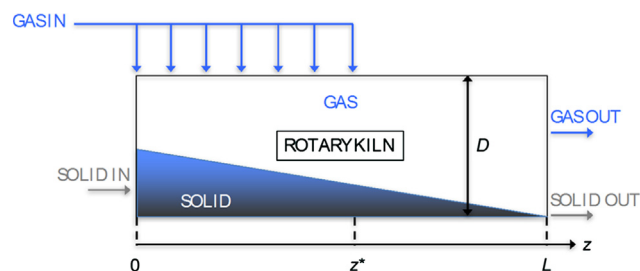


Fig. 1. Scheme of the oxy-pyrolyser reactor with uniform gas staging up to a critical axial coordinate.

operation and is considered isothermal with respect to the solid fuel. The solids discharge from the RK is designed so that the ballast is retained in the reactor – due to its coarser dimension – and only the pyrolysed sludge is continuously drained.

The axial motion of the solid fuel particles and of the gas follows the plug flow pattern. Radial mixing within the solid phase is effective to the point that segregation phenomena along the radial coordinate of the reactor could be neglected. Each of the two (solid and gas) phases is considered radially isothermal, though the difference in temperature between these two phases has been taken into account. The axial profile of the reactor wall temperature has been assigned. Intraparticle temperature profiles have been neglected. Table 1 gives the meaning of the symbols used throughout the article, together with related values.

### 2.2. The kinetic model

The kinetic mechanism of fuel decomposition and homogeneous reactions of primary products is reported in Fig. 2.

Immediately after feeding to the converter, the solid fuel undergoes rapid drying first, then devolatilisation. Any contact between the solid fuel and oxygen is ruled out in this stage, so that devolatilisation develops along a purely thermally activated – rather than oxygen-enhanced – decomposition path [33,34]. The gaseous species generated from fuel thermal decomposition and those present in the gaseous feeding eventually undergo homogeneous reactions according to the kinetic mechanism that is hereby detailed.

The following gaseous species are considered: O<sub>2</sub>, N<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>. Additionally, fuel devolatilisation yields tar. In the context of the present model, a semi-lumped scheme for tar evolution has been used as resulting from the reduction of a more comprehensive kinetic mechanism. Accordingly, tar is assumed to be composed of two components: a primary tar, T1, which is directly produced by fuel devolatilisation, and a secondary tar, T2, which is the product of secondary gas-phase pyrolytic reactions of T1. The secondary tar T2 may undergo further pyrolytic gas-phase dissociation to yield soot, which is assumed to remain suspended in the gas and is treated as a pseudo-gaseous compound. Primary and secondary tars differ as to their H/C ratio, which expresses the degree of aromatisation. For the purpose of the present computation, hexadecane (C<sub>16</sub>H<sub>34</sub>) was assumed as a surrogate of T1 and naphthalene (C<sub>10</sub>H<sub>8</sub>) of T2.

The following homogeneous gas-phase reactions have been considered:



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