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Theoretical and experimental procedure for scaling-up RDF gasifiers: The Gibbs Gradient Method

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ABSTRACT

The thermodynamic Model "Gibbs Free Energy Gradient Method" (GMM), published on the Vol. 90 (2011) of this Journal and validated with literature data, is now applied to the simulation of an experimental campaign realized at the ENEA Research Centre of Trisaia (Italy). The GMM well reproduces the experimental results of steam gasification of refuse-derived fuel (RDF) obtained on two laboratory and pilot scale rotary kilns.

Consequently, the experimental syngas composition is put in relation to the main process parameters through a new approach incorporating the GMM for identifying a reliable correlation between the extent of reactions and the gasifier temperature. This correlation appears independent from the scale of the rotary kiln and the residence time in the investigated range of variables. On this basis, the GMM is adapted to become a tool for designing industrial gasifiers starting from experimental data since the required final composition of the syngas and the required performances may be obtained by designing a gasification zone operating at the temperature calculated by the proposed method. It is believed that this procedure is extendable to other geometries and different type of apparatus by studying and including the effect of other parameters.

1. Introduction

The gasification is the thermo-chemical conversion of a solid carried out by a controlled amount of a gasification agent (air, O_2, steam). It involves the partial oxidation of fuels with the production of combustible gas and residues as heat, tars and solids. Therefore, the chemical energy of the solid is converted (under sub-stoichiometric conditions) into both thermal and chemical energy of the gas, a mixture of syngas (H_2 and CO) with a variable amount of CH_4 and CO_2 [1,2]. The process of gasification works in an ample range of operating conditions: pressure of 1–30 bara, temperature of 1000–1700 K and different gasifying agent. Air-based gasifiers typically produce syngas with high N_2 concentration and low LHV in the range 4–6 MJ/N m^3. O_2/steam-based gasifiers, on the other hand, produce syngas with high concentration of H_2 and CO and with a LHV in the range of 10–20 MJ/N m^3 [2]. The process can be realized in different configurations as fixed bed, fluidized bed and rotary drum gasifiers [2,3].

In the context of fossil fuel depleting and related climate changes, the biomass gasification is deemed as the most promising conversion technique for sustainable energy production thanks to its flexibility as regards both the feedstock and the produced fuels [4,5]. Moreover, the production of syngas from solids (instead of direct combustion) presents higher flexibility and chance of integration with advanced high-efficiency systems (as fuel cells) and the synthesis of alternative energy carrier or high valued materials [6,7].

The process of gasification has been developed from 1950s in order to transform coal in "town gas" and has been aimed at industrial use (Fischer–Tropsch synthesis) [8] or electric energy production [9] afterward. More recently, the biomass gasification has been subject of a renewed interest worldwide because of the environmental and political pressures to mitigate CO_2 emissions [10]. Indeed, nowadays, it plays an important role in the decarbonisation roadmap as the way to separate and capture the CO_2 from fossil fuels before the energy conversion processes [11]. Although these great potentialities, it has still a little commercial impact because is limited by technical problems (as the tar production and non-technical barriers) the spatial distribution and the lack of a supply chain [12].

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Nomenclature

Acronyms and variables

C_C	carbon conversion (wt%)
C_w	water conversion (wt%)
D	internal diameter of the kiln (m)
H	enthalpy (kJ/kg)
G	Gibbs free energy (kJ/kg)
L	kiln length (m)
LHV	low heating value (kJ/kg)
m	mass flow rate (kg/h)
N	rotation velocity (rpm)
MSW	municipal solid waste
Q_1	thermal power transfer to the process in step 1 (kJ/h)
Q_2	thermal power to the process in step 2 (kJ/h)
Q_{steam}	thermal power required for steam generation (kJ/h)
RDF	refuse-derived fuel
S	kiln slope (°)
SR	steam to RDF ratio (kg/kg)
t	residence time
w	volumetric flow rate (Nm^3/h)
Y_g	gas yield (kg/kg)

Subscripts

C	relative to carbon
char	relative to the char
dry	on dry basis
daf	on dry and N_2 free basis
g	relative to the gas
RDF	refuse-derived fuel
s	relative to the solid
w	relative to water

Greek letters

α	reaction coordinate of water gas shift reaction
β	reaction coordinate of steam reforming reaction
γ_s	carbon reforming parameter for steam gasification
γ_a	methane combustion parameter for air gasification
δ	Boudouard reaction parameter
η_{cold}	cold gas efficiency (–)
η_{comb}	combustion efficiency (–)
η_{hot}	hot gas efficiency (–)
θ	dynamic angle of response (°)

Thermal conversion processes are fundamental for the waste management systems in order to reduce the mass of waste and for recovering the energy content from unrecyclable materials. The gasification of waste has been exploited as alternative to combustion for the waste to energy (WtE) processes in order to improve the performances and the distributed WtE policy [13]. The conventional direct combustion process has the highest efficiency but worries public opinion and consequently the policy makers due to the pollutant emissions [11,14]. Although associated with lower power production and higher complexity, the gasification of solid wastes can count about a hundred of operating plants having a capacity in the range 10–250 $\cdot$ 10^3 tons per year and represents a valid alternative in the field of waste management [13,15,16]. Moreover, gasification-based technologies enable the reduction of waste amount to disposal in comparison to the conventional combustion-based WtE units and allows alternative strategies for the syngas utilization [16,17].

A gasifier is a complex equipment to realize and to operate; its efficacy depends on the concatenated phenomena of pyrolysis, partial oxidation of gaseous products, char gasification and conversion of tar and lower hydrocarbons. Moreover, the exploration of various working conditions in experimental apparatus is difficult and expensive. Although several valuable works investigate the process performances through experiments [18–21], many difficulties arise in the performance prediction because of the intrinsic process variability and the mathematical effort needed to model such a complex group of concatenated phenomena [22,23]. As a matter of fact, the complex task of simulating gasifier performances can be accurate only under limited conditions. Generally, kinetic models provide essential information on mechanisms but require the knowledge of several chemical–physical parameters and sophisticated experimental measurements [22]. Therefore, these models are limited to clearly defined mechanisms or go wrong at higher complexity [23,24]. On the other hand, equilibrium models are valuable for the investigation of thermodynamic limits as a guide to feasibility studies and techno-economical evaluations but generally fail to match experimental results (particularly at large scale and low reactor temperatures) [23–26]. This failure is commonly attributed to the hypothesis that the residence time is sufficiently long to reach the equilibrium state as well as to the disaggregation of specific reaction mechanisms from the transport phenomena. To overcome these limitations, some authors proposed to upgrade the equilibrium models by implementing adjustable parameters and semi-empirical correlations [24–28].

With this premise, we believe that it is of strategic relevance to improve the predictive capacity of engineers in designing, optimizing and scaling-up gasifiers by developing non-equilibrium models correlated to lab-scale experiments. Barba and co-authors ideated the Gibbs Free Energy Gradient Method Model (GMM) in 2011 validating it by simulating literature data of biomass gasification [29]. This novel approach introduced a reliable way to model gasification experimental results characterized by a finite residence time and the presence of non-reacted carbonaceous residue, once known proximate and ultimate analysis of the feed and operating conditions such as pressure, temperature and steam/feed ratio. The model, adjustable to any other kind of thermochemical conversion process and different feedstocks, is recognized in the literature among the non-stoichiometric non-equilibrium models, at the basis of the simulation of different gasification processes with low tar production [26,30–33]. Antonopoulos et al. stated that the Gibbs Free Energy Gradient Method Model (GMM) may be properly applied in a downdraft gasifier by providing synthesis gas composition for various biomass types at selected gasification temperatures with reasonable accuracy and implemented for designing a commercial gasification plant [33].

On the basis of what previously illustrated, seems fair to say that GMM Model got positive reception from the scientific community devoted to gasification studies. Only now we decided to use the Model to interpret our experimental data finalized to the industrial scaling up of a rotary kiln gasifier.

To this end, we have planned and conducted an experimental campaign based on the use of two rotary kiln (laboratory and pilot scale) whose volume ratio is equal to 70. We utilized the Model to simulate our experimental data as well as to show the possible application of the GMM for scaling up. Hence the correlation of experimental data is not only an extended validation of the model but becomes functional to its use.

The scope of the present work is to present a criteria of process simulation and scaling up based on the GMM utilizing the experimental data of refuse-derived fuel (RDF) gasification. We present