Fuel 153 (2015) 499–509

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

# Mass yield as guide parameter of the torrefaction process. An experimental study of the solid fuel properties referred to two types of biomass

M. Grigiante *, D. Antolini

*University of Trento, Department of Civil, Environmental and Mechanical Engineering, Via Mesiano 77, 38123 Trento, Italy*

ARTICLE INFO

*Article history:*
Received 23 May 2014
Received in revised form 21 January 2015
Accepted 12 March 2015
Available online 23 March 2015

*Keywords:*
Torrefied biomass
Mass yield
Energy yield
Experimental measurements

ABSTRACT

The objective of this experimental study consists in investigating the effects of torrefaction treatment on two different woody biomass chosen from softwood as *spruce pine* and annual grass lignocellulosic hardwood as *reed*. This thermal pre-treatment has been conducted in a small batch reactor directly fluxed by a controlled nitrogen flow. Tests have been carried out at different temperatures, ranging from 250 °C to 310 °C, and reaction time from few minutes to 1 h. Properties involved in this investigation are ultimate analysis, thermal quantities among which caloric value (HHV), fibers distribution and equilibrium moisture content. The obtained results confirm that torrefaction is a viable thermal pre-treatment to upgrade biomass and looks promising for a new generation of biomass derived fuel. As main topic, this research focuses on evaluating the role of the Mass Yield (MY) as synthetic parameter of the process. In particular it is made evidence that the properties of the torrefied samples can be led back to the MY without making reference to their thermal-time pathway. As example, considering two samples presenting the same MY of 80%, the former torrefied at 280 °C for 76 min, the second at 310 °C for 17 min, it is verified that the values of the aforementioned properties are very similar for both the samples even if submitted to different thermal pathways. The potentiality of the MY has been enhanced by extending this investigation to additional species of biomass pertaining to two groups, woody biomass and non-woody biomass. Inside the conditions ranges of the proposed experimental tests and for each of the indicated biomass type, an accurate linear correlation is obtained between MY and Energy Yield (EY) with a determination coefficient of ($R^2$) 0.98 and 0.97 for woody and non-woody biomass respectively.

Besides confirming the benefit of the torrefaction in enhancing the quality of the treated biomass, the use of the MY as synthetic parameter can be exploited to improve the torrefaction modeling schemes and to optimize the selection of the process working conditions. The proposed approach can therefore be useful to examine the relevant amount experimental data till now produced on this issue in view of exploiting and orienting their use towards real scale plant design.



## 1. Introduction

In these last years the torrefaction thermochemical pre-treatment, referred also to as mild-pyrolysis, is receiving a growing interest due to its high expectations for biomass upgrading [1–3]. During this thermal process raw biomass is usually heated in an oxygen-free atmosphere. However, some tests have recently been carried out in presence of oxygen [4] and non inert gases [5]. A recent investigation [6] has used microwave as heating source in place of inert gas. Despite these different approaches, during torrefaction biomass modifies into a solid biofuel product that, from a process point of view, has superior grindability [7,8], co-firing [9,10] and milling capability [10], improved fluidization properties [11] and, if pyrolyzed, the quality of the resulting bio-oil increases [12]. Biomass presents a complex composition, mainly comprised of hemicelluloses, cellulose, lignin, different types of compounds including extractives (fatty acids, tannins, resins) and ash. Torrefaction alters the composition of the biomass structure due to the thermochemical degradation of the hydrophilic polysaccharides and hydroxyl radicals which increases the percent of lignin content, causing also an increment in the energy per unit mass that can be moreover improved by pelletization process [13,14]. For torrefied pellets, handling and storage properties have been recently investigated [15] together with the influence in bio-resistance [9], the reduction in the hydroscopicity [16] and a

* Corresponding author. Tel.: +39 0461 282653; fax: +39 0461 282670.
*E-mail address:* maurizio.grigiante@unitn.it (M. Grigiante).

http://dx.doi.org/10.1016/j.fuel.2015.03.025
0016-2361/

carbon-like appearance [17,18]. Additional benefits of torrefied biomass include solid fuel combustion properties [19], a favorable impact on gasification [20], a reductions in $CO_2$ emissions when compared to coal combustion [21]. Besides the volatilization of highly oxygenated species, the further released volatiles, mainly composed of phenolic compounds, acetic and lactic acid and methanol [18,22,23], give rise to an energy flow whose recovery has been recently investigated [24]. For a full-scale review of this biomass pre-treatment, reference is made to Van der Stelt et al. [25], Chew and Doshi [26]. In summary, a wide range of torrefaction conditions are documented as reported also in the cited papers. Most of the experimental activities carried out and significantly incremented in these last years have focused the attention on monitoring the effects of time and temperature on the resulting properties of the torrefied biomass. Usually temperature is randomly selected on a range from 200 to 400 °C while duration from several minutes to 1–2 h. The present work expands this investigation as it assumes the Mass Yield (MY) as a constrain parameter to be imposed to the process. Pursuing this approach, this investigation consists in imposing the same MY but carrying out the process by following different temperature–time pathways. What emerges is that the macroscopic properties of the torrefied samples here investigated (energy yield, caloric value, fibers content, hydrophobic behavior) can be led back only to the MY imposed to the process, due to the fact that, for a selected MY, the time–temperature process pathway has no impact on the values of the corresponding obtained properties. This behavior has two relevant consequences: the first is that the MY parameter is directly correlated to the final state of the process independently from the pathway imposed to the process: this means that the macroscopic properties of the torrefied biomass can be directly deduced only from the knowledge of the MY of the treated samples; the second is that the process pathway can be optimized without having impact on the final quality of the resulting torrefied material: this means that the *temperature profile* and the *residence time* of the reactor can be optimized without having impact on the pursued MY and, consequently, on the final properties of the torrefied material. Investigations aiming at enhancing the role of the mass loss have been lately proposed, confirming therefore the interest for this approach. The effects of temperature and duration have been investigated [27] seeking to retrace their effects on defining a control protocol in continuous torrefaction analysis. Further, the potentiality of the MY as synthetic indicator has recently been considered [28,29], but from a different point of view and without verifying the effective role of this parameter as good for the characterization of the final quality of the torrefied biomass.

The theoretical justification of these results is not included in this work as this topic pertains to an extended work in progress involving an in-deep and well structured analysis. On this issue and specifically on transformation of wood constituent during torrefaction, significant works have been recently published [30,31]. Making reference to the actual state of art of this technology, it emerges that only a reduced number of productive units are active, most of which limited to pilot scale plants. As a consequence, also the economic aspects of this technology can, at the moment, only be estimated [32,33]. Limited to European countries scenarios, complete investigations in evaluating technical and economic feasibility of large scale torrefaction units have been proposed by Bergman et al. [9] and Bridgwater [34]. The results emerged during this investigation can be helpful to extend the knowledge of the torrefaction process from the actual pilot /small scale investigations to prototype industrial plants design. Further, the proposed approach could provide a key pattern to examine the huge amount of experimental data till now produced in view of their exploitation for large scale process applications.

## 2. Experimental torrefaction unit and material preparation

### 2.1. Experimental unit

The proposed investigation has been carried out on a dedicated equipment outlined on Fig. 1. It consists of a vertical stainless steel tube of 200 mm in length and 56 mm in diameter. The biomass is loaded on the upper part of the reactor and is hold at 50 mm above the bottom by a distributor plate that favors a uniform distribution of the hot gas that percolates, from the bottom, the biomass bed. A convective heating approach has been selected for this investigation as it conforms the most commercial heating solutions till now proposed. It is to point out that the actual configuration of this pilot reactor does not consider the use of any electrical tracing around the wall so that biomass is primarily heated only by convection. A flow of hot nitrogen, kept constant by an electronic flow controller in conjunction with a controller readout (Bronkhorst Instruments), flushes the biomass bed at a rate of 40 ± 0.20 l min$^{-1}$ (STP). The inert conditions are maintained by the continuous detection of the oxygen ($O_2$ concentration 0.0 ± 0.001%) monitored by an electrochemical sensor equipped on an Emission Monitor System (MRU GmbH Delta 1600). Nitrogen is electrically heated and its temperature controlled by an electrical resistance device (Leister Mini Sensor 800 W) before entering the reactor. This direct heating approach jointly with the high gas flow rate, allows to achieve a high heat flux between gas and particles to such the thermal homogeneity inside the bed and the reproducibility of the tests are satisfactory. The upper section of the reactor is the only one that can be opened for samples loading and, during the tests, is hermetically sealed by a suitable screw device. The temperatures monitoring is performed by using *k* type thermocouples fixed at suitable positions inside the equipment as evidenced on Fig. 1. For sake of clearness it is to point out that the temperature of the biomass bed is monitored by thermocouples $T_2$, $T_3$ and $T_4$ symmetrically buried inside the bed and located at a half radius distance from the reactor center. The amount of the biomass charge is selected in order to reach a bed height of 100 mm and to maintain a constant distance of 50 mm between $T_2$ and $T_4$ sensors. The in/out flow temperature is monitored by the thermocouples $T_1$ and $T_5$ while the ambient and the external reactor surface temperatures, also recorded, are not indicated. The entire rector surface is

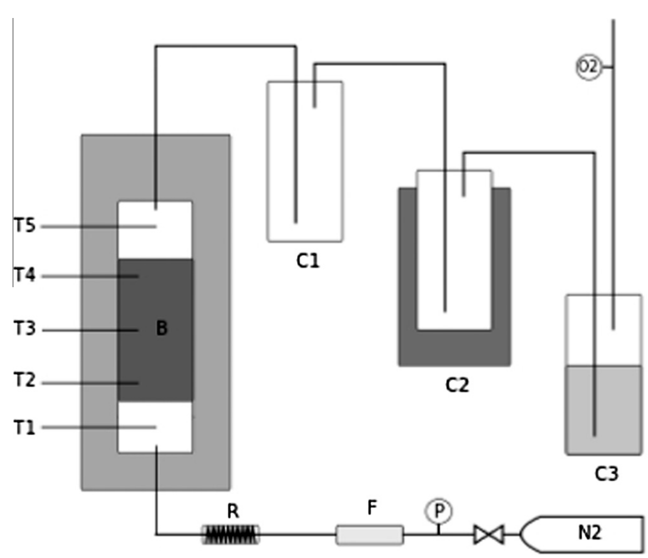


**Fig. 1.** Scheme of the torrefaction batch reactor: T1 to T5 – thermocouples; C1-ambient trap; C2-cold trap; C3-water trap; P-pressure sensor; F-flow controller; R-electrical resistance; O2-oxigen detector.