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Biomass gasification under high solar heat flux: Experiments on thermally thick samples

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HIGHLIGHTS

- Beech wood is exposed to radiative heat flux higher than 1000 kW/m^2.
- Sample geometry evolves dramatically.
- Temperature higher than 1500 °C are reached.
- Tar yield is lowered by thermal cracking and steam reforming.
- Initial moisture content plays key role in the biomass behavior.

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ABSTRACT

In this study, thermally thick samples of beech wood are exposed to radiative heat flux above 1 MW/m^2 (1000 suns). It was motivated by the fact that concentrated solar energy allows to achieve temperatures higher than 1200 °C where char gasification, tar thermal cracking and tar steam reforming can take place. It is achieved using a new experimental device made of an artificial sun and a new reaction chamber, that monitors the sample mass throughout a run and can trap the produced tars using a liquid nitrogen cooled tar condensing device. Thanks to this experimental device, it is possible to compute the average wood consumption rate as well as drying water, char, gas and tar production rates. The produced light gases are also analyzed using microGC. Furthermore, a radiometer is used to monitor surface temperature, which is around 1500 °C. First, a new behavior has been highlighted. Under high radiative heat flux, a char crater which mirrored incident heat flux distribution, is formed inside of the sample. Then, using this device, the impact of two major parameters was tested: wood fiber orientation relative to the solar flux and initial moisture content. Wood fiber orientation (end grain and with the grain) was shown to only have a minor impact on the production rates, gas composition and crater formation. Three initial moisture contents (0, 9 and 55 %wb) were tested. It was shown that increasing the sample moisture leads to direct drying steam gasification of the char produced by the pyrolysis. Moreover, steam also promotes tar steam reforming and therefore decreases the tar yield. Finally, form an energetic point of view, the dry samples can achieve an energetic conversion efficiency of 90%, capturing up to 72% of the incident solar power in chemical form.

1. Introduction

Mankind is currently facing an increase in energy cost and a climate change problem. Its reliance on fossil fuel has to decrease in favor of renewable energy sources. Among the candidates, biomass pyro-gasification is of note. This process allows to produce carbon neutral gaseous energy vector from biomass. Yet, the transformation of biomass into an energy rich gas is a succession of complex phenomena. It starts with the drying of biomass [1] around 100 °C, where water evaporates from the biomass. Then, pyrolysis takes place around 500 °C. This complex stage turns dry biomass into three main products: light gases (from H_2 to C_3H_8), tars (a mixture of more than 300 molecules [2]) and char [3]. Finally, around 800 °C, steam – and to a lesser extend CO_2 – can oxidize char and transform it into syngas (H_2 and CO). This high temperature also enables tar thermal cracking [4] and tar steam reforming [5]. The produced raw gas is therefore potentially a mix of pyrolysis gas, syngas and thermally cracked and steam reformed tars. Once cleaned, filtered or upgraded, this gas can be used in a wide variety

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of processes [6]: fuel cells [7], gas turbines [8], combustion for heat, Fisher Tropsch synthesis [9] or methanol synthesis [10]. Pyro-gasification is highly endothermic. Classically, heat is supplied by burning a fraction of the inlet biomass feed. Two main drawbacks come with this technique: the efficiency with respect to the biomass is lowered and the produced syngas is diluted by N_2 if air is used to power combustion in the gasification reactor [11,12].

Supplying the required heat using solar energy would avoid these drawbacks. Indeed, even on a large scale, solar concentrated power plants can achieve incident heat flux higher than 1000 kW/m^2. Hence, it is possible to reach a temperature of 1200 °C or higher and lead pyrolysis and gasification reactions [13].

Studies on the combination of biomass gasification and concentrated solar power have been led in the past. However, they mainly focused on reactor scale experiments and modeling. These studies have yielded more insight on the design of the reactors (fixed bed [14–17], fluidized bed [18,19], cyclonic [9,20]) and the possibilities of the technology. Two reviews are available on the subject [21,22]. Yet, they do not permit better understanding of biomass and solar power interaction.

The combination of solar energy and biomass still raises several questions at the sample scale. Radiative power has long been seen as a way to achieve high heating rates [23,1,24–27]. Recently, solar pyrolysis has been studied in order to assess produced char properties [13]. The study featured agglomerated wood powder pellets that were suitable to lead a thermally thin experiment, but not to understand the interaction between biomass and solar energy. Furthermore, the behavior of a thermally thick virgin piece of biomass under high solar heat flux has never been studied. Wood is an anisotropic material, thus fiber orientation relative to the incident heat flux may have an impact on the behavior of the sample. The initial moisture content may also alter the sample transformation. Indeed, char produced by biomass pyrolysis can undergo gasification if in contact with steam from drying. Moreover, tar thermal cracking [4] and tar steam reforming [5] may be favored. One could therefore expect a smaller tar yield and a higher direct raw gas production.

The aim of this article is to investigate the behavior of a thermally thick biomass sample under high solar heat flux. The biomass behavior is observed qualitatively, by examining its shape evolution, and quantitatively, by monitoring mass, gas compositions and temperatures. These measurements allow to expose a never reported before behavior as well as to draw closing mass and energy balances, providing valuable insights on the biomass solar pyro-gasification process.

2. Material and methods

A new experimental device was built in order to investigate the effect of the initial moisture content and of the fiber orientation on wood pyro-gasification behavior. The aim of the device is to expose thermally thick beech wood samples to radiative heat flux above 1 MW/m^2 (1000 suns). In order to achieve such high heat flux, an artificial sun was used [28–31]. Two main parameters were varied during this study: initial moisture content and fiber orientation.

2.1. Experimental apparatus

Fig. 1 provides a schematic of the reaction chamber. The beech wood sample is placed in an enclosure. A quartz window placed above the sample allows the radiative power to enter the enclosure and reach the sample surface. The sample is continuously swept by nitrogen in order to prevent gas and tars released by the sample to reach and soil the quartz window. This nitrogen sweep also ensures that no oxygen is present in the device at any time.

The sweeping nitrogen then carries released gas and tars through a tar condensing system. This system is made of a liquid nitrogen cooled condenser and a cotton trap. The condenser lowers the gas temperature, allowing the tar to condensate into small droplets. These droplets are then captured by the cotton trap. The condensing device is removable. It is also possible to run experiments where tars escape from the reaction chamber. It allows for the quantification of the tar production following a procedure described further.

During a run, the whole system is weighted using a scale. Therefore, the sample mass loss can be accounted for. A pyrometer is set in such a way that it measures sample surface temperature at the focal spot (Optctra 1MB CF2 CB3, working wavelengths: 0.7–1.1 μm, measurement range: 600–1800 °C). A set of three type K and S thermocouples is placed inside of the sample in order to monitor its core temperature. The repeatability of these measurements was very poor and they therefore are not reported. Finally, part of the gas escaping the condenser and the cotton trap were collected and analyzed using a microGC.

A xenon arc lamp is used as radiative power source. Its radiation is concentrated toward the sample surface using an elliptical mirror. This kind of device has long been used to emulate concentrated solar energy in terms of density and spectrum. It is often referred to as an artificial sun or solar simulator [32]. In our case, the biomass sample surface is set at the focal spot of the device. It receives about 655 W of Gaussian distributed radiation with a maximum above 1100 kW/m^2 (Fig. 2) [33].

2.2. Samples and varied parameters

The samples used are beech wood cylinders with a height of 5 cm and a diameter of 10 cm. Such massive samples were chosen to behave as slabs during a 5 min run. Knowing that wood is an anisotropic material, special care was taken in choosing the wood fiber orientation. Two batches of sample were used for the experiments: a first batch of sample made of end grain wood where the wood fibers are parallel to the cylinder axis (Fig. 3a), a second made of with the grain wood where the wood fibers are perpendicular to the cylinder axis (Fig. 3b).

Sample moisture content is also a parameter that was varied in this work. Three different moisture contents were used for the experiments: 0 %wb, oven dried until mass stabilized, 9 %wb, water content stabilized after several month under room condition and 55 %wb, impregnated in water until mass stabilized which is thought to be a representative state of the wood after cutting [34]. Because of the induced swelling and shrinking, the wood density varies with moisture content. The densities are 652 ± 40, 579 ± 38 and 535 ± 8.0 kg of wood/m^3 for, respectively, 0, 9 and 55 %wb initial moisture content samples.

2.3. Experimental procedure

The following steps were strictly followed for every run:

- weighting the sample, the reaction chamber, the condenser and the cotton
- cooling the condenser by immersing it in liquid nitrogen
- placing of the sample in the reaction chamber
- loading the liquid nitrogen cooled condenser and the cotton trap
- set up of the cell at the focal spot
- exposing the sample for 5 min while collecting gas sample
- cooling the sample under nitrogen sweep for 5 min
- extracting the sample
- weighting the sample, the reaction chamber, the condenser and the cotton