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Full Length Article

# Biomass gasification under high solar heat flux: Advanced modelling

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ABSTRACT

This article presents a new numerical model describing the behaviour of a thermally thick wood sample exposed to high solar heat flux (above 1 $MW/m^2$). A preliminary study based on dimensionless numbers is used to classify the problem and support model building assumptions. Then, a model based on mass, momentum and energy balance equations is proposed. These equations are coupled with liquid-vapour drying model and pseudo species biomass degradation model. By comparing to a former experimental study, preliminary results have shown that these equations are not enough to accurately predict biomass behaviour under high solar heat flux. Indeed, a char layer acting as radiative shield forms on the sample exposed surface. In addition to this classical set of equations, it is mandatory to take into account radiation penetration into the medium. Furthermore, as biomass contains water, medium deformation consecutively to char steam gasification must also be implemented. Finally, with the addition of these two strategies, the model is able to properly capture the degradation of biomass when exposed to high radiative heat flux over a range of sample initial moisture content. Additional insights of biomass behaviour under high solar heat flux were also derived. Drying, pyrolysis and gasification fronts are present at the same time inside of the sample. The coexistence of these three thermochemical fronts leads to char gasification by the steam produced from drying of the sample, which it is the main phenomenon behind medium ablation.

## 1. Introduction

World primary energy consumption has dramatically grown over the last thirty years, from 7.14 Gtoe (Giga ton of oil equivalent) in 1980 to 13.2 Gtoe in 2012 [1]. This increase heavily rested upon fossil fuels (oil, coal and natural gas) and led to the emission of important quantities of green house effect gases in the atmosphere [2]. In turn, these gases induced global warming and climate change [3]. To stop them, mankind reliance on fossil fuel has to decrease in favour of renewable energy sources.

Among the candidates, the combination of biomass pyro-gasification and concentrated solar energy is of interest. Indeed, a synergy of these two energy sources can be envisioned. Biomass pyro-gasification allows to produce carbon neutral syngas ($H_2$ and CO). Yet, it is an highly endothermic process which is classically powered by burning a fraction of the fed biomass. This technique induces two main drawbacks: the efficiency with respect to the biomass is lowered and the produced syngas is diluted by $N_2$ from the combustion air [4,5]. Concentrated solar energy can be used to supply the required heat. The produced syngas could therefore be considered as a new vector of solar energy. It would also allow to avoid the biomass combustion associated drawbacks. Economical assessments have shown the potential viability of this approach [6], while technical studies have aimed at understanding and increasing the efficiency of solar gasification reactors [7–12,5,13,14,5,15,10,16,17].

Until recently, studies mainly focused on reactor scale experiments and reactor modeling. These studies have yielded valuable insights on the design of the reactors [10,13,18,14,19,15,16,20,17,21] and the potentialities of the technology. Yet, they do not permit better understanding of biomass and solar power interaction. Only few studies have dealt with direct interaction of solar energy and biomass. Furthermore, they were restricted to solar pyrolysis [22–24]. In this context, modelling of the whole solar biomass pyro-gasification process can be of help.

Modelling such a process is challenging because several phenomena are at stake during biomass solar pyro-gasification. Biomass degradation starts around 100 °C with the drying of the feedstock [25]. During this stage, water evaporates from the biomass, leaving dry wood. Then, pyrolysis takes place around 500 °C. This complex process turns dry biomass into three broad categories of products: light gases, tars (a mixture of more than 300 molecules [26]) and char [27]. The last stage is char gasification. At temperatures around 800 °C, steam – and to a lesser extend $CO_2$ – can oxidise char and transform it into syngas. Furthermore, this level of temperature also enables tar thermal cracking [28] and tar steam reforming [29].

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**Nomenclature**

*Latin symbols*

| | |
|---|---|
| $A$ | frequency factor, 1/s |
| $a$ | pyrolysis water production factor, – |
| $Bi$ | Biot number, – |
| $b$ | pyrolysis char production correction factor, – |
| $c_p$ | specific heat capacity, J/kg/K |
| $D$ | diffusivity, $m^2/s$ |
| $d$ | diameter, m |
| $Da_{III}$ | Damköhler III number, – |
| $Ea$ | activation energy, J/mol |
| $g$ | gravity acceleration, $m/s^2$ |
| $h$ | convective heat transfer coefficient, $W/m^2/K$ |
| $k_B$ | Boltzmann constant, J/K |
| $k$ | reaction rate coefficient, 1/s |
| $L$ | characteristic length, m |
| $M$ | molar mass, g/mol |
| $P$ | power, W |
| $Pe$ | Péclet number, – |
| $p$ | pressure, Pa |
| $Q$ | volume heat source, $W/m^3$ |
| $q$ | relative permeability, – |
| $r$ | radius, m |
| $\mathfrak{R}$ | ideal gas constant, J/mol/K |
| $Re$ | Reynolds number, – |
| $S$ | pore liquid water saturation, – |
| $T$ | temperature, K |
| $t$ | time, s |
| $u$ | velocity, m/s |
| $Y$ | mass fraction, – |
| $z$ | height, m |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | absorptivity, – |
| $\Delta h$ | reaction heat, J/kg |
| $\delta$ | difference symbol, – |
| $\epsilon$ | emissivity, – |
| $\zeta$ | porosity, – |
| $\kappa$ | permeability, $m^2$ |
| $\lambda$ | thermal conductivity, W/m/K |
| $\mu$ | dynamic viscosity, Pa.s |
| $\nu$ | stoechiometric coefficient, – |
| $\xi$ | radiation penetration coefficient, – |
| $\rho$ | density, $kg/m^3$ |
| $\sigma$ | Stefan–Boltzmann constant, $W/m^2/K^4$ |
| $\phi$ | incident heat flux, $W/m^2$ |
| $\Psi$ | radiative heat loss function, $W/m^2$ |
| $\omega$ | reaction rate, $kg/m^3/s$ |

*Subscripts*

| | |
|---|---|
| *benzene* | benzene |
| *bulk* | bulk |
| *bw* | bound water |
| *cap* | capillary |
| *char* | char |
| *eff* | effective |
| *fs* | focal spot |
| *g* | gas phase |
| *gasi* | gasification |
| *I* | gaseous species index |
| *ini* | initial |
| *is* | intermediate solid |
| *J* | solid species index |
| *K* | reaction index |
| *long* | longitudinal |
| *lw* | liquid water |
| *pen* | penetration |
| *pore* | pore |
| *pyro* | pyrolysis |
| *s* | solid phase |
| *sat* | saturation |
| *sp* | sample |
| *steam* | steam |
| *sur* | surrounding |
| *water* | water |
| *wood* | wood |

*Superscripts*

| | |
|---|---|
| $M$ | total number of solid specie |
| $N$ | total number of gaseous specie |
| $O$ | total number of reaction |

*Other symbols*

| | |
|---|---|
| . | scalar product |
| $\boldsymbol{A}$ | vector and matrix notation |
| $\boldsymbol{n}$ | normal vector, – |
| $\nabla$ | nabla operator, 1/m |
| $\prod$ | product |
| $\sum$ | sum |
| $\|\ \|$ | norm |

In a previous work [30], solar pyro-gasification of thermally thick wood samples was conducted experimentally. Beech wood cylinders (10 cm diameter, 5 cm high) were directly exposed to radiative heat flux above 1 $MW/m^2$. The influence of two parameters was questioned: sample initial moisture content and wood fiber orientation with respect to the incident heat flux. The importance of biomass initial moisture content was emphasized while wood fibers orientation was shown to have little impact on biomass behaviour under high solar heat flux. Furthermore, this study has highlighted the potential couplings between different stages of biomass degradation, especially drying and char steam gasification. Finally, this study showed that sample geometry dramatically evolved during a run.

In the present work, modelling of the solar pyro-gasification of beech samples under the very same conditions is undertaken. In the first part of this article we show that conventional modelling approach is not able to capture the experimentally observed behaviour. The aim of this work is to enrich this conventional approach so that it can provide proper results. In order to do so, two advanced modelling strategies have to be implemented: moving mesh and radiation penetration inside of the medium. The model predictions are then validated against the experimental results obtained in [30]. Once the validity of the model has been established, its predictions are used to derive further insights on biomass behaviour under high solar heat flux.

## 2. Experimental device

The experimental device used to investigate solar pyro-gasification of thermally thick wood samples is extensively described in [30], only the main features are recalled here. It is made of an artificial sun producing heat flux above 1 $MW/m^2$ (1000 suns) and a reaction chamber