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Modelling and evaluating a solar pyrolysis system

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A B S T R A C T

This study investigates the use of solar energy for producing biofuels through pyrolysis. A model is outlined to define the ideal parameters and evaluate the annual performance of a solar pyrolysis system. The model is demonstrated by considering a linear Fresnel reflector (LFR) system operating in Seville, Spain. The ideal operating temperature and total residence time were determined to be 571 K and 149 min, respectively. Subsequently, an LFR system was sized to have a total reactor length of 3.23 m, a polar inclination angle of 39° and an effective concentrating aperture area of 4.55 m^2. The maximum char yield fraction was found to be 40.8 wt.%; however, the annual variability of the solar input resulted in the system producing 1375 kg of biochar from 13.9 t of biomass. The model developed in this study can be applied to evaluate a range of solar thermal technologies in other localities for producing char, gar and oils through the pyrolysis process.

1. Introduction

Pyrolysis involves the thermal degradation of a substance in the absence of oxygen. The outputs from the process are gas and liquid products, and a carbon-rich solid residue called char. Densifying biomass into a biochar through pyrolysis provides several benefits as it increases energy density, reduces cost of transportation, makes it more grindable and provides a more homogeneous product. Whilst biochar can be utilised as a solid fuel, it can be used in a range of applications to achieve agricultural and environmental gains [1]. Biochar can be used for improving water retention and increasing soil fertility. Energy can be generated from pyrolysis gas and liquid products and, as biochar acts as a long-term carbon sink, there is the potential for systems to be carbon negative [2].

Slow pyrolysis, which involves relatively low temperatures (300–500 °C) and long residence times (minutes to hours), produces comparable liquid, gas and biochar yields. Fast pyrolysis (>500 °C) is used to increase the liquid fraction [3,4] and torrefaction (200–300 °C) is a mild form of pyrolysis used primarily for char production [5]. Typically, electricity or fossil fuels are used to provide the heat to a pyrolysis system, as the energy input can be easily controlled. However, to improve the sustainability of pyrolysis systems, alternative renewable energy sources are being investigated [6]. In hot rural areas there is an abundance of solar energy and grid electricity is often unavailable or unreliable, thus there has been a growing interest in the use of solar energy [7].

Concentrating solar thermal power (CSP) systems comprise a concentrator and a receiver. Several authors have investigated using a solar concentrator to provide the heat input to a receiver acting as a pyrolysis reactor. Morales et al. [8] evaluated the use of a parabolic trough collector (PTC) for pyrolysis using ray-tracing, but they did not go on to consider the impracticalities associated with solar tracking, off-axis rays and variable diurnal and seasonal irradiance levels. A fast pyrolysis system using a parabolic dish reflector (PDR) was proposed by Joardder et al. [9]. Their study focused on the biomass and solar resource availability in Bangladesh. Zeng et al. [10] outlined a two-stage heliostat-PDR concentrator with a shutter system for controlling heating rate and temperature of a pyrolysis reactor. Their study addressed the effects of temperature (600–2000 °C) and heating rate (5–450 °C/s) on char yield and properties, rather than on the performance of the system. Zeaiter et al. [11] built and tested a solar pyrolysis system using a Fresnel lens with two-axis tracking. The system reached temperatures of 550 °C and was used to pyrolyse waste rubber.

High temperature CSP systems have been examined for producing hydrogen and syngas. Abanades et al. [12] looked at obtaining hydrogen through the pyrolysis of natural gas using solar energy, and Kruesi et al. [13] studied solar gasification of bagasse. Z'Graggen & Steinfeld [14] investigated the use of a solar furnace for hydrogen production via steam-gasification, and they used a kinetic

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Nomenclature

A	Pre-exponential factor (1/s)
A_c	Effective concentrating aperture area (m^2)
A_s	Area of biomass particle (m^2)
b	Time constant (-)
B_i	Biot number (-)
C_p	Specific heat capacity of biomass (J/kgK)
DNI	Direct normal irradiance (W/m^2)
D_p	Biomass particle diameter (m)
D_r	Reactor diameter (m)
$E_{a,cj}$	Activation energy of char reaction (kJ/mol)
$E_{a,tj}$	Activation energy of tar reaction (kJ/mol)
F_{rp}	View factor between the reactor wall and the biomass particles (-)
h_p	Enthalpy for pyrolysis (MJ/kg)
h_r	Height of reactor from concentrating elements (m)
h_{rad}	Radiation heat transfer coefficient between reactor wall and biomass (W/m^2K)
$IAM_{(\theta t,\theta l)}$	Incidence angle modifier (-)
k_b	Thermal conductivity of biomass feedstock (W/mK)
k_{cj}	Char-reaction rate coefficient for each biomass component (1/s)
k_{tj}	Tar-reaction rate coefficient for each biomass component (1/s)
L_{op}	Reactor length for processing feedstock at an ideal operating temperature (m)
$L_{reactor}$	Total reactor length (m)
L_{heat}	Reactor length for biomass heating (m)
$\dot{m}_c$	Mass flow of produced char (kg/s)
$\dot{m}_g$	Mass flow of produced gas (kg/s)
$\dot{m}_j$	Mass flow of each component (kg/s)
$\dot{m}_{j0}$	Mass flow of each component introduced into the reactor (kg/s)
$\dot{m}_t$	Mass flow of produced tar (kg/s)
Q_{in}	Heat delivered to solar receiver absorbing surface (W)
Q_{loss}	Heat loss (W)
Q_u	Heat gained by biomass particles (W)
R	Universal gas constant (kJ/molK)
T_a	Ambient temperature (K)
T_i	Initial biomass temperature (K)
T_{op}	Ideal operating temperature (K)
t_{op}	Residence time (s)
t_{perm}	Total residence time (s)
T_r	Reactor wall temperature (K)
t_{heat}	Time for biomass particles to reach ideal operating temperature (s)
U_L	Heat loss coefficient (W/m^2K)
$\dot{V}$	Feeding rate (m^3/s)
V_s	Volume of each biomass particle (m^3)
X_{cj}	Char-gas mass proportions (-)
Y_c	Char yield fraction (%)
Y_j	Biomass component mass fraction (-)
α_s	Solar altitude angle (degrees)
γ_s	Azimuth angle from the south (degrees)
ε_p	Biomass void fraction (-)
ε_r	Inner reactor wall emissivity (-)
$\eta_{0=\theta}$	Collector optical efficiency at normal incidence angle (%)
$\eta_{end\text{-}loss}$	End-loss efficiency (%)
η_{total}	Total optical efficiency (%)
θ	Incidence angle (degrees)
θ_l	Longitudinal angle (degrees)
θ_p	Collector inclination angle (degrees)
θ_t	Transversal angle (degrees)
ρ_s	Biomass density (kg/m^3)

model to size the reactor and specify operational parameters. Several other authors have considered using a CSP system to provide heat indirectly for gasification processes [15–18]. Whilst an indirect system will increase cost and complexity, it does offer improvements in control and stability.

Issues with using a CSP system to provide the heat input to a pyrolysis reactor arise due to the variable nature of solar energy and the need for solar tracking. Additional difficulties are caused when using a PTC and PDR system, as they use expensive fragile receivers that need to move with the tracking system. An alternative CSP technology is the linear Fresnel reflector (LFR), which is a relatively simple and inexpensive technology. The receiver tower is fixed—removing the need for flexible hosing and a fragile evacuated tube—and insulates a single pipe or multiple tubes. Biomass could, therefore, be fed into this heated pipe and transformed into char, gas and pyrolysis oil products (see Fig. 1). Unlike expensive parabolically shaped mirrors, the LFR also uses low-cost flat mirror element segments that can be rotated to control receiver temperature. However, an LFR's individual mirror elements are normally driven by independent motors, which can increase complexity. Another disadvantage of the LFR system is that it captures less energy than other solar collectors due to a lower optical efficiency. As with all CSP systems, there is a need for research to provide methods for sizing them for specific applications and evaluating daily and annual performance.

This study aims to outline a theoretical model for sizing and evaluating the performance of solar pyrolysis systems by integrating pyrolysis kinetics, sun-earth geometry relations and solar thermal performance calculations. Using this model, the LFR technology and the impact of variable solar irradiance levels on biochar production and other system outputs is to be investigated. This will enable diurnal and seasonal changes in the product yields from a solar pyrolysis system to be modelled for specific locations.

In the following section, the method used to achieve this study's aim is outlined. In Section 3, a model is developed for simulating

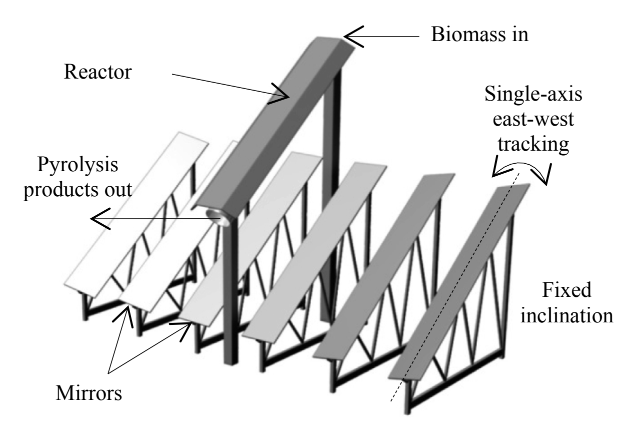

Fig. 1. A linear Fresnel reflector with a polar alignment and east-west single-axis tracking.