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Solar pyrolysis of carbonaceous feedstocks: A review

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ABSTRACT

Solar pyrolysis of a carbonaceous feedstock (coal, biomass and wastes) is a process in which carbon-containing feedstocks are used as chemical reactants and solar energy is supplied as high-temperature process heat. This process has the potential to produce higher calorific value products with lower CO_2 emissions than conventional pyrolysis processes. As a consequence, the intermittent solar energy is chemically stored in the form of solar fuels. Solar pyrolysis was first demonstrated in an indoor environment using a solar simulator (image furnace) for exploring the fundamental mechanisms of carbonaceous feedstock pyrolysis under severe radiative conditions (high temperatures and heating rates) in comparison to conventional pyrolysis. More recently, low-temperature solar pyrolysis has been demonstrated to be a good technology for bio-oil production. Our high-temperature solar pyrolysis process produces more combustible gas products than other processes. This paper reviews developments in the field of solar pyrolysis processing by considering fundamental mechanisms, experimental demonstrations, models and challenges.

1. Introduction

Fossil fuels supply approximately 78.4% of the world's overall energy needs in 2013 which are widely used for transportation, electricity generation, industrial processes, and heating. At the same time, fossil fuel combustion is a major source of greenhouse gas emissions, which are contributing to global warming. Moreover, there is an increasing awareness that the increased deployment of renewable energy, such as solar energy, is critical for addressing climate change, the energy crisis and creating new economic opportunities. In 2013, renewable energy contributed 19% of the global energy consumption. Of the renewable energy sources, solar energy contributed less than 1.0%, as shown in Fig. 1 (REN21, 2014). Fig. 2 indicates that the expected development of renewable energy production between 2010 and 2040 (from 19% to 47.7%) will include a significant increase in solar energy (from 0.24% to 10%) (IEA, 2014).

Solar energy is viewed by some experts as the alternative with the greatest intermediate to long-term potential to replace fossil fuels. Solar energy technology development has been largely focused on electricity generation. While solar energy is important, solar electricity does not fulfill the main advantages of high-energy density fuels (accounting for approximately 70% of the overall energy needs) for transportation, industrial processes, and heating. Consequently, it is important to utilize solar energy for the production of clean alternative fuels (Bensaid et al., 2012). Two important challenges must be overcome to attain this goal. The first challenge is the need to increase the solar radiation flux density given the dilution of terrestrial solar radiation (only approximately 1 kW/m^2 for a clear day). Optical reflective concentration devices (such as parabolic troughs, linear Fresnel reflectors, parabolic dishes and central towers) have been used to focus incident solar radiation on surfaces that are much smaller than the collection surfaces of the mirrors. The second challenge is the need to provide appropriate reactants for the conversion of intermittent solar energy into fuels. Carbonaceous feedstocks (coal, biomass and wastes) consisting of carbon and hydrogen could be appropriate reactants because they can store energy in the combustible form due to thermochemical transformation. There are two solar thermochemical processes that combine concentrated solar energy and carbonaceous feedstocks together for converting solar energy to chemical fuels. The first process is solar gasification for syngas production, which has been investigated in the last 20 years (Piatkowski et al., 2011). The second process is solar pyrolysis for bio-oil, biochar and gas production, which entered the research field in the last 40 years and now has garnered renewed interest (Zeng et al., 2015a,

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Nomenclature

Latin letters

A	pre-exponential factor (1/s)
a	stoichiometric coefficient for gas (–)
b	stoichiometric coefficient for tar (–)
C_p	heat capacity (J/kg/K)
D	diffusion coefficient (m^2/s)
E	activation energy (J/mol)
F	momentum source term (Pa/m)
g	gravity (m/s^2)
k	reaction rate constant (1/s)
L	length (m)
M	molar mass/moisture content (kg/mol/wt%)
m	mass (kg)
P	pressure (Pa)
Q	heat generation (W/m^3)
R	radius (m)
R_g	ideal gas constant (J/mol/K)
x	cylindrical coordinate m
r	cylindrical coordinate m
S	source term (kg/m^3/s)
T	temperature (K)
t	time (s)
v	velocity (m/s)
HHV	higher heating value (MJ/kg)
LHV	lower heating value (MJ/kg)
X	mass fraction (wt%)
U	upgrade factor (–)
$\vec{u}$	intrinsic velocity vector (m/s)

Greek letters

Δh	reaction heat (J/kg)
ΔT	temperature difference (K)
Δt	time difference (s)
ε/ξ	porosity (–)
$\lambda/\bar{\lambda}$	thermal conductivity (W/m/K)
μ	viscosity (Pa s)
ρ	apparent density (kg/m^3)
η	pyrolysis degree/Efficiency (–)
ω	reaction term (kg/m^3/s)

Subscripts

s	solid
i	component (w, c, is)
Ar	argon
c	char
cond	conductive
eff	effective
g	gas
is	intermediate solid
r	radial direction
rad	radiative
t1	primary tar
t2	secondary tar
V	volatiles (g, t1, t2)
w	wood
C	carbon
H	hydrogen
O	oxygen
N	nitrogen
S	sulfur
A	ash
oil	bio-oil product
gas	gas product
char	biochar product
feedstock	carbonaceous feedstock

2015b, 2015c, 2016, 2017a, 2017b, 2014, 2015; Li et al., 2016; Soria et al., 2017).

Gasification is a process in which carbonaceous materials are reacted with a controlled amount of oxygen, CO_2 and/or steam at high temperatures (>700 °C) to produce CO, H_2 and CO_2. However, the generation of unwanted char and tar is a serious issue preventing the broad implementation of gasification technology. In contrast, if the carbonaceous feedstock is heated in the absence of oxygen, then a mixture of gases, bio-oils, and biochars is generated. The most obvious differences between solar gasification and solar pyrolysis are the different reaction pathways caused by the differences in the surrounding atmosphere. Solar gasification itself combines solar pyrolysis and subsequent oxidation reactions. During the solar pyrolysis process, the concentrated solar radiation supplies high-temperature process heat for carbonaceous feedstock pyrolysis reactions (Chueh et al., 2010). Then, solar energy

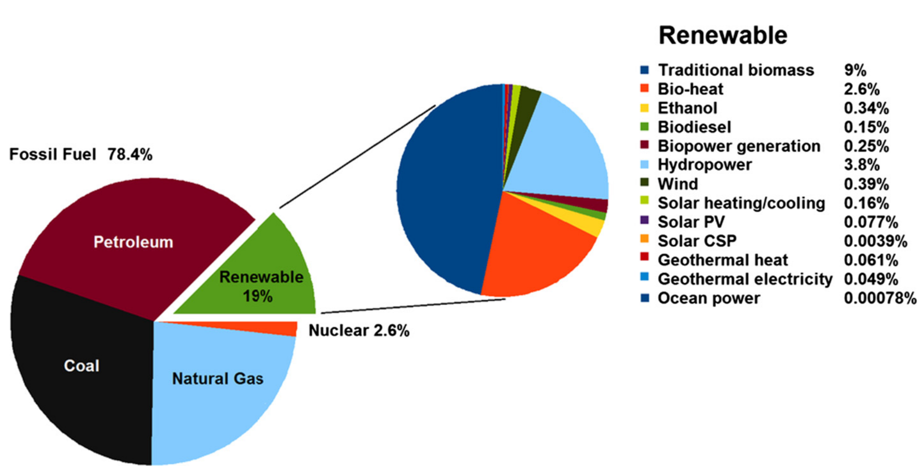

Fig. 1. Total world energy consumption by source in 2013 (REN21, 2014).

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