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Circulating fluidized bed gasification tests of seed cakes residues after oil extraction and comparison with wood

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HIGHLIGHTS

- Sunflower and jatropha seed cakes.
- CFB gasification.
- The fate of inorganic constituents contained in ash.

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ABSTRACT

Cake residues derived from seed crops after oil extraction could be used as fuel to cover a part of heat or power demands of such a procedure. These can be accomplished effectively via thermochemical processing, such as gasification. Contrary to the gasification of woody materials which has been investigated extensively, there is fewer data on gasification applications of residues from newly introduced oil crops after their oil extraction. In this work, seed cake residues of sunflower and Jatropha were gasified.

Air gasification tests of these cakes were conducted in a 100 kW_{th}, atmospheric, circulating fluidized bed (CFB). The effect of temperature and bed material on the composition of product gas and tar formation from was compared to willow. Experimental results show that the Carbon Conversion Efficiency (*CCE*) and cold gas efficiency (*CGE*) were higher in the case of cakes, especially for sunflower. On the other hand, tar levels were also higher compared to willow. Pilot scale tests were carried out using either olivine and quartz as bed materials. The examination of bed material particles revealed that potassium and calcium derived from the ash accumulated inside the olivine structure, which was not apparent in the case of silica sand where a calcium external layer was observed.

Since the biomass ash content and speciation affects the operability of the gasifier, after the end of each trial, fly ash samples from the removal system of particulates, as well as bed ash samples were collected. Various characterization techniques such as X-ray Fluorescence (XRF), Thermogravimetric Analysis (TGA), Ash Fusion Temperature (AFT) and Scanning Electron Microscopy (SEM)/Energy Dispersive X-ray Spectroscopy (EDS) were performed to determine the physicochemical properties of each fuel ash in detail, as well as the fate of inorganic elements initially contained in it.

1. Introduction

Biomass is a renewable energy source which has been traditionally used to produce heat by combustion. Lately, it has gained further interest due to the limitation of fossil fuel supplies and the demand for lower CO_2 emissions. Apart from direct combustion for power generation, biomass may be used for biofuel production through biological and thermochemical processing [1]. Liquid biofuels derived from oil crops via extraction techniques are considered as first generation biofuels, while bio-liquids produced from residues (such as seed cakes) after further pressing or thermochemical processing (pyrolysis or gasification) and Fischer–Tropsch are second generation biofuels [2].

1.1. Sunflower

Sunflower (*Helianthus annuus* L.) is an annual coarse, erect plant with a large flower head which belongs to the Asteraceae family [3]. Originated in North America, sunflower was introduced to

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Nomenclature

C	carbon content in biomass, %
H	hydrogen content in biomass, %
S	sulfur content in biomass, %
N	nitrogen content in biomass, %
O	oxygen content in biomass, %
ASH	ash content in biomass, %
C_D	drag coefficient of a single particle
d_p	mean particle diameter, m
$c_{CO}, c_{CH_4}, c_{CO_2}, c_{tar}, c_{in}$	rate of carbon mass contained in CO, CH_4, CO_2, tar and biomass feeding, kg/s
CCE	carbon conversion efficiency, %
CGE	cold gas efficiency, %
ER	equivalence ratio
g	gravitational acceleration, m/s^2
h_g	latent heat of steam, MJ/kg
HHV	higher heating value of solid fuel, MJ/kg
LHV	lower heating value of solid fuel, MJ/kg
LHV_s	LHV of syngas produced, MJ/m^3_N
$\dot{m}_{fuel}$	mass flow rate of fuel, kg/s
M	moisture percentage in ash free basis,%
M_g	mass flow of product gas, kg/s
$\dot{\eta}_{air}$	air inlet rate, mol/s
$\dot{\eta}_{N_2,in}$	N_2 inlet rate, mol/s
$\dot{\eta}_{syngas}$	gas outlet rate, mol/s
P	pressure of gas mixture, Pa
Q_{in}	thermal input, kW
T	temperature, K
u_{mf}	minimum fluidization velocity, m/s
u_s	superficial velocity, m/s
u_t	terminal velocity of a single particle of the bed inventory, m/s
$X_{CO}, X_{CO_2}, X_{CH_4}, X_{H_2}, X_{N_2,out}$	fraction of CO, CO_2, CH_4, H_2 and N_2 in syngas, %
y_i	the content of each inorganic element in fly ash, %
x_i	the content of each inorganic constituent in fuel, %
m_{flyash}	the mass of collected fly ash, kg
m_{fuel}	the mass of biomass, kg
t	the total duration of gasification run

Greek letters

ε_{mf}	voidage at minimum fluidization
λ	equivalence ratio (same as ER)
μ	fluid viscosity, Pa s
ρ_g	fluid density, kg/m^3
ρ_s	solid particle density, kg/m^3
φ_s	sphericity factor of a particle

Europe through Spain and nowadays, a large share of its worldwide production is in Russia [4,5]. In addition, it is cultivated in Asia and Africa [3,4]. It is tolerant to temperatures as low as −5 °C at cotyledon stage while freezing temperatures can destroy the plant at other stages. Although it is not drought-tolerant, it has a better performance at lower levels of irrigation compared to other crop. It grows in a wide range of soil types from sands to clays [3,5]. Nevertheless a salty soil is inappropriate for sunflower cultivation and its growth requires the use of fertilizers containing nitrogen, phosphorus and potassium. The plant can grow up to 1–3 m and its life cycle lasts about 120 days [6]. The sowing period starts at March or April and harvesting occurs at September or October, producing an approximate seed yield of about 0.3 kg/m^2 [5,7]. The oil content of sunflower seeds is 40–50% per dry mass [5,8,9]. The average plantation density is 4 $plants/m^2$ [9]. Sunflower is a crop from which first generation biofuels can be produced, as it's a famous edible-oil producer. A typical range of the productivity of oil extraction plants using sunflower seeds is 6300–7500 Mt of oil per month and 4000–5500 Mt of seed cake [10–12]. A power plant of 25 MW_{th} capacity could operate by using these solid residues [10–12]. Current research focuses on energy and bio-fuel production from sunflower seed cake after oil extraction, which is also used as livestock feed [9]. Seeds of non-oil varieties can be used for human consumption, while the plant itself can be used for fodder, silage and as a green manure crop. In addition to being an excellent food source, sunflower oil is also used in soap, lubrication and pesticide industry [5].

1.2. Jatropha

Jatropha (*Jatropha curcas* L, JCL) is a large shrub or small tree which belongs to the Euphorbiaceae family. It is native to Mexico and Central America, however it is also found in Africa and Asia after its distribution by Portuguese seafarers in the 16th century [13]. Jatropha's adaptivity to a wide rainfall range, varying from 250 to 3000 mm per annum, is of great importance as it can be grown even at non-irrigated fields [14]. Furthermore, it is tolerant to high temperatures and has low nutritional requirements, apart from the restriction of it being cultivated in a soil pH below 9 [15–18]. The plant grows fast and its final height can be up to 8 m with favorable conditions or commonly up to 3 m [19,20], while its life expectancy can be up to 50 years [17]. The seed yield ranges from 0.05 to 1.2 kg/m^2 per year and contain 30–35% oil per dry mass, which is not edible due to the toxicity of JCL seeds [13]. Therefore, it can generally be described as a second generation crop. Planting density has been estimated from 2 × 2 to 5 × 2 m^2 per plant, the latter in order to ensure cultivation under mechanized practices [21]. In India, a typical annual turnover for 200,000 m^2 is ∼19,000$ while the cultivation cost (for the same area 200,000 m^2) is ∼9500$ [22].

Jatropha curcas tree is used for medical purposes such as skin diseases, rheumatic and muscular pains [23] or for its antibiotic activity against yellow fever [24,25]. Also, it opposes soil erosion, improves soil quality and acts as a live fence to protect gardens and crop fields from livestock or as a fire barrier [26]. The seed cake after oil extraction can be used as fertilizer, fuel and feedstock for biogas production [24]. Seed oil and oil extracts can be used as cooking and lighting fuel, bio-pesticide, biodiesel through transesterification, as well as in soap industry [26]. In addition, its oil can be used for the production of liquid fuels, which can be used for transport purposes, etc. [25,27]. Furthermore, its residual seed cakes can be utilized as feedstock for small decentralized gasification (or combustion) plants [28].

1.3. Willow

Willow (genus *Salix*, *Salicaceae* family) is a perennial woody crop which is mainly distributed in temperate and arctic zones, basically in the Northern Hemisphere, but some species are also found in the tropical and subtropical zone [29]. Height of different willow species varies from a few centimeters for shrubs to 25 m for trees or even higher, up to 40 m [29,30]. Willow is planted in rows in March–April and it is harvested every 4 years, between December and April [31]. High plantation density and rapid growth are the major advantages of cultivating willow. According to literature, an average yield of 1–1.2 kg/m^2 per year and a planting density of