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Experimental and numerical simulation study of oxycombustion of fast pyrolysis bio-oil from lignocellulosic biomass

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ABSTRACT

Experimental measurements and numerical simulations were conducted to examine the effects of varying O_2 concentrations, oxidant velocity (V_o) levels, and bio-oil proportions on the combustion characteristics of the bio-oil/kerosene mixtures. The results indicated that when the O_2 concentration was 30% and the liquid fuel flow rate in the spray combustor was fixed, the flame associated with the spray combustion of pure kerosene decreased in length and increased in luminosity as V_o increased; moreover, the flame temperature increased. When $V_o = 5.53$ m/s, this phenomenon was more visible when the bio-oil was added to the kerosene. When the bio-oil proportion was 15% and $V_o = 3.87$ m/s, the flame luminosity increased; however, the flame luminosity decreased when V_o exceeded 3.87 m/s. When the O_2 concentration reached 40%, the length, luminosity, and temperature of the flame increased; nevertheless, when $V_o = 5.53$ m/s, the flame temperature decreased. The effect of the bio-oil proportion was not apparent. Because the bio-oil contained more volatile substances and O_2 than did the kerosene, the combustion efficiency of the bio-oil-fossil fuel mixtures varied according to the bio-oil proportion and O_2 concentration.

1. Introduction

Fast pyrolysis bio-oils are completely different from petroleum fuels and other bio-fuels available in the market, as regards both to their physical properties and chemical composition [1]. Bio-oil is produced through the fast pyrolysis of biomass, and its composition varies with the condensation temperature in the fast pyrolysis process [2–7]. Bio-oil can be categorized into two phases, oily and aqueous [8]. Bio-oil contains a higher amount of volatile biomass substances when condensed at a lower temperature. Therefore, all the aforementioned factors affect the efficiency of bio-oil in power machines. Yang et al. [8] produced bio-oil through the fast pyrolysis of various biomasses, and they categorized the phase of the produced bio-oil into two types, namely oily and aqueous phases, according to its condensation temperature; this categorization was based on the varying biomass compositions during the pyrolysis process. Ferdous et al. [9], Wang et al. [10], and Raveendran et al. [11,12] have indicated that the compositions, pyrolysis temperature, and condensation temperature of biomass affect the characteristics of bio-oil including its heating value, viscosity, boiling temperature, and pH value. In addition, the stability of bio-oil storage is associated with biomass compositions [13]. Lappas et al. [14] used catalysts to improve the quality of bio-oil relative to that of fossil fuel products.

Currently, bio-oil is typically mixed with fossil fuel and subjected to spray combustion for application in power plants. Because bio-oil and fossil fuel differed in their compositions, they must be emulsified to ensure that they are mixed appropriately for spray combustion. Stamatov et al. [15], Nguyen and Honnery [16], and Zheng and Kong [17] have investigated the spray combustion characteristics of bio-oil with different biomass contents when mixed with fossil fuels. Because the combustion of bio-oil is difficult, the bio-oil was added to flammable polar additives or mixed with fossil fuels such as alcohol, kerosene, diesel, and heavy oil. The results revealed that the flames produced by the bio-oil were shorter and brighter because of the flammable polar additives [15]. After an increase in ambient pressure, soot was produced in the outer ring of the spray combustion flame [16]. The exhaust gases emitted by the spray combustion of the bio-oil/fossil fuel mixture contained carbon monoxide (CO), nitrogen oxide (NO_x), and sulfur oxide (SO_x) [17]. All of these results are related to the characteristics of bio-oil such as its heating value, composition, and moisture.

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Nomenclature

B	constant
C	constant
C_D	drag coefficient
D	mass diffusivity
E	energy
F	body force
h	enthalpy of ideal gases
J	diffusion flux of species
k	thermal conductivity
k_t	turbulent thermal conductivity
K	wave number
p	pressure
Pr	turbulent Prandtl number
r	diameter of droplet
Re	Reynolds number
S	mass source vaporized
S_{ct}	effective Schmidt number for the turbulent flow
T	temperature
Y	mass fraction of species
Vo	oxidant velocity
Z	Ohnesorge number
We	Weber number

Greek symbols

τ	time scale
μ	dynamics viscosity
ρ	density, kg/m^3
σ	surface tension
τ	stress
Λ	wave length
Ω	frequency
v	droplet velocity

Subscript

d	droplet
ε	dissipation rate
g	gas phase
i	species
k	turbulence kinetic energy
l	liquid
m	mass
t	turbulent
KH	Kevin–Helmholtz model
RT	Rayleigh–Taylor model

Mailboom and Tauzia [18] applied bio-oil generated through the fast pyrolysis of wood in a Petter AVB test engine. Yang et al. [19] emulsified bio-oil generated through the fast pyrolysis of cedar with diesel, and they tested its performance in a single-cylinder diesel engine.

In a previous study, the O_2 concentration in oxidants was increased to change the diffusion and equivalence ratios of reactants, and this increase influenced the equivalence ratios, temperatures, burning velocities, and stability of the flame [20]. Numerous studies have explored the combustion characteristics of coal and biomass through O_2-rich combustion in boilers [21–26]. Tan et al. [21] employed a 0.8-MWth pilot-scale oxy-fuel-fired circulating fluidized bed (CFB) to convert an air-fired operation to an oxy-fuel-fired operation, revealing that the CO_2 concentration exceeded 90% after the oxy-fuel-fired condition was stabilized. Additionally, the desulfurization rate was associated with the characteristics of the fuel and the temperature of combustion and thereby affected the mode of combustion. Lupiáñez et al. [22] conducted an experiment to examine the effects of the bed temperature and O_2 concentration on SO_2 and NOx emissions from the coal oxy-firing process in bubbling fluidized bed combustors. Through numerical simulation and experimental measurement, Dual et al. [23,24] adopted numerical simulation and experiment measurement to conduct a flue gas recycling operation on a 50-kWth CFB combuster, testing various types of fuel and examining the conditions for stable oxy-CFB operations in consideration of the unstable heat transfer, mass transfer, and chemical reactions in the gas–solid phase. The results indicated that the combustion process with 22.2%–23.4% O_2 concentration yielded higher carbon burnout than did that of normal air combustion, thus improving the desulfurization efficiency. Moreover, the fuel nitrogen conversion ratio in oxy-fuel was much lower than in air combustion. Krzywanski et al. [25,26] established a mathematical model to predict the SO_2 emission processes of large and small CFB boilers in air and O_2-rich combustion. They revealed that the flame temperature of the powdered coal and air decreased significantly when the O_2 concentration reached 21% and that the coal was fully combusted; when the O_2 concentration exceeded 21%, an increased proportion of CO and NO_x was generated in the primary combustion zone, and burnt char particles were produced around the flames. However, liquid biofuel exhibits a high moisture content and low heating values, and it must be mixed with petroleum fuel, which features higher heating values, to improve its combustion characteristics. Because liquid biofuel and fossil fuel are almost incompatible, emulsifiers are typically required to mix these two fuel types.

2. Approaches

This study applied experimental measurements [27] and numerical simulations [28] to investigate the combustion characteristics of mixtures of kerosene and a bio-oil, which was produced through the pyrolysis of cedar, at various O_2 concentrations. Fig. 1 illustrates the burner employed in this study, indicating that it comprises a fuel inlet, an atomizer having two tangential openings, and a flame holder. The liquid fuel and oxidant coaxially entered the burner through the fuel inlet, and the fuel was released from the burner through the two tangential openings of the atomizer, collided to form droplets, and mixed with the oxidant. The fuel droplet–oxidant mixture was then combusted through the flame holder, preventing flashbacks and stabilizing the flame.

2.1. Experimental methods

Fig. 2 depicts the spray combustion test platform adopted in this study for examining the combustion characteristics of kerosene mixed with the cedar bio-oil. This platform comprised the spray-atomized combustor (Fig. 1), fuel supply systems, an image capture system, and temperature and emission analyzers. The