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Combustion performance of pyrolysis oil/ethanol blends in a residential-scale oil-fired boiler ☆

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HIGHLIGHTS

- We test the combustion of pyrolysis oil/ethanol blends in a small waste oil boiler.
- We examine viscosity of these blends and how it effects spray atomization.
- Blends of 20% pyrolysis oil and 80% ethanol are ideal for this application.
- These blends produce elongated flames but no change in efficiency vs. #2 fuel oil.
- Pyrolysis feedstock selection can change NO_x emissions by an order of magnitude.

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ABSTRACT

A 40 kWth oil-fired commercial boiler was fueled with blends of biomass pyrolysis oil (py-oil) and ethanol to determine the feasibility of using these blends as a replacement for fuel oil in home heating applications. An optimal set of test parameters was determined for the combustion of these blends with minimal soot and carbon monoxide formation. These set parameters were used to compare the performance of blends of ethanol with different concentrations of py-oil (10%, 20%, and 30% py-oil by mass) and py-oil produced from different biomass feedstocks, including switchgrass, miscanthus, eucalyptus, pennycress, forest residues, and soiled animal bedding, using #2 fuel oil as a control. Performance was measured in terms of the total heat input, the axial temperature profile of the combustion chamber, the gross heat output, and heat losses to the flue gas. Exhaust gas was analyzed for O_2, CO_2, CO, NO_x, and total hydrocarbon concentration. It was found that a blend of 20% py-oil/80% ethanol could be used as a fuel in residential boilers with minimal retrofitting. This blend ratio produced no detectable change in the CO and hydrocarbon emissions compared to #2 fuel oil. When the py-oil fraction of this blend was produced from biomass with low amounts of nitrogen such as eucalyptus, NO_x emissions were reduced by 12% compared to #2 fuel oil. When the py-oil was produced from proteinaceous feedstocks the py-oil stability improved but high nitrogen led to an order of magnitude increase in NO_x emissions.

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1. Introduction

Increasing combustion of fossil fuels for heat and power in recent years has led to a rise in the concentration of greenhouse gases in Earth's atmosphere. Perhaps the most viable mitigation strategy is the use of renewable fuels from biomass resources. For this biomass pyrolysis oil, also known as 'py-oil,' 'bio-oil,' or 'biocrude' can be a viable alternative to fossil fuels use in boilers or for use as a starting feedstock for producing fungible liquid fuels. Py-oil is a dark brown, viscous liquid produced from the thermal decomposition of biomass in the absence of oxygen, that has the potential to be upgraded into drop-in fuels and chemicals. One major attraction for pyrolysis oil is the fact that it can be produced from a wide variety of different biomass feedstocks, however, this causes its physical and chemical properties to vary greatly depending on the feedstock type as well as the pyrolysis conditions [1].

While the production of raw py-oil has been proven to be high yielding and technically efficient at the industrial scale [2], there are currently no corresponding efficient processes to upgrade and refine py-oil beyond the bench scale although research in this area is picking up speed in recent years [3]. Although the ultimate goal of the current alternative fuels drive is to produce transportation

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Nomenclature

A, B, C, D, E	empirical coefficients
c_p	specific heat capacity (kJ/kg K)
d	diameter (m)
h	specific enthalpy (kJ/kg)
m	mass (kg)
M	molecular weight (kg/kmol)
P	pressure (kPa)
Q	heat transfer rate (kJ)
SMD	sauter mean diameter (m)
T	temperature (°C)
U	velocity (m/s)
w	weight fraction
W	mass flow rate (kg/s)
x	volume fraction
μ	dynamic viscosity (cP)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

A	air
a	ambient
atm	atmospheric
blend	py-oil/ethanol blend
comb	combustion
dx	dry exhaust
eth	ethanol
f	fuel
g	gas
in	inlet
l	liquid
n	normalized
O	oriface
out	outlet
ph	preheater
py	pyrolysis oil
R	air relative to fuel
s	stack
vx	vapor exhaust
w	water

fuel molecules similar to diesel or gasoline from the abundant sources in the raw pyrolysis oil, an immediate application of the py-oil intermediate could be its direct combustion in spray burners. There is no doubt that a successful use of py-oil in home heating could impact the home heating market for example in the areas of the northeast United States with vast biomass resources, and where 13.7 billion liters of fuel oil is used annually [4]. While such a proposition appears to be straightforward on the surface, pyrolysis oil combustion has proved to be a formidable task that has gone wanting for research on its own right. Much work has been done regarding the combustion of py-oil in spray burners of various scales [1,5,6], that has shown that combustion of raw py-oil in unmodified, commercially produced, residential-scale burners is not feasible, due to the oil's high viscosity, corrosivity, high water content, and tendency to polymerize to form residues on burner components. If the untreated py-oil is stored for a month or more at ambient conditions, these properties will worsen due to 'aging' characterized by oligomerization reactions leading to formation of oxygenated compounds to larger molecular weight compounds [7], limiting the 'shelf life' of the fuel. This body of work has shown that the viscosity of pyrolysis oil "as produced" is especially problematic for small-scale burners, as these have small fuel passageways that tend to clog thereby preventing sufficient atomization of the fuel for good air/fuel mixing. However, pyrolysis oil is highly miscible with fuel ethanol, also a biorenewable fuels resource. Blending of pyrolysis oil with fuel ethanol may reduce some of py-oil's undesirable characteristics, especially the viscosity [8] and 'aging' tendenies [7], and perhaps the right mixture might have the potential to fuel small-scale burners designed for home fuel heating oils. Also, while raw py-oil "as produced" and saturated hydrocarbons do not mix due to the polarity of many py-oil components research has shown that certain fuel oil or biodiesel could be mixed with pyrolysis oil through the use of a co-solvent [9] or an emulsifying agent [10] although its economic viability is questionable.

Previous work on small-scale py-oil/ethanol spray combustion has been performed by Tzanetakis et al. [8] in a specially designed 10 kWth spray burner with a blend of 80% wood-derived py-oil and 20% ethanol. Stamatov et al. [11] performed combustion testing of wood-derived py-oil in its pure form as well as blends of 80% py-oil/20% ethanol and 20% py-oil/80% ethanol, compared with pure ethanol and #2 fuel oil. The work presented herein will build on these previous studies by utilizing py-oil ethanol blends in an unmodified commercial heating system designed for use with #2 fuel oil. This work will study the production and use of py-oil/ethanol blends from several py-oil sources (feedstock and process) and their utility as a source of fuel for combustion in a small-scale (40 kWth) home heating boiler. It will establish the relationships between system temperature profiles, ethanol concentration, and viscosity of py-oil/ethanol blends, thermal output as well as combustion gas emissions of recent interest. The possibility of adding either fuel oil or biodiesel into these blends, considered as one potential to increase their energy content, will also be examined.

2. Materials and methods

2.1. Pyrolysis oil production and analysis

Most pyrolysis oils are produced at about 500 °C using a fluidized bed reactor to provide rapid heat rates. We produced raw pyrolysis oils from a variety of feedstocks including switchgrass, wood chips, equine waste, eucalyptus, miscanthus, and pennycress using the bubbling fluidized bed reactor developed at the Eastern Regional Research Center (ERRC). The reactor features have been described previously [12] and will not be detailed here. However, the main design feature is the condensation system which allows separation of the liquid product into aqueous phase condenser oil and a dense phase electrostatic precipitator (ESP) oil from which most of the work reported here is based. There are two distinct production processes the first being the traditional fluidized-bed operational process where the fluidization is carried out under nitrogen atmosphere. This will be the typical process with high yields of pyrolysis oil with the highly unstable compositional characteristics reported widely in the open literature [13,14], and is the process by which most oil used in this study is produced. The second is the Agricultural Research Service (ARS) process [15] where a reactive fluidized-bed environment is created by recycling effluent gas to partially or fully replace the inert fluidizing nitrogen. The py-oil from the latter process used in this study comes from a process with an ideal concentration of recycled gases (65–80%) which maximizes the heating value of the fuel while minimizing the acidity, viscosity, and water content.