



Research article

Effect of thermophysical properties of heat carriers on performance of a laboratory-scale auger pyrolyzer

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ABSTRACT

This study evaluated the effect of thermophysical properties of heat carriers on the performance of a laboratory-scale auger reactor. Heat carriers tested included stainless steel shot, fine sand, coarse sand and silicon carbide. The results showed similar organic yield and composition of bio-oil among the heat carriers when pyrolyzing red oak. Significant differences in yields of reaction water, char and non-condensable gases were observed. It was also found that residual carbon contributed to as high as 20 wt% of total char yield and attrition of heat carrier as high as 7% on a mass basis were present after as little as 2 h of operation. Tradeoffs between physical performance, material cost, and product yields may exist when selecting heat carrier materials for pyrolysis of biomass in an auger reactor.

1. Introduction

Fast pyrolysis is a promising pathway to convert biomass into fuels and value added products [1]. Bio-oil is the primary product of fast pyrolysis and resembles that of petroleum but is approximately half the energy density and is compositionally very different [2]. As a result, much of pyrolysis research is focused on producing a higher quality bio-oil through techniques such as biomass pretreatments [3–7], both in-situ and ex-situ catalytic pyrolysis [8–11], and the addition of reactive gases to the inert pyrolysis atmosphere [5,12–16].

Bubbling fluidized bed reactors are widely employed in pyrolysis applications due to their technological maturity and ability to achieve high liquid yields [2,17–19]. Fluidized bed pyrolyzers use a pre-heated sweep gas to fluidize a bed of heat carrier material creating a homogenous environment with short vapor residence times and high heating rates from convection [20]. However, fluidized bed reactors have various disadvantages at commercial scales. Sensitive hydrodynamic conditions prevent both the use of feedstocks that cause bed agglomeration [5] and the use of bed material with high densities requiring high fluidization velocities [21]. Additionally, the use of fluidization sweep gas leads to increased energy input and cost. These disadvantages have led to research in alternative pyrolysis reactors such as the auger reactor.

Auger reactor pyrolyzers offer advantages over traditional fluidized bed pyrolyzers while achieving similar product yields [22,23]. Advantages include minimal requirements of sweep gas, the ability to

convey robust materials, and reduced solid particle entrainment in the primary product effluent stream. Several studies using indirectly heated auger pyrolyzers have been conducted to test the effect of temperature and solid residence times [23–26]. Puy et al. [25] concluded that bio-oil yield reached a maximum at 500 °C, although a solids residence time of at least 2 min was required for complete feedstock conversion. Other researchers have proved the viability of using indirectly heated auger reactors for the pyrolysis of both acid and thermal pretreated biomass [7,27–29].

Direct heat transfer through the use of heat carriers in auger pyrolyzers offers higher biomass heating rates than indirect heating of the reactors. Additionally, heat carriers allow for flexibility in selecting materials with different thermophysical properties. Sand and steel shot are often employed [4,22,30–32]. These studies focused on the effect of biomass pretreatment [4], catalytic pyrolysis [30–32], and optimization of operating conditions [22]. Brown [33] tested multiple heat carriers and optimized pyrolysis conditions with steel shot [22]. However, to our knowledge no study has systematically compared different kinds of heat carriers in auger pyrolyzers.

One of the essential features of a fast pyrolysis process is very high heating and heat transfer rates [34]. Rapid heating combined with small biomass particle sizes (typically < 2 mm) are required to achieve high liquid yields. To achieve this rapid heating, the biomass is heated either by gas-solid heat transfer through convection or solid-solid heat transfer driven by conduction [20]. The relative contribution from different modes of heat transfer in a pyrolysis reactor varies depending

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on reactor configuration. Heat transfer in fluidized beds is thought to be dominated by conduction at 90% with a small contribution of convection at up to 10% [20]. Circulating fluid beds and transport reactors will have a higher contribution of heat transfer due to convection (up to 20%) [20]. Conversely, auger reactors utilize very little carrier gas, thus the primary modes of heat transfer in auger reactors will be conduction and radiation. Directly heated auger reactors with heat carrier materials will have primarily solid-solid heat transfer from conduction with additional contribution from radiation. Therefore, to achieve high heat transfer rates, it is desirable to select a heat carrier material with advantageous thermal properties.

The objective of the present study is to determine the effect of thermophysical properties of heat carriers on the performance of an auger pyrolyzer. For solid heat carriers with no internal heat generation, we hypothesize that only the thermophysical properties influence temperature changes in the heat carrier. This study investigates the effect of three thermophysical properties (thermal conductivity, heat capacity, density) covering a wide range of a heat carrier thermal diffusivities. The larger the thermal diffusivity the faster temperature changes will propagate through the heat carrier. Therefore, it is theorized that heat carriers with large thermal diffusivities will provide higher heat transfer rates to the biomass resulting in improved product yields and composition. Four different heat carriers (stainless steel shot, fine sand, coarse sand, silicon carbide) were selected for comparison in pyrolysis trials of red oak using a laboratory-scale, twin screw reactor.

2. Materials and methods

2.1. Feedstock preparation

Northern red oak (*Quercus rubra*) obtained from Wood Residuals Solutions (Montello, WI) was used as feedstock for all trials in this study. The as-received feedstock was dried to moisture content of 7.3 ± 0.1 wt% and ground using a Schutte-Buffalo Hammermill® Model 18-7-300 pilot-scale Circ-U-Flow Hammer Mill with a 1/8" screen. Additional size reduction was completed using a Retsch® Type SM2000 Heavy-Duty Cutting Mill with a 750 μm screen. The feedstock was then sieved to a final particle size range of 300–710 μm using a W.S. Tyler Ro-Tap® sieve shaker. Proximate and ultimate analysis of the red oak feedstock used in this study is reported in Table 1.

2.2. Heat carrier preparation

Three different heat carriers with a wide range of thermophysical properties were obtained and tested in this study. Stainless steel cut-wire shot (Type 316) and silicon carbide were obtained from Pellets

LLC. (North Tonawanda, New York) and sieved to particle size ranges of 710–1000 μm and 710–1180 μm , respectively. Quikrete® All-purpose Sand No. 1152 was obtained from Lowe's (Ames, Iowa) and sieved into two size fractions: 250–600 μm denoted as fine sand and 600–1000 μm denoted as coarse sand for this work. All heat carriers were sieved using a W.S. Tyler Ro-Tap® sieve shaker. Copper cut-wire shot was also obtained from Pellets LLC., but was abandoned during trials due to reactor operational difficulties caused by the hot copper shot becoming soft. The thermophysical properties and characteristics of the heat carriers tested in this study are shown in Table 2.

All heat carriers were aged prior to pyrolysis trials to clean and remove any impurities. The aging procedure was as follows: as-received heat carrier was sieved to desired particle size (e.g. 600–1000 μm). The heat carrier was then cycled through the reactor system at specific operating conditions in the absence of biomass. After cool down, the heat carrier was re-sieved to its original particle size range (e.g. 600–1000 μm) with any particle fines (e.g. < 600 μm) discarded. The remaining heat carrier was then used for experimental trials.

2.3. Pyrolysis experiments

A laboratory-scale auger reactor first described by Brown and Brown [22] and later by Dalluge et al. [4] was used in this study. A schematic of the modified reactor set-up is shown in Fig. 1. The reactor is equipped with 1" OD (2.54 cm) twin-screws which co-rotate to effectively mix the heat carrier and biomass. The red oak was calibrated and fed into the reactor at 1 kg/h for all trials using a Tecweigh® Flex-Feed® Volumetric Feeder Model No. CR5. Nitrogen was used as an inert sweep gas controlled by an Alicat® mass flow controller and purged at a rate of 2.5 standard liters per minute (SLPM) for all trials. The heat carrier was preheated to a desired temperature and fed at a calibrated mass flow rate into the reactor via the heat carrier preheat system. During pyrolysis, heat carrier and reacting biomass were concurrently conveyed through the reactor at an auger speed of 54 rpm and dropped into a solids catch. This correlates to an approximate solids residence time of 12 s. The pyrolysis vapors (pyrolysate) and sweep gas were directed out of the reactor through the first vapor port located 10.8 cm axially down the length of the reactor from the heat carrier inlet.

The pyrolysate and sweep gas entered a cyclone to remove entrained solids followed by a bio-oil collection unit that condensed pyrolysis liquids. The vapors were then quenched using a cold gas quench system first described by Dalluge et al. [4]. Liquid nitrogen was used to quench the exiting pyrolysis stream from approximately 515 °C to 110 °C. An electrostatic precipitator (ESP) was then used to collect this first stage fraction (SF1), also known as heavy ends. A shell and tube heat exchanger was used to collect the remaining condensable vapors at a wall temperature of -5 °C. This second stage fraction (SF2) is known as light ends. The non-condensable gases (NCGs) then passed through a Ritter® TG5/4-ER1 bar drum type gas meter to determine the total gas flow rate before being vented.

Baseline heat carrier trials were conducted with the stainless steel shot at optimized operating conditions for this reactor as determined by Brown and Brown [22]. A stainless steel shot mass flow rate of 15 kg/h was used, correlating to an approximate heat carrier volumetric flow rate of 0.0033 m³/h. The stainless steel shot was preheated and fed into the reactor at a temperature of 575 °C. After mixing with biomass, a pyrolysis reaction temperature of approximately 515 °C was measured via an internal thermocouple located 5.4 cm axially from the heat carrier inlet port.

In order to provide an accurate comparison across all heat carriers, the total volumetric flow rate and pyrolysis reaction temperature were held constant. The heat carrier mass flow rate was adjusted to maintain a constant volumetric flow rate of 0.0033 m³/h. The required mass flow rate was calculated based on the heat carrier's bulk density. This resulted in a constant solids residence time and volumetric fill ratio across all varying heat carrier trials. The heat carrier inlet temperature was

Table 1
Proximate and ultimate analysis of Northern Red Oak (*Quercus rubra*).

Proximate analysis	wt%
Moisture content	7.3
Volatiles	78.8
Fixed carbon	13.2
Ash	0.7
Ultimate analysis	wt% dry, ash-free
Carbon	50.4
Hydrogen	5.9
Nitrogen	0.1
Oxygen ^a	43.6
Higher heating value (HHV) ^b	MJ/kg
HHV	18.5

^a Determined by difference.

^b Determined by theoretical calculation [38].

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