



# A critical comparison of pyrolysis of cellulose, lignin, and pine sawdust using an induction heating reactor



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## ARTICLE INFO

### Article history:

Received 7 December 2015

Received in revised form 7 February 2016

Accepted 15 March 2016

### Keywords:

Pyrolysis

Lignin

Cellulose

Induction heating

Biofuel

Bio-oil

## ABSTRACT

Fast pyrolysis of pinewood sawdust and two of its major components, namely lignin and cellulose was carried out using a laboratory scale induction-heating reactor. The effect of five different temperatures (500, 550, 600, 650 and 700 °C) was tested on the product yield and quality. The products were characterized to evaluate the water content, elemental composition, chemical composition and energy content. The char yield decreased with temperature for all of the biomasses. The maximum liquid yield of 55.28% was achieved at 600 °C for pine sawdust, and the highest liquid yields for cellulose and lignin were obtained at 500 °C. Water content in the liquid fraction decreased as reaction temperature increased. The GC–MS revealed that the bio-oil from cellulose was rich in anhydrosugars while majority of the liquid from lignin had high phenolic contents. Analysis of the gas fraction shows that as the temperature increases the gas yield increases, which, when paired with the declining char masses, showed an increase in the biomass breakdown at higher temperatures. Liquid fraction from pine sawdust has the highest HHV with a peak at 550 °C.

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## 1. Introduction

Thermochemical conversion of biomass has an advantage of being capable of readily producing liquid fuel from any organic matter, most importantly lignocellulosic biomass [15,41]. Pyrolysis is an effective thermochemical process for biomass conversion, which uses an oxygen free environment, and operated at reactor temperatures between 300 °C and 700 °C to produce bio-oil [15].

There are several different reactor designs that have been tested for the production of bio-oil through pyrolysis including: fluidized bed reactors, ablative pyrolysis reactors, vacuum pyrolysis reactors, and fixed bed reactor [31,33]. Some of the recent designs for effective pyrolysis include fixed bed drop-type reactor [31], solar pyrolyzer [55]. These systems are all designed to optimize liquid yields from the pyrolysis of lignocellulosic biomass. Despite the distinct differences in design and execution of these different methods, they each share several key features that allow for the maximum liquid yields. These features are important in the design of any pyrolysis reactor where high liquid yields are the primary

goal and include rapid heating rates, high heat transfer rates to the biomass, precise control of the reactor temperature, the rapid removal of the pyrolysis vapors from the reactor, and rapid cooling of these vapors.

Many of these traits can be achieved using an induction heating mechanism, which uses an AC power supply to create an oscillating magnetic field which then heats any ferromagnetic material within the confinement of induction coils. Induction heating offers a contactless heating method that meets the required pyrolysis reactor features needed for high liquid yields, which are: rapid heating rates, precise temperature control, and high energy efficiency [22,29,34]. Some of the associated drawbacks of this system are high initial cost and energy, low design flexibility and probable scale-up issues. Although there is limited research available in the literature on application of induction heating reactor for pyrolysis, a few detailed studies investigating the effect of a batch scale induction heating reactor shows that induction heating mechanism can be effectively used for pyrolysis of biomass as well as further bio-oil upgrading [22,28,34,49,50].

Pyrolysis has multiple drawbacks associated with the quality of bio-oil achieved [34]. The bio-oil is rich in oxygenated compounds and has low energy content. Many studies have investigated different methods for upgrading pyrolytic bio-oil [8,17–19,34].

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However, the composition of biomass also affects the product yield and quality [26]. This study was concerned with understanding the pyrolysis of pine sawdust, a common waste material from many forestry and industrial sectors, which demonstrates potential to be used as a biofuel feed stock [24]. Pine sawdust, like all woody biomass consists mostly of three compounds that account for the majority of its mass: cellulose, hemicellulose, and lignin, with approximately 40% cellulose, 10% hemicellulose, and 30% lignin with the remainder of the biomass accounting for as extractives such as resins, oil and ash [3].

The chemistry of pyrolysis has been vastly studied by pyrolyzing wood components separately in order to understand the reaction kinetics and pathways [5,39,42,43,48,53,54]. Yang et al., performed a thermogravimetric (TGA) analysis of cellulose, hemicellulose and lignin pyrolysis and investigated the temperature range at which each component breaks down. They concluded that there is no interaction among the three components on the wood [54]. Similar results were reported by Zhang et al., while studying the pyrolysis of cellulose lignin and hemicellulose and its various mixtures [56]. Beis et al., studied the pyrolysis of different types of lignin [5] and showed that the liquid yield from lignin ranges from 16% to 20% whereas the kinetic parameters and chemical composition varies considerably for each lignin sample [5]. While Wang et al., studied the effect of catalytic pyrolysis on individual biomass components and showed that cellulose contributed to maximum aromatic yield [52]. Hilbers et al., studied the lignin–cellulose interaction and found that lignin enhances yields of levoglucosan but decreases the yield of dehydration products [23]. Studies have shown that the cellulose fraction is the primary contributor to the production of bio-oils, and that lignin is the primary fraction of biomass to contribute to the char yields [10,42,48]. Qu et al., studied the pyrolysis of three major components of wood namely, cellulose, hemicellulose and lignin and showed that the additivity law can reasonably predict the bio-oil yield and quality as long as the biomass composition is known [42]. The study on effect and relationship between the three components on product yield and composition at laboratory scale is limited [42]. Although pyrolysis of wood components has been investigated previously, most of the studied were limited to micro scale pyrolysis studying the kinetics and reaction mechanism. More recently, Stefanidis et al., studied the pyrolysis of biomass components on batch scale (1.5 g sample) as well as TGA analysis along with catalytic upgrading at 500 °C in a traditional reactor and showed that there is a heat transfer lag during pyrolysis for component mixtures [48].

In this paper we report, for the first time to our knowledge, the effect of pyrolysis of pinewood sawdust and its major components namely; cellulose and lignin using a bench scale induction heating reactor with high biomass loading (30 g). The effect of different temperatures on product yields and quality was investigated for each component (i.e. lignin and cellulose). Optimum parameters were reported. The contribution of individual component on the yield and bio-oil composition was studied and the results were compared to the ones reported in the literature. This study can have a profound impact on forestry and pulp and paper industries that generate large quantities of lignin as byproducts, as well as on the nascent cellulosic bioethanol industry that produces large amounts of lignin as well.

## 2. Materials and methods

### 2.1. Materials

The detailed procedure for preparing the pine chips is given elsewhere [21]. Briefly, the pine chips were ground to a particles size in the range of 0.5–1.0 mm in diameter and then dried

overnight at 105 °C. The moisture content of the biomass was determined to be 1.93% by weight using an LJ16 Moisture Analyzer (Mettler Toledo, Switzerland). The dried biomass was then stored in sealed plastic bags in the freezer to minimize moisture absorption during storage until the experiments were carried out.

The cellulose and lignin were obtained from Pure Lignin Environmental Technology Ltd. (Kelowna, BC, Canada). The cellulose was rinsed thoroughly with hot water over a fine mesh to remove any remaining lignin particulates and water soluble hemicellulose. It was then placed overnight in a 100 °C oven to dry. The moisture content was determined to be 7.027% by weight using the LJ16 Moisture Analyzer (Mettler Toledo, Switzerland). The material was then sealed in plastic bags and stored in a –20 °C freezer to prevent water absorption. The lignin supplied was in a suspended solution that needed to be separated to acquire the pure lignin for pyrolysis. This was accomplished by evaporating off the solution leaving behind only the solid lignin fraction as per the procedure provided by Pure Lignin Environmental Technology Ltd. (Kelowna, BC, Canada). The moisture content of the lignin was 6.97% by weight.

### 2.2. Equipment

An induction heating system (Low Frequency, RDO Induction L. L.C., Washington, NJ) was used to test a range of experimental temperatures from 500 to 700 °C in 50 °C increments. The details of the equipment are discussed elsewhere [22]. An infrared Omega IR2C PID controller (Omega Engineering, Inc., Stamford, CT) was used to control the temperature of the reactor. The feedback controller used a 4–20 mA signal to control the power output of the induction heater.

The liquid collection system consisted of a round bottomed flask suspended in an ice bath at 0 °C and an electrostatic precipitator to prevent the bio-oil from volatilizing and also lowered their temperature to reduce the occurrence of secondary reactions. The detailed description of the collection system is given elsewhere [22].

### 2.3. Experimental procedure

The biomasses (pine sawdust, cellulose, and lignin) were pyrolyzed in a batch induction pyrolysis system at five different operating temperatures: 500, 550, 600, 650, and 700 °C. These experiments were performed in triplicates in order to ensure reproducibility. Preliminary studies at 400 and 450 °C for cellulose and lignin indicated small yields of bio-oil, hence only temperatures above 500 °C were used in this study (ISE document). The biomass was weighed out in 25 g sample sizes, which were then packed into the center of the pyrolysis reaction tube. The empty collection flask was also weighed before the experiments in order close the mass balance and get accurate pyrolysis yield values. The reaction tube was placed between the induction heating coils and connected to the gas inlet and outlet. Nitrogen gas flowing at 1.0 L min<sup>-1</sup> was used to purge the system of oxygen for 20 min. The induction heater was then operated based on the reaction temperature. The reaction time for each temperature was previously determined [34]. The pyrolysis reaction produced bio-oil vapors along with non-condensable gases; these were carried out of the reaction chamber using the carrier gas. The vapors then flowed into the collection system that was immersed in an ice bath, where the ESP prevented the vast majority of condensable bio-oil droplets from escaping the collection system [4]. After the predetermined operation time, the induction heater was powered off and the reaction chamber was allowed to cool. The collection flask was then weighed and the oil samples were stored in a scintillation vial at –20 °C to minimize secondary reactions. The char residue was weighed to obtain the yields. The unaccounted weight after

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