Voltage-Enhanced Processing of Biomass and Biochar

Gerardo Diaz

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To my wife, Kathleen, and my two wonderful children

Preface

One of the biggest lessons learned from the COVID-19 pandemic is that it has highlighted how vulnerable humanity is with respect to potential threats that had been predicted for decades and that we thought we were prepared to resist. Another important lesson is that shelter-in-place requirements mandated by governments around the world showed the impact of human activity in air quality and carbon emissions to the atmosphere. Clean skies were seen in places where a thick layer of smog was a common daily sight. The recent sixth assessment report from the Intergovernmental Panel on Climate Change concluded that widespread and rapid changes have occurred unequivocally due to human influence in warming the atmosphere, ocean, and land. As long as world leaders do not take strong action to limit carbon emissions to the atmosphere, we will continue to live in a world threatened by climate change, which will end up exposing more vulnerabilities of our society. Just in the United States, it is estimated that around 1 billion dry tones of biomass per year could be produced sustainably. This is in addition to the already available biomass that decomposes releasing methane and other pollutants to the atmosphere. The conversion of biomass to useful forms of energy such as electricity and heat, as well as the production of value-added products such as biochar and activated carbon, constitute a viable way to reduce biomass, generate renewable energy, and sequester carbon in a stable form. This book provides an overview of conventional biomass processing techniques as well as a description of technologies that utilize voltages and currents to enhance processing capabilities. The term plasma processing of biomass is usually associated with thermal plasma torches used for gasification of organic material. This book not only describes thermal plasma processing of biomass, but it also presents applications where nonthermal plasma discharges can be utilized in biomass processing plants, and applications where Joule heating of carbonaceous materials can be implemented. The book is intended for senior level undergraduate students and first year graduate students, who might not have a background in plasma, but are familiar with concepts of calculus, differential equations, and numerical algorithms. Chapter 1 provides a description of relevant properties of biomass, biochar, and activated carbon, while Chapter 2 gives a description of conventional methods of processing biomass and biochar. Chapter 3 provides an introduction to plasmas for thermal and nonthermal discharges, and Chapter 4 describes technologies that are suitable for utilizing the effects of applied voltages to enhance biomass processing. As properties of biomass vary after thermochemical decomposition, yielding a material with better electrical properties, Chapter 5 focuses on the analysis of the effects of applying voltages in processing of biochar. Thermal runaway behavior can be obtained with heating rates not achievable by conventional heating techniques. Chapter 6 provides an introduction of numerical simulation of plasmas. Finally, the inherit variability and even chaotic behavior of thermal arcs are analyzed in Chapter 7 in the context of the development of control techniques that can stabilize these discharges.

Gerardo Diaz

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Acronyms

AC
: alternating current

AI
: artificial intelligence

APGD
: atmospheric pressure glow discharge

BET
: Brunauer, Emmett, and Teller

CEC
: cation exchange capacity

DBD
: dielectric barrier discharge

DC
: direct current

DR
: Dubinin–Radushkevich

EHD
: electrohydrodynamics

GAC
: granular activated carbon

HHV
: high heating value

ID
: inside diameter

IMC
: internal model control

LHV
: low heating value

LTE
local thermodynamic equilibrium

MOSFET
metal oxide semiconductor field effect transistor

MSW
municipal solid waste

NTP
nonthermal plasma

OD
outside diameter

PID
proportional-integral-differential

RF
radio frequency

TC
thermocouple

TLUD
Top-Lit UpDraft

UV
ultraviolet light

VOC
volatile organic compound

ZVS
zero voltage switching

Introduction

It has become evident that over the past decades, the impacts of climate change are increasing in severity and frequency. This situation has surpassed the threshold of affecting just our comfort level with higher average temperatures, heat waves, and modified precipitation patterns, but it is starting to threaten our livelihood. Climate change has been considered by some researchers as the biggest environmental challenge of our existence. For instance, average ambient temperatures continue to increase, severe drought conditions are occurring in several areas of the world, and six out of ten of the most extreme historical floods have taken place in the last 25 years. In addition, wildfire frequency and intensity are also increasing, partly due to climate change, but also due to outdated forest management practices and a large supply of biomass. It is here where there is great potential to utilize carbon-negative processes to reduce emissions and sequester carbon in a stable way. Well-established biomass processing techniques include combustion, gasification, pyrolysis, hydrolysis and hydrothermal liquefaction, which are suitable for a variety of applications that require steam, process heat, electricity, biochar, fuel gases, or synthetic liquid fuels. However, the utilization of voltage-driven techniques for the processing of biomass and biochar has been shown to have advantages for certain applications. This book concentrates on voltage-enhanced processing of carbonaceous materials, describing aspects related to thermal and nonthermal plasmas as well as the effects of Joule heating in the temperature distribution and conversion rate. In certain cases, it is necessary that the plasma discharge provides most of the energy required for the conversion. For these cases, a brief description of thermal plasma torches available is provided and experimental results of the conversion utilizing steam plasma are described. Results are compared against a thermodynamic model that predicts synthesis gas composition under the presence of a thermal plasma discharge. Simulation results of Joule heating of biomass, biochar and pyrolytic graphite are also provided. The thermochemical conversion of carbonaceous materials can also be enhanced with nonthermal plasma (NTP), in which the presence of the discharge generates ionized and excited species, radicals, etc., that are not present in conventional conversion processes. The purpose of the plasma in this case is not to provide the entire energy for the process but to enhance conversion. The book provides a description of the way that voltage is used to generate a NTP discharge, which exhibits highly energetic electrons with ions and neutral species at near-ambient temperature. A description of the physics related to these discharges is provided with experimental and simulation results of biomass gasification and plasma activation. Results related to tar breakdown are also provided as NTP is used to reduce pollutant emissions and to increase the fraction of hydrogen in synthesis gas by decomposing tars. An introduction to numerical simulations of non-equilibrium plasma discharges is provided and, a brief description of the control of these discharges is provided in the last chapter.

1
Carbonaceous Material Characterization

1.1 Material Characterization

The thermochemical conversion of biomass by means of processes such as torrefaction, pyrolysis, or gasification, produces a char-like material with properties that differ considerably from the original feedstock. Further processing in the form of chemical or physical activation continues to modify the properties of the carbonaceous materials produced. The following Sections (1.1.1–1.1.4) provide a description of the main properties needed to characterize carbon-based materials for applications of biochar production and energy conversion.

1.1.1 Thermophysical Properties

Thermophysical properties are directly related to the structure and composition of the carbon-based materials. There is a large volume of studies that have analyzed their variation due to the effects of thermochemical conversion processes (Balogun et al., 2018). These properties not only have an impact in the operating conditions of processing equipment but also affect transportation costs and pollutant emissions. The thermal and physical properties have a strong dependence on parameters such as moisture content and temperature (James, 1975; Skaar, 1988; Dietenberger et al., 1999; Zelinka et al., 2007); therefore, various models have been developed to represent them as a function of these factors. The most relevant properties include thermal conductivity, density, and specific heat.