Applied Energy 205 (2017) 511–528

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Predictive temperature modeling and experimental investigation of ultrasonic vibration-assisted pelleting of wheat straw

Qi Zhang[a,1,*], Zhenzhen Shi[b,1], Pengfei Zhang[c], Zhichao Li[d], Majid Jaberi-Douraki[b,e,*]

[a] College of Mechanical Engineering, Yangzhou University, Yangzhou, Jiangsu 225127, China
[b] Institute of Computational Comparative Medicine, Anatomy and Physiology, Kansas State University, KS 66502, USA
[c] Jiangsu Muyang Holding Co., Ltd., Jiangsu, 225127, China
[d] Department of Industry and the System Engineering, North Carolina Agricultural & Technical State University, 27411, USA
[e] Department of Mathematics, Kansas State University, KS 66502, USA

HIGHLIGHTS

- Develop thermal models for analysis of temperature profiles.
- Calibrate and validate the predictive mathematical model with experimental data.
- Report the first HPT and LPT distributions of pelleting using 2^3 factorial designs.
- Provide a guideline for improving the pellet quality during UV-A pelleting process.

ARTICLE INFO

Keywords:
Biomass
Ethanol
Pelleting
Temperature
Ultrasonic vibration
Mathematical model

ABSTRACT

Ethanol made from cellulosic biomass is an alternative to petroleum-based liquid transportation fuels. However, large-scale manufacturing of cellulosic ethanol is hindered by several factors. The main factor driving this hindrance is the low density of cellulosic biomass. Ultrasonic vibration-assisted pelleting can effectively increase cellulosic biomass density by compressing raw biomass into pellets, reducing transportation and storage costs. Pelleting temperature has also been identified as a key parameter influencing pellet quality. In this paper, a predictive mathematical model of pelleting temperature using spatio-temporal dynamics was developed to study multiple factors affecting temperature rise through pelleting. The mathematical model was then validated with experimental data along with high goodness of fit (average $R^2 > 0.83$). Effects of three input variables (ultrasonic power, pelleting pressure, and pellet weight) on temperature ranges (highest temperature point and lowest temperature point) were investigated using a 2^3 (two levels and three variables) factorial design. Our results indicated that friction between mold and biomass has a marginal effect on the temperature profiles, and demonstrated the highest and lowest temperature points are significantly correlated to the input variables (ultrasonic power, pellet weight, and pellet pressure) and their interaction effects. The proposed mathematical model delivers a new guideline by avoiding unnecessary experiments and provides a systematic understanding of temperature profiles during the biomass pelleting process. Knowledge transferred from the current study fulfills the literature gap between mathematical modeling research and an optimal, ultrasonic, vibration-assisted pelleting process; and, therefore, provides insight into improving biomass quality in energy-related ultrasonic manufacturing.

1. Introduction

Cellulosic biomass is referred to as herbaceous, woody, and generally inedible portions of plant matter abundantly available in nature. Its three main components are cellulose, hemicelluloses, and lignin [1]. Both cellulose and hemicelluloses contain glucose molecules that can be converted to ethanol [1]. Ethanol produced by cellulosic biomass is an alternative to petroleum-based liquid transportation fuels. Recent studies suggest that more than 30% of current petroleum consumption in the United States can be replaced by cellulosic ethanol because land

* Corresponding authors at: Institute of Computational Comparative Medicine, Anatomy and Physiology, Kansas State University, KS 66502, USA (M. Jaberi-Douraki) and College of Mechanical Engineering, Yangzhou University, Yangzhou, Jiangsu 225127, China (Q. Zhang).
E-mail addresses: qizhang@yzu.edu.cn (Q. Zhang), jaberi@ksu.edu (M. Jaberi-Douraki).
[1] Contribute equally as the first author.

http://dx.doi.org/10.1016/j.apenergy.2017.07.080
Received 4 May 2017; Received in revised form 3 July 2017; Accepted 20 July 2017

Nomenclature

Abbreviations

UV-A	ultrasonic vibration-assisted
HPT	highest pelleting temperature
LPT	lowest pelleting temperature
MC	middle center of biomass pellets
MS	middle side of biomass pellets
TC	top center of biomass pellets
TS	top side of biomass pellets
BC	bottom center of biomass pellets
BS	bottom side of biomass pellets

Main symbols

μ_f	temperature due to the friction (K)
μ_v	temperature due to the vibration of the pelleting tool (K)
P_{cp}	contact pressure (N/m^2)
P_n	nominal pressure (N/m^2)
Q_f	heat generated per unit area of contact (J/m^2 s)
c	specific heat capacity of cellulosic biomass (J/kg K)
ρ	density of cellulosic biomass (kg/m^3)
K	thermal conductivity of cellulosic biomass (W/m K)
I_0	ultrasonic intensity at the top surface of biomass (W/m^2)
m	mass of biomass in the mold (kg)
ν	Poisson's ratio (–)
δ	absorption coefficient of cellulosic biomass (–)
μ	coefficient of friction for biomass (–)
T_p	pelleting time (s)
h_0	initial height of cellulosic biomass (m)
h_1	height of biomass after the pelleting pressure (m)
R	radius of cellulosic biomass (m)
F_n	nominal force on the biomass (N)
F_{cp}	contact force between biomass and mold (N)
v_{b0}	initial velocity of biomass (m/s)
I_{AVE}	average current (A)
E	energy consumption
V	voltage (120 V in the experiments)

resources are sufficient to sustain the necessary annual production of biomass [2]. Furthermore, adoption of cellulosic ethanol can mitigate accumulation of greenhouse gases in the atmosphere and revitalize the rural economy [3].

Several factors hinder large-scale and cost-effective manufacturing of cellulosic ethanol. One major challenge, known as the low density of raw cellulosic biomass (ranging from 24 to 266 kg/m^3 [4]), causes high collection, handling, transportation, and storage costs. Therefore, an effective compression is required to increase cellulosic biomass density by converting the raw organic matter into pellets so that associated costs of transportation and storage can be reduced. Pelletizing is a process of increasing biomass density by mechanical pressure, and produces dry pellets with uniform size and shape [4–6]. Pellets that have high densities (more than 600 kg/m^3 [5–7]) are easier to handle with existing equipment for grain processing than raw cellulosic biomass [5]. As a result, transportation and storage costs of pelleted cellulosic biomass are decreased by a factor of two and ten, respectively, compared with raw cellulosic biomass [8,9].

Ultrasonic vibration-assisted (UV-A) pelleting is a new pelleting and pretreatment method that uses an ultrasonically vibrating tool to compress unheated biomass and produce pellets [10]. Previous studies show UV-A pelleting produces pellets whose density and durability are highly comparable to those produced by traditional pelleting methods [6,10]. In addition, corn stover and sorghum stalk processed by UV-A pelleting produced 20% higher sugar yield than pelleting without the UV-A process [6,11–13].

During UV-A pelleting, pelleting temperature has been identified as a key factor affecting pellet quality. The glass-transition (a reversible transition in amorphous materials from a hard and brittle state into a viscous state) temperature of lignin is 333.15–413.15 K [14]. Lignin could exhibit thermosetting properties and act as the binder material for biomass particles to form pellets [15]. Faborode [16] reported biomass should be heated to 373.15 K to produce high-density and durable pallets. Reece [17] reported biomass should be heated to

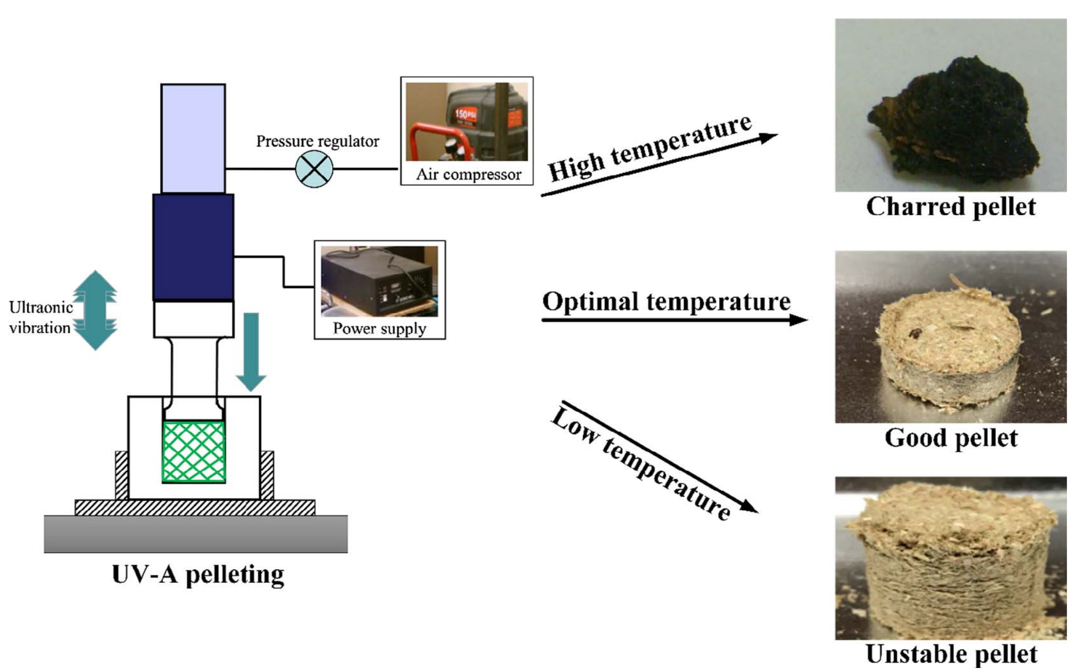

Fig. 1. Temperature recognized as a key factor during UV-A pelleting.