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Research article

Optimization of a straw ring-die briquetting process combined analytic hierarchy process and grey correlation analysis method

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ABSTRACT

Briquetting of biomass is an attractive option to mitigate the energy crisis and environmental problems. A device to make this transformation is called ring-die briquetting system. In this research, a study on the optimization of a rice straw ring-die briquetting process combined analytic hierarchy process and grey correlation analysis was presented. Optimization variables include moisture content, particle size of the raw material, temperature, and the gap between the roller and ring-die while the average energy consumption, productivity, density and the rate of qualified biofuels were optimization objects. Results showed that moisture content and clearance between die and roller influenced productivity, energy consumption and product density significantly. The optimum process condition was obtained around moisture content of 20%, with a clearance between die and roller of 2.5 mm, die temperature of 120 °C and particle size between 20–35 mm. Experimental verification results indicated that this combination of factors produced a better overall pelleted fuel.

1. Introduction

With the growing energy crisis and environmental problems [1], utilization of biomass has gained a lot of attention [2,3]. But the majority of these resources have a low energy/bulk density, which makes them unsuitable for direct combustion and long distance transportation. Briquetting (densification) of these loose and low density biomass resources is an attractive option [4]; the need for this transformation has been widely justified, as shown by works Panwar et al. [5] and Hu et al. [6]. A device to make this transformation is called ring-die briquetting (R-D for short) system [7]. The R-D system has many advantages such as versatility and flexibility to different types of low density biomass compared with the system of screw bar pressing and piston pressing [8]. Hence, the R-D system at present can strongly support the large scale production of densified solid biofuels [3], but the shortcoming of high energy consumption, short life time of the ring-die and variable quality of the produced briquettes during the densification process still exist [9].

Some studies have focused on the bonding mechanism [10], specific energy consumption and product quality affected by various factors [11–13]. Moreover, parameter optimization of this densification process has been extensively studied [14–21].

Bonding and failure mechanisms in fuel pellets from beech, spruce and straw under different pelletization conditions were studied by Stelte et al. [10], they found that both temperature and chemical composition have a significant influence on the bonding quality. Preheating temperature, particle size, and moisture content played a significant role in improving the energy efficiency and pellet density, and hot-pressing temperature strongly affects the air-dry density of the rice straw briquette [11]. Miao et al. [12] also indicated that the specific energy consumption for mini-bale densification of biomass was a function of the particle size, moisture content, and feedstock type. Kashaninejad et al. [13] found that higher compressive forces and larger particle size increased the durability of wheat straw pellets, and the specific energy increased with compressive load and particle size using an Instron testing machine as well.

Arshadi et al. [14] indicated that it is possible to obtain a fairly reliable estimate of pellet quality (bulk density, durability and moisture content) as well as energy consumption for the industrial pelletizing process of sawdust when moisture content, fractions of fresh pine, stored pine and spruce were taken as process parameters. Adapa et al. [15] tested the specific energy requirements for the compression of chopped alfalfa at different pressures (9.0, 12.0, 14.0 MPa), holding times (10 and 30 s) and leaf content (0% to 100%, by mass in increments of 25%) were taken into account, but the mathematic model was not established, only a regression equation to predict the durability of alfalfa cubes was obtained in the followed work [16]. Song et al. [17] applied response surface methodology (RSM) to the development of a predictive model for the energy consumption in UV-A pelleting of wheat straw, results shown that prediction accuracy of the predictive model was 3.2%. Meanwhile, Gillespie et al. [18] also developed multiple linear

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regression models to predict the real-time pellet quality (higher heating value and mechanical durability) of biomass.

To obtain the optimum densification conditions, Yumak et al. [19] pointed out that moisture contents between 7% and 10%, pressure of 31.4 MPa, and temperatures of 85–105 °C were suitable for briquetting soda weed through lab-scale testing when density was taken as the main evaluative parameter. While Lam et al. [20] concluded that the optimum processing condition of Douglas fir pellets were 100 °C die temperature, 126 MPa applied pressure and 30 s relaxation time when using a heated piston–cylinder unit. The suitable conditions for terrified Douglas fir pellets in a press machine were a moisture content of 10% and die temperature of 230 °C [21].

We could conclude that the biomass densification process was affected by many factors [22], such as the structural parameters of the device, moisture content and the particle size of the raw material, temperature, the gap between the roller and ring-die, and numerous other parameters. And the average energy consumption, productivity, and the product quality are the most important evaluation indexes for all the biomass briquetting systems. But the mathematical models between the optimization objective and processing variables are limited based on the current literature. Most of the models merely focused on energy consumption or density, while an improvement of one of the performance characteristics may be a detriment to another, which depends on the same controlling factors. What's more, the optimized results vary considerably, mainly due to the different material types and experimental conditions. In addition, there is a significant difference between the lab-scale testing and actual briquetting process [23].

Owing to the complexity of biomass briquetting process, especially, the optimization objects are multiple and interdependent, the analytic hierarchy process (AHP for short) and grey correlation analysis method were adopted. AHP was a tool for multi-criteria decision analysis [24, 25]. AHP is a flexible method for complex problems where both qualitative and quantitative aspects are considered. It helps the analyst organize the critical aspects of a problem into a hierarchical structure similar to a family tree. There are numerous studies performed using AHP in the energy sector. Okello et al. [26] applied AHP to evaluate the four bioenergy technologies in Uganda. Results showed that this methodology is effective in evaluating stakeholder preferences for bioenergy technologies. Amer and Daim [27] presented an AHP model to select and prioritize the various renewable energy technologies for electricity generation in Pakistan. They found that results of the proposed decision model can be used for the development of long-term renewable energy policy and energy roadmap for the country. Grey relational analysis is a part of grey system theory, which is suitable for solving the complicated inter-relationships between multiple factors and variables [28]. Grey relational analysis is defined as a quantity analysis of developing trend in various systems, and the calculated relational extent is proportional to the similarity of developing trends; that is, the more similar are the developing trends, the greater is the relational extent. Grey relational analysis provides a useful tool to deal with the problems of limited and superficially ruleless data processing, for searching primary relationships among the influential factors and determining important factors that significantly affect the defined objectives [28,29]. Meanwhile, application of AHP and grey relational analysis for optimizing the briquetting process is not found in the current literature.

This research presents a study on the multi-objective optimization of a biomass R-D system, in particular for briquetting rice straw. Moisture content, particle size of the raw material, temperature, and the gap between the roller and ring-die were selected as optimization variables while the average energy consumption, productivity, density and the rate of qualified biofuels were optimization objects. For this purpose, grey relational analysis, combined with AHP, was applied as a tool for the selection of the most suitable parameters of this briquetting process, in order to achieve the highest efficiency and best product quality.

2. Materials and methods

2.1. Working principle of the straw R-D process

The working principle of the straw R-D process is shown in Fig. 1. The ring die is fixed on the machine. When straw material is fed into the cavity formed by ring die and press roller, the roller (driven by a spindle) starts to rotate and grabs the material. The material then is compressed and squeezed into the die holes. Lignin and cellulose contained in the raw material begins to soften and then bond together under the action of heating (there are some electric heating tubes lies in the ring-die, and the heating temperature is controlled by the temperature controller connected with the heating tubes). After a specific holding time (20–50 s) the straw is extruded out as a briquetting fuel with a certain shape (diameter of 20 to 30 mm, length of 40 to 80 mm) and density (0.8 to 1.1 g/cm^3) [7].

2.2. The AHP methodology calculating priority weight

The AHP methodology, developed by Saaty in the 1970s, allows decision makers to decompose a complex problem into a hierarchy of goal, criteria, and alternatives available, can then be used to convert uncertain factors into quantifiable indicators. Further, by performing extensive pair-wise comparisons using a suitable scale, usually ranging from one to nine, the ranking for available alternatives was obtained. Results of the pairwise comparison exercises are transformed into positive pairwise comparison matrices N, illustrated by Eq. (1):

$$N = [N_{ij}]_{n\times n} = \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & \ldots & w_n/w_n \end{bmatrix} \quad i,j = 1,2 \cdots n \quad (1)$$

where, N_{ij} (w_i/w_j) is the relative importance of factor i and factor j. The scale value is shown in Table 1.

The key steps involved in this methodology are: For each comparison matrix calculate: maximum eigenvalue, consistency index (CI), consistency ratio (CR), and normalized eigenvector to obtain priority weights for each criteria/alternative; Then the judgment over various levels of hierarchy is integrated, and an overall priority ranking for alternatives is produced.

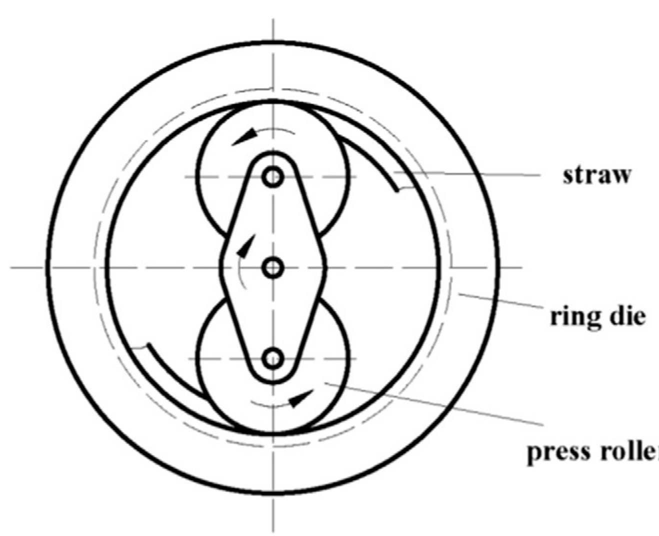

Fig. 1. Scheme of the straw ring-die briquetting (R-D) process.