Fuel 161 (2015) 157–167

Contents lists available at ScienceDirect

Fuel

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

Prediction of ash-induced agglomeration in biomass-fired fluidized beds by an advanced regression-based approach

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HIGHLIGHTS

- Modeling of maximum agglomeration-free operating temperatures for 83 biomass fuels.
- Application of advanced regression methods based on a large set of experimental results (350 individual data-points).
- Translation of prediction error into generally applicable agglomeration probabilities.
- Validation of predictions through long-term tests.

ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form 20 August 2015
Accepted 20 August 2015
Available online 31 August 2015

Keywords:
Fluidized bed combustion
Ash agglomeration
High ash biomass fuels
Predictive modeling

ABSTRACT

Energy crops and biogeneous residues offer the highest potential for future growth in biomass utilization. Traditional forest grown wood types, along with their consistent combustion characteristics, will thus be replaced by fuels with highly heterogeneous composition. Reliable prediction of their combustion characteristics and in particular of their ash behavior is essential for plant designers and operators trying to harvest this potential for energy conversion. In fluidized bed combustion, the fuel–ash induced agglomeration of the bed materials is one such behavior that needs to be described. In this paper a black-box model for agglomeration prediction was created through multivariate regression modeling using R-statistics v3.0.2. It based on the input variables bed ash concentration, particle size, fluidization velocity and fuel ash composition and predicts the maximum operable agglomeration-free temperature. Three linear and nine non-linear modeling algorithms have been applied to the data, optimized and validated in independent subsets. This validation was performed on results of controlled agglomeration tests, partly performed on our own test reactors and partly derived from literature. The final data set comprises 350 test results, covering 83 different fuels tested in seven different reactors. The validation revealed good predictive performance of the regression models, in particular of non-linear ensamble algorithms such as random forests, or cubist. These exhibit average deviations of around 60 K between model predictions and experimental results, which is very promising given the complexity of the system. After transformation of these prediction errors into agglomeration probabilities, a set of operational parameters unlikely to cause agglomeration can reliably be identified. A final evaluation of selected cases in controlled long-term tests could confirm the validity of these predictions.

1. Introduction

Ever since the discovery of the defluidization phenomenon in fluidized beds of adhesive particles by Gluckman [1], attempts have been made to predict its occurrence through mathematical correlations. Gluckman himself postulated a linear increase of the minimum fluidization velocity due to adhesive forces. Basu [2] followed up on this concept and extended Kunii and Levenspiel's [3] equation for the calculation of the minimum fluidization velocity by an adhesive force term (1). The influence of the coal ash composition in this case was supplied by dilatometrically determined sintering temperatures. The influences of particle size and bed height ($f_1(d_p)$ and $f_2(L)$, respectively) as well as the constant "K" for the temperature influence were provided by regression. While the predictions were close to the experimental results provided by Basu, its applicability to other systems is quite limited due to the close fitting of model parameters to the specified experiments.

$$U_{mf} = \frac{1}{1650}\frac{d_p^2 g}{\eta_f}(\rho_s - \rho_g + (K(T - T_s)f_1(d_p)f_2(L))) \quad (1)$$

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http://dx.doi.org/10.1016/j.fuel.2015.08.040
0016-2361/

Moseley [4] incorporated the granular energy of fluidized bed particles into an agglomeration model, a concept derived from molecular dynamics simulations. This energy can be translated into an average velocity of the particles in the dense phase, which was combined with an adhesive factor derived from the ash sintering temperature to determine stickiness in particle collisions. The model is based on an energy balance of kinetic (granular) energy and dissipative energy in molten ash layers. Models "1" and "2" apply different approaches for calculation of the granular energy. Numerical constants have been derived from the experimental boundary conditions with a fitting parameter in the range of $0 > k_1 > 1$. The resulting increase in minimum fluidization velocities (2) follows the reported experimental data very well, especially at bed temperatures above 1000 °C as shown in Fig. 1.

$$U_{mf,s} = C_0 + C_3 \frac{\left(\frac{T}{T_s} - 1\right)^{5p}}{\left[1 - \frac{150(1-\epsilon_{mf})}{\epsilon_{mf}^3}\ (T-273)^{1.75/\epsilon_{mf}^3}\right]} \tag{2}$$

Factor	Model 1	Model 2
p	1	4/3
C_0	U_{mf}	0
C_3	$\frac{68.27}{k_1^{0.5}} \frac{\nu^{0.5}(1-\nu_p)^2}{\rho_f^{0.5}}$	$0.041 \frac{d_p^{8/9} \rho_f^{16/9} (1-\nu_p)^{8/3}}{\rho_p^{4/9} \eta_f^{52/27}}$

Seville [5] defined a viscous flow sintering mechanism as the driving force for agglomeration. The model uses the static pressure of the bed on particles in the dense phase and viscosities determined by a regression fitted Arrhenius approach to describe the sintering behavior (Fig. 2). Knight [6] successfully applied this approach to solid state sintering as observed in the defluidization of small iron particles.

$$(U_{mf,s} - U_{mf}) = \frac{K_1 K_2}{\eta_0 e^{\left(\frac{E}{RT}\right)}} \tag{3}$$

Factor	Coefficient	Description
K_1	$\frac{2D_b}{3}$	Bubble diameter
K_2	$\left[\left(\frac{2x}{d_p}\right)^2 \frac{t}{k_1}\right]$	Critical size of sinter neck (x = neck radius at time t)
k_1	$\left(\frac{16\gamma}{5d_p} + \frac{8}{5\pi}\frac{\epsilon_p}{1-\epsilon_p}\ \sigma\right)$	Material properties and applied stress γ (γ = surface tension; ϵ_p = particle porosity)

Tardos [7] developed a model for the agglomeration induced increase in minimum fluidization velocity by considering the breaking of agglomerates through bubble forces. He defined a stable bed to be present, if the gas flow produces bubbles strong enough to break a cylindrical agglomerate covering the whole bed cross section. By comparing equations for bubble force and wet agglomerate strength, published by Livshits [8] and Rumpf [9] respectively, he derived the following equation for the increase in minimum fluidization velocity:

$$\frac{(U_{mf,s} - U_{mf})}{U_{mf}} = \left[\frac{k_2(1-\epsilon)^2\gamma_m}{\epsilon^{7/2}\ W_{bed}\ g}\right] \left(\frac{\rho_f\ d_{ag}\ D_b}{\rho_p}\right)^{0.5} \left[\frac{W_m}{\rho_{liq}(d_p^3\ D_b\ \Phi)^{0.5}}\right] \tag{4}$$

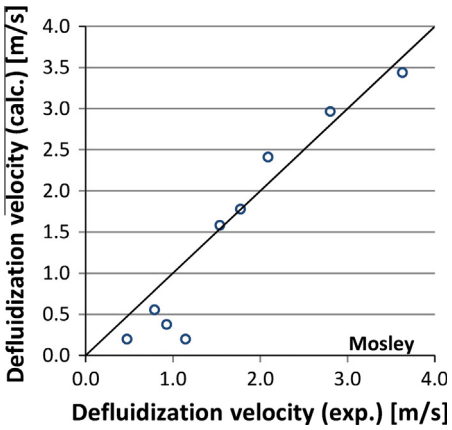

Fig. 1. Modeling results reported by Moseley [4].

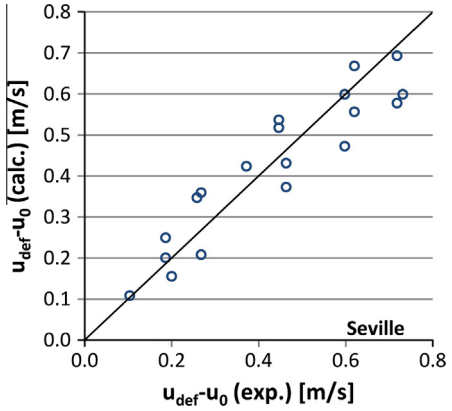

Fig. 2. Modeling reports by Seville [5]. Line represents modeling results.

with: $k_2 = \frac{0.675\pi g^{0.5}}{D_{bed}}$.

A comparison with in-house experiments revealed good agreement of the model, a validation with literature results, however, was not convincing [10]. The prediction model presented by Arena [11] simulates two-particle collisions similar to Moseley's approach. The adhesive force in this investigation originated from polymer coatings around quartz particles. The condition for agglomeration was a critical coating thickness δ_{crit} that would diminish the particles' kinetic energy through viscous dissipation (Eq. (5)). While the method seems very promising, the defluidization time (t_{def}) results depending on the polymer pyrolysis rate $k(T)$ (Eq. (6)) can only predict experimental data with an error margin of ±50% (see Fig. 3).

$$\delta_{crit} = d_p \left[e^{\frac{4mu_0}{\mu\pi d_p^2}} - 1\right] \tag{5}$$

$$t_{def} = k^{-1}(T) \ln\left\{1 - \frac{\left[\left(0.5e^{\frac{4mu_0}{\mu\pi d_p^2}} - 1\right) + 1\right]^3 - 1}{\frac{Q_{pp}\rho_p}{W_{bed}\rho_{pp}}\ k^{-1}(T)}\right\} \tag{6}$$

Lin [12] developed a model for agglomeration prediction in biomass fired fluidized beds, describing SiO_2/K_2O coatings as the source of adhesive forces. The model determines a critical buildup of coating thickness, the coating viscosity – by an Arrhenius equation – and the separating force as proportional to the excess gas