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Unified Ignition – Devolatilization model for fixed bed biomass Gasification/Combustion

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Abstract

Counter-current flame propagation through fixed packed beds serves as a canonical form for understanding biomass thermochemical conversion phenomenon – this is due to the 'universal behavior' of fuel consumption rate per unit area with superficial velocity variation. This behavior is directly related to the particle density scaled ignition time being independent of biomass type, varying only with superficial velocity. But when the devolatilization time exceeds ignition time for a particle, the predicted fuel consumption rates will be higher than the actual values due to overlap of ignition and devolatilization. This situation is relevant for larger particles (> 30 mm equivalent sphere) and thin wood chips, due to sharp edges aiding quick ignition. The current work aims at generalizing the 'universal propagation model' to account for this effect which is critical to designing grate furnaces. Towards this, packed bed experiments were performed in a 500 mm dia, 1 m height cylindrical reactor with groundnut shell briquettes (GSB; dia 100 mm, lengths varying from 40 to 110mm) and pellets (dia 8mm and length varying between 15 to 20mm) at a superficial velocity of 20 and 30 cm/s. The fuel mass flux is calculated by two methods 1) from the slope of time-mass curve 2) from time-Temperature plots measured at fixed thermocouple locations along the reactor. Fuel flux measured using the two methods match closely for pellets, but with GSB, the fuel flux from method 2 is higher than method 1 by about 15 %. This indicates that subsequent fresh layer of biomass ignites before complete devolatilization of the previous layer leading to oxygen starvation. This also indicates a transition from ignition controlled to devolatilization rate controlled flame propagation, consistent with the expectations based on variation of ignition and devolatilization time with particle size measured for single particles in an earlier study at our lab. These results are used to develop a unified ignition-devolatilization model for single particle combustion, which is used to modify the 'universal propagation model' to account for particle size and shape effects. The predictions from this model are shown to closely match with the observed results.

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Keywords: Biomass, Fixed bed, Grate furnace, Ignition-Devolatilization, Modeling

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1. Introduction

Agro-residue based briquettes are increasingly used for medium scale process steam generation and other applications. With maximum capacity required in such applications limited to 10 tons/hr of steam, cross-current grate firing is the most preferred configuration. Generally, systems designed for wood chips are adopted for briquettes with design changes by trial and error. While many attempts have been made to model processes on a grate it is not clear how far these ideas have been translated into design principles which can be used by practitioners. A review of these modeling efforts can be found in [1]. Varunkumar et al [2] sought to remedy this by recognizing the equivalence between cross- and counter-current packed bed configuration through a coordinate transformation. By using the 'universal flame propagation' (denoted UFP hereafter) behavior of counter-current configuration, which is well understood in terms of a simple diffusion controlled model capable of capturing the abundant data available from earlier work [3], a simple kinematic equation connecting the grate parameters (speed and length) with system design parameters (steam generation rate, initial bed height) is obtained in [2]; the essential idea being that the residence time of fuel particles on the grate must be at least equal to the conversion time determined by the UFP model. This model is shown to rationalize the current design and further suggestions for improvement are brought out in [2]. This effort also brought out certain minor limitations of application of UFP model to practical grate furnaces. This is related to the assumption of 'ignition' controlled propagation which leads to the kinematic grate equation being valid for only particles of size less than 30mm (equivalent sphere). This aspect is elucidated with single particle experiment that show the devolatilization time to exceed the ignition time for particles larger than 30mm (see Fig. 8 in [2]) thereby bringing out the need for modification of the UFP model. The need for further experiments with larger briquette particles in a 500mm lab scale counter-current reactor is brought out in [2]. Current work reports experimental results from such a reactor and attempts to improve the UFP model with a new *'unified ignition-devolatilization'* framework.

2. Experiments

Experiments are carried out in a cylindrical furnace 500mm in diameter and 1200mm in length made of SS310 insulated with high grade ceramic wool. A schematic of the experimental setup is shown in Fig. 1. The entire reactor is mounted on a weighing scale (10 g accuracy, 200 kg max) for mass loss measurement and thermocouples are placed at a uniform distance along the length of the reactor for measuring flame propagation rate. Air is fed through the grate by a centrifugal blower metered through a calibrated orifice plate. For uniform distribution, air stream is split and fed as three jets separated at 120 degrees at the bottom of the reactor through the grate.

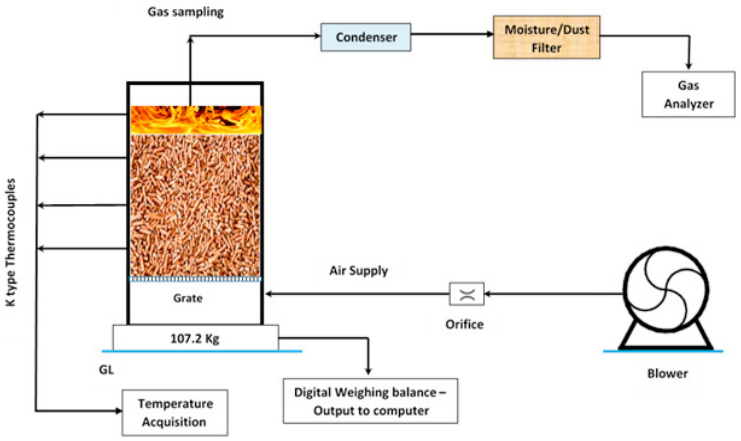

Fig. 1. Schematic of the Experimental setup

Online sampling of gas is made from the top of the reactor through a sampling line connected with condenser, dust/moisture filter and gas analyzer downstream (results not reported here). A total of seven experiments - six with groundnut shell briquettes and one control experiment with Oorja pellets were done. The properties and the pictures of the biomass used in the experiment are given in Table 1 and Fig. 2 respectively.

Figure 2. Photographs of Biomass used in the experiments

Table 1. Properties of fuels used for the study

Property	Groundnut shell briquettes(GSB)	Oorja pellets(OP)
Size and shape	Φ100 mm X L 20-90 mm	Φ8 mm X L 15-20 mm
Moisture content, %	5	6
Ash content, %	10 - 12	10
Particle density, kg/m3	1110	1260
Packing density, kg/m3	545	612

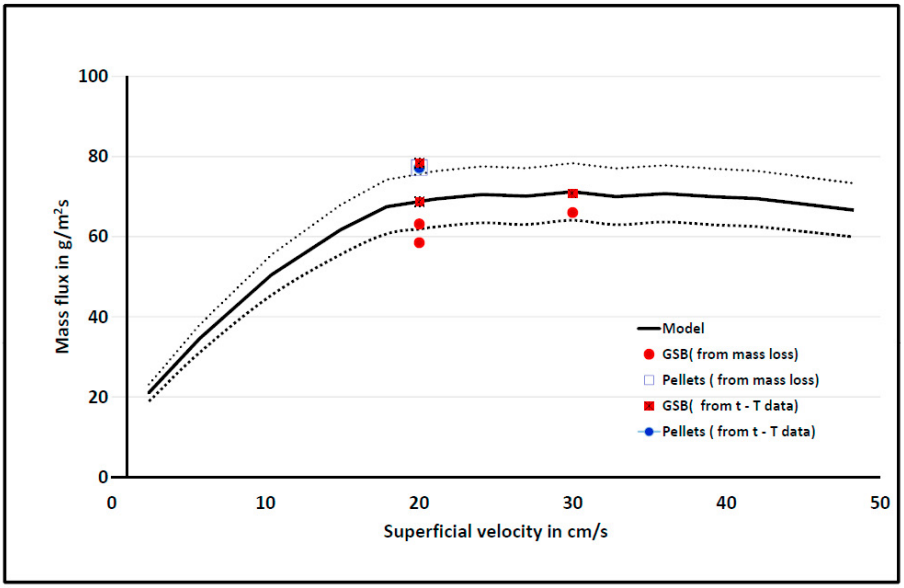

Figure 3 Fuel mass flux variation with superficial velocity in relation to the Universal propagation limits

Results of mass loss rate measured using weighing balance (Method 1) and thermocouple data (Method 2) are shown in Fig. 3. As expected from the model, there is very little variation in the fuel mass flux with superficial velocity beyond 18 cm/s - hence it is clear that there will not be any performance reduction if the primary air flow is brought down to these levels. Though within the limits set by Universal propagation model, the mass flux with briquettes is lower than that of pellets. This is consistent with the observations related to variation of relative magnitudes of ignition times (t_{ig}) and devolatilization times (t_v) with particle size described in [2]. Deviation of the mass flux estimated from

the temperature data compared to weighing scale method (shown in Fig. 4) is also consistent with this observation indicating overlap of devolatilization in multiple layers as opposed to a single layer as assumed in the model. This clearly indicates that for larger particles (>30mm) devolatilization can become rate limiting and hence must be accounted for in the UFP model. Towards this, a unified ignition-devolatilization modelling framework is presented here.

3. Unified Ignition – Devolatilization model

Biomass combustion is a well-known stage wise process of moisture evaporation, ignition, devolatilization and char combustion or heterogeneous combustion as a sequential process. As explained earlier, out of these, time for ignition and devolatilization can be rate controlling and a unified framework for estimating these quantities is required for accurate prediction of fuel burn rate and hence furnace design. The framework presented here is an extension of the devolatilization model developed by Mukunda et al [4] to capture the ignition process.

3.1. Ignition

A biomass particle exposed to an ignition source (assumed to be a stream of hot gases at 1500 K with a convective heat transfer coefficient of 15 W/m^2-K) is considered ignited if a stable envelope diffusion flame is established around it. Analysis of mass loss plots of particles of various sizes exposed to a stream of hot gases from [2] indicate that this occurs at about 15% mass loss. By solving simultaneously, the transient heat conduction equation coupled to the solution of quasi-steady gas phase equation with a convective boundary condition (see eq. 1) the time required for 15% mass loss is calculated and taken as the ignition time. It is assumed that the process is spherically symmetric and 2D effects are accounted for in this framework using a quasi-1D approach as explained in Mukunda et al [4].

$$\frac{G_p r_p^2 C_p}{r_s^2}\left[T_s - T_p + \frac{H_d}{C_p} + \frac{\dot{q}_w''}{G_p C_p}\right] = h(T_\infty - T_s) \tag{1}$$

Where G_p is fuel mass flux in kg/m^{2}s at the pyrolysis front (r_p), $r_s$is the surface radius, C_p is the specific heat at constant pressure, T_s , T_p and T_∞ are the surface, pyrolysis front and free stream temperatures respectively, H_d is the heat of pyrolysis and $\dot{q}_w''$ is the heat flux into fresh biomass.

3.2. Devolatilization

In this unified approach the ignition-to-devolatilization transition is accounted for by a switch from convective boundary condition to a thin flame boundary condition (eq. 2) obtained from application of droplet combustion theory as given in Mukunda et al [4]. This combined with the heat flux condition at the pyrolysis front (eq. 3) and transient conduction equation (eq. 1 in [4]) is used to estimate the devolatilization time. A fixed pyrolysis front temperature of 473 K is assumed. The devolatilization rate obtained is used in eq. 4 to track the pyrolysis front and the time taken for 75% mass loss is taken as the devolatilization time.

$$\frac{G_p r_p^2}{r_s^2}\left\{\frac{\frac{H_c Y_{o,\infty}}{s} + C_p(T_\infty - T_s)}{exp\left(\frac{G_p C_p r_p^2}{k}\frac{1}{r_s}\right) - 1} Nu_0 - C_p\left(T_s - T_p\right) - H_d - \frac{\dot{q}_w''}{G_p}\right\} = \epsilon\sigma T_s^4 \tag{2}$$

$$ln\left[\frac{\frac{H_d}{C_p} + \frac{\dot{q}_w''}{G_p C_p}}{T_s - T_p + \frac{H_d}{C_p} + \frac{\dot{q}_w''}{G_p C_p}}\right] = \frac{G_p r_p^2 C_p}{k}\left[\frac{1}{r_s} - \frac{1}{r_p}\right] \tag{3}$$

$$\frac{dr_p}{dt} = -\frac{G_p}{\rho_p} \tag{4}$$

Where H_c is the enthalpy of combustion of volatiles, $Y_{o,\infty}$ is the free stream oxygen mass fraction (0.232), s is the

stoichiometric A/F of volatiles (1.53), k is the thermal conductivity of air, Nu_0 is the Nusselt number and ρ_p is the particle density.

3.3. Model results

The transient conduction solver is coded in MATLAB® and the same is used to get the ignition temperature profile and heat flux into the fresh biomass ($\dot{q}''_w$). Beyond the ignition time the thin flame boundary condition (eq. 2) is incorporated. Then eqs. 2, 3 and 4 are simultaneously solved for r_p , G_p and T_s using the value of $\dot{q}''_w$ obtained from the solution of the transient conduction equation. The iteration continues till mass is reduced to 25% of the initial mass. Thermodynamic and transport property values used in the model are taken from [4]. A typical mass loss plot obtained from the model along with experimental results is shown in Fig. 4 and the comparison is very good. The results reported are on dry ash free basis and excluding char content.

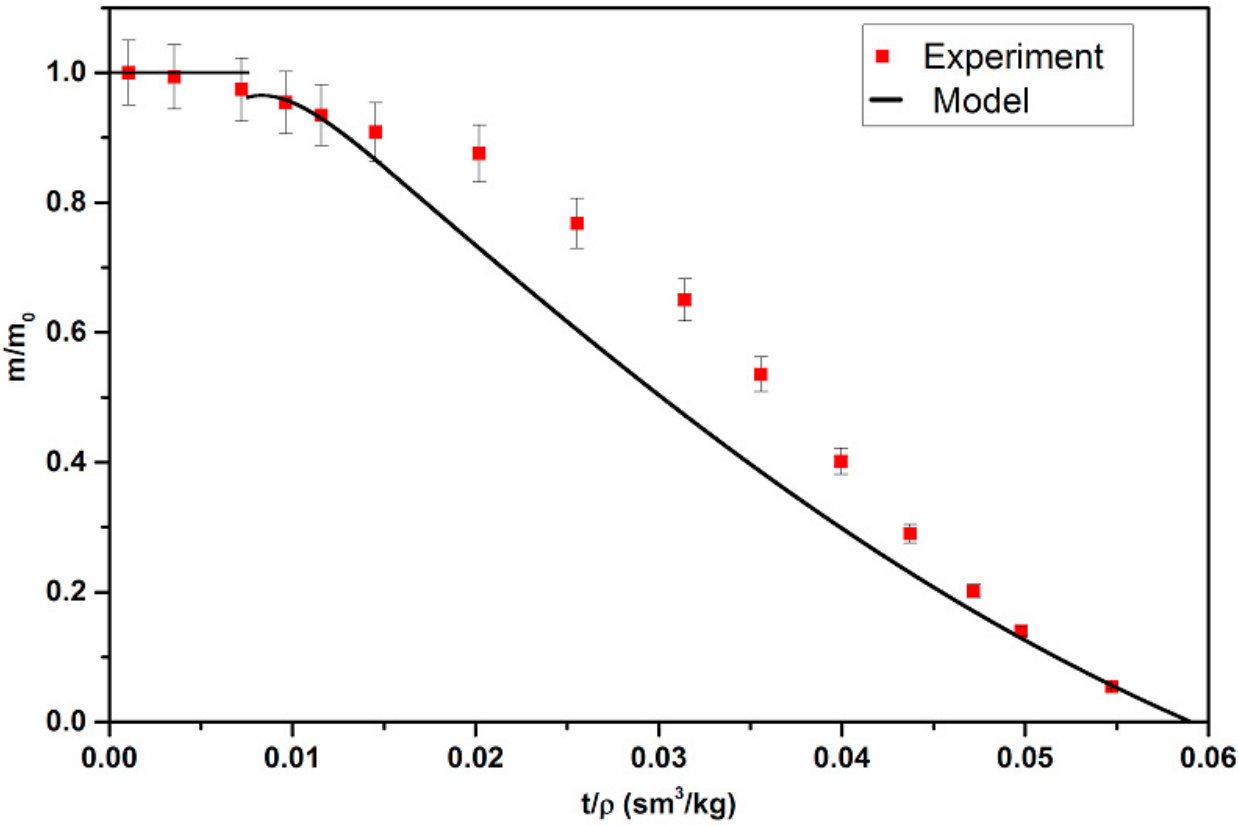

Figure 4 Comparison of predicted mass loss variation with experiments

Ignition and devolatilization time predicted for particles of different sizes is shown in Fig. 5. The variation is qualitatively similar to the experimental results shown in Fig. 8 of [2] - the devolatilization time increases much faster than ignition time as the particle size increases. This is consistent with the observation that devolatilization time becomes rate controlling beyond a critical size. The actual value of the critical size is dependent on the flow conditions and reactor dimensions and further calculations are required to elucidate these effects.

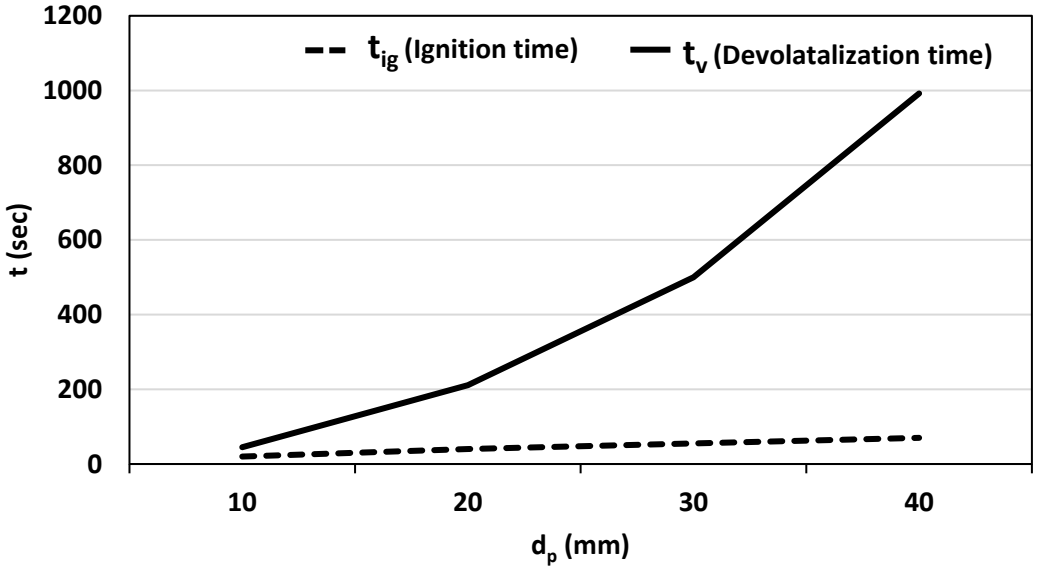

Figure 5 Ignition and Devolatilization time with particle size

4. Conclusion

Counter-current flame propagation experiments are carried out in a 500 mm dia cylindrical lab furnace with biomass. The expected deviation from the UFP model due to particle size is demonstrated using the experimental results. Towards modifying the UFP model to account for particle size effects, an unified ignition-devolatilization modeling framework is developed here. Encouraging preliminary results capture the qualitative behavior found in experiments - that the devolatilization time increases much more rapidly as compared to ignition time as the particle size is increased. Further results will be used to modify the UFP to develop a predictive tool for grate furnace design.

Acknowledgements

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