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HYDRODYNAMIC MODEL FOR A BIOMASS GRATE FIRED SYSTEM

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Abstract The present paper describes a hydrodynamic model for the solids motion in a grate fired combustion system. The overfed bed material is considered in a Lagrangian referential until the particles stop in a position over the bed or exit the domain. The solid material in the grate is then considered as an incompressible continuous media. The momentum balances are applied in an Eulerian referential to particle elements to calculate their velocity in the grate direction. For the conditions considered the calculated velocity of the elements increase always from the start of the grate towards the exit, so the motion in the vertical direction is always downward. This motion is calculated from continuity and the two components enable the definition of the solids flow within the bed. The application of the model for solids motion is shown to be representative of different situations that are analysed for a vibrating grate working with wood pellets. The distribution of solids in the bed is visually and computationally characterised for three situations: i) feeding particles above the bed over an inclined still grate, ii) vibrating an initial bed promoting the motion of particles and iii) vibrating the bed and feeding above the grate in order to achieve a continuous evolution. The comparison of the results show that the model provides a good representation of reality although it can be improved by adjusting model parameters. The model allows for the generation of solids flow patterns in the bed and is a base for the development of a model for grate fired combustion systems.

Keywords: grate combustion, modeling solids motion, biomass pellets.

INTRODUCTION

Grate fired systems being one of the older combustion systems, is more difficult to represent by a numerical model due to the large inter particle effects that dominate their behaviour. The direct calculation of the motion of solid particles in a bed is possible with large computational effort using a Lagrangean referential for the particles and integrating their momentum balances simultaneously. This is the basis of the Discrete Element Method that has been recently developed and used for several applications [1-3]. The main problem with this approach is the large computational effort that can be manageable when considering equivalent spherical particles. However due to the great geometrical complexity of real solids, friction coefficients and other forces are introduced to obtain a representative behaviour of the bed.

The alternative representation of the bed in combustion systems is based on column models that are assumed to travel along the grate with uniform velocity and treated as a fixed bed for the calculation of conversion [4-5]. Due to the strong coupling of radiation heat transfer from the freeboard and the bed, the solution for the bed has to be done iteratively, with some level of discretization, leading to models that divide the bed in zones with different stages of solid conversion [6-7]. In these models the motion of the bed is considered uniform or simply ignored. The mass sources at the surface of the bed are specified to fit the total fuel input. The behaviour of the combustion systems in most cases depends mainly from the processes in the freeboard and therefore the use of CFD models is very useful. The present contribution is focussed on the solids motion within the bed. itself proposing a method to calculate the solids motion.

The calculation of the motion of solids as a continuous media has been formulated e.g. by Mills et al [8] considering a global momentum balance leading to the conclusion that the velocity profile is approximately linear with zero gradient at the surface. This continuous layer however is not representative of a finite grate where the slope of the free surface is larger than that of the grate. The behaviour of granular materials presents some particularities compared to other continuous media [9] that is the no-tension effect that basically introduces a different stress-strain relationship for compression and tension. Expansion does not introduce traction while compression produces forces. Further the motion of solid elements is only possible when the net force exceeds the friction reaction forces. The different behaviour of the solids under different conditions leads to different regimes that are analysed for problems involving granular materials [10].

In this paper the following section starts from a general equation of motion and presents its application for individual particles above the bed and for elements of solids within the bed. The following section presents briefly an experimental facility that was built to test at laboratory scale the combustion of wood pellets or other biomass fuels and in the present work was used to observe the behaviour of solids in isothermal conditions. In section 4 numerical results for the velocity distribution of solids and gases is presented with comparisons of the free surface of the bed.

NUMERICAL MODEL

The momentum equation applied to a single particle or to an element of particles is similar and can be written in the following form:

$$m\frac{Dv_i}{Dt} = mg_i + \sum_{j=1}^{k} F_{ij} \qquad (1)$$

where the velocity component in a given direction (i) can be calculated considering the component of the weight in the flow direction and the sum of forces acting on the body due to the interaction with other solids or with the gas. This equation can be integrated to calculate the velocity in consecutive time steps and therefore the position of the elements in a Lagrangean framework. The equation can also be used to calculate the variation of the velocity in the bed in an Eulerian referential.

Single Particle Motion Above the Bed.

For simplification the particles are considered here as spherical and the momentum balances are considered in two orthogonal directions, during their flight. The initial velocity of the particles is a input parameter and the direction is chosen from the position of the overbed feeding. The feeding is considered in dilute form that is the particles are tracked neglecting any collision with other particles except when they reach the bed surface. The bed is defined by the particle concentration in a grid and when the particle tracked reaches the bed it may rebound and/or slip over the bed surface.

The aerodynamic force above the bed can be calculated from the drag coefficient C_D and the velocity of the gas relative to the particle. The integration of the equations may then be used to calculate the velocity at each time step:

$$u^{t+1} = u^t e^{-A\Delta t} + u_G\left(1 - e^{-A\Delta t}\right) \qquad (2a)$$

$$v^{t+1} = v^t e^{-A\Delta t} + \left(v_G - \frac{g}{A}\right)\left(1 - e^{-A\Delta t}\right) \qquad (2b)$$

where $A = \frac{\pi D^2}{8}\rho_G C_D \left|U_G - U\right|$ is considered constant in the integration time step Δt. The position of the particles can be readily obtained and the collision with the bed surface can be found by superimposing the position in a grid containing the volume fraction of solids in the bed. When reaching the bed surface restitution coefficients are used to obtain the normal component of the velocity that was considered to be zero so the particle remains only with a velocity parallel to the bed. The energy balance to the solids may be used to calculate the energy dissipation in the collision. The velocity of the particle at the bed surface can be calculated from the momentum balance according to figure 1.

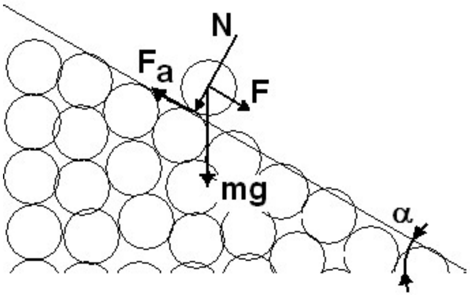

Figure 1. Forces acting on the particle colliding with the bed surface

Applying the Newton law in the bed surface direction considering the weight component of the particle in that direction and the friction as a result of the normal force, leads to:

$$m\frac{du}{dt} = F - F_a = mg(\sin\alpha - \mu_d \cos\alpha) \tag{3}$$

where μ_d is the dynamic friction coefficient. The velocity of the bed surface is neglected in this collision analysis but the net force resulting from the collision is accounted for the momentum balance in the bed element at the surface. When the force in the direction of the particle motion is smaller than the friction force the particle is decelerated but is not allowed to acquire a velocity in the direction of the friction force, once this is only a reaction force.

Motion of Particle Elements Within the Bed

The particle flow in the bed is analysed in an Eulerian referential based only on the momentum equation balance in the grate direction. Therefore only this velocity component is calculated. Based on the results of this analysis it is possible to define the vertical velocity component that is calculated in order to obtain a constant density of solids in all elements while the elements close to the surface may have a fraction of solids below unit. Figure 2 presents the grid used for the analysis.

The momentum equation in the direction of the grate (x) becomes:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial u}{\partial x}\rho u + \frac{\partial u}{\partial y}\rho v = \frac{\partial(\tau_{xx} - P)}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \rho g sin\theta + I_{gx} \tag{4}$$

This equation can be solved in the x direction and time (t) considering the terms in the perpendicular direction (y) calculated at each time step, explicitly. Eliminating the advection terms provides a large simplification eliminating the non-linear behaviour. The last term is the interaction force between the gas and the solid momentum in the direction of the grate (x).

The influence of the gas flow was investigated in a development of the present work where the gas flow was calculated by a Forchheimer approximation and was found to have a minor effect in the results, so it can be neglected. The reverse is not true, that is the gas flow is strongly affected by the solids flow and distribution and was one of the motivations for the present work.

The computation of the tensors is one of the major difficulties in solving the momentum equation. For the motion of solids with strong contact between particles the sum of the forces applied have to be larger than the yield strength, otherwise the solid bed remains static.

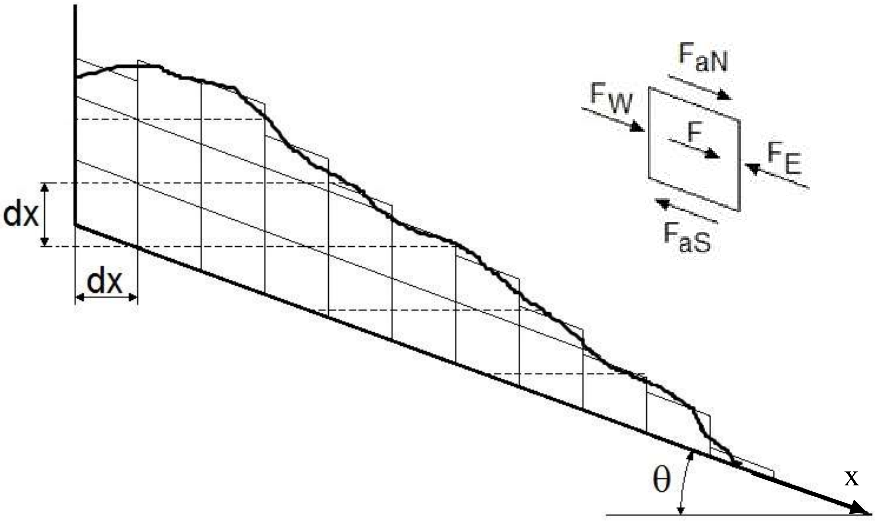

Figure 2. Grid referential used for solids motion in the bed.

The forces acting in the direction of the grate are the component of weight, the friction forces in the upper (north) and lower (south) faces and the normal forces from the neighbour elements. An explicit formulation was implemented here considering these forces and neglecting the advection terms and the interaction with the gas flow, keeping of course the weight. Based on these assumptions the following equation was obtained for an element of bed volume (V):

$$(\rho V)_{i,j}a_{i,j} = +\rho g sin\theta + F_W - F_E + F_{aN} - F_{aS} \tag{5}$$

The friction forces are calculated based on a friction coefficient multiplied by the normal force acting on the element. The normal force in the element is obtained from the weight of material above the element considered multiplied by the acceleration perpendicular to the grate that is the sum of a component of the weight and the acceleration that may be produced by vibration in the bed material.

$$F_{aN} = \mu \sum_{i+1}^{n}(\rho V)_{i,j}(gcos(\theta) + a_v) \tag{6a}$$

$$F_{aS} = \mu \sum_{i}^{n}(\rho V)_{i,j}(gcos(\theta) + a_v) \tag{6b}$$

The effect of the vibration is considered as an acceleration perpendicular to the grate. This is the vibration system that was implemented in the system analysed in the present work. In general the vibration may introduce acceleration in both the normal and the parallel direction of the grate. In the case of a moving grate the movements of the grate introduces an extra friction force depending on its velocity that can be included in F_{aS} in the element in contact with the grate.

The normal forces acting at the East and West faces of the element are considered only when they are positive, that is only compression forces are considered and no stretching force is considered due to the nature of the solids. These forces are calculated from the difference in the acceleration of neighbor solid elements in the same layer of the bed.

$$F_W = max\left(0, \left((\rho V)_{i,j-1} + (\rho V)_{i,j}\right)/2 \times \left(a_{i,j-1} - a_{i,j}\right)\right) \tag{7a}$$

$$F_E = max\left(0, \left((\rho V)_{i,j+1} + (\rho V)_{i,j}\right)/2 \times \left(a_{i,j} - a_{i,j+1}\right)\right) \tag{7b}$$

Replacing equations (6 and 7) in equation 5 leads to a linear system of equations that can be solved by the Thomas algorithm to calculate the acceleration of the elements in the bed in the grate direction x. The velocity parallel to the grate can thus be calculated from the previous value and from the variation in the time step considered.

Following the calculation of motion in the grate direction, the vertical velocity components can be calculated from a mass balance in order to obtain a constant bed density. At the elements close to the bed surface the fraction of solids is defined. At each location the sum of the two components calculated defines the velocity that will be analysed below.

RESULTS AND DISCUSSION

To evaluate the model behaviour three tests were performed, namely i) the case of the fixed grate with continuous overbed feeding to compare the shape of the bed surface, ii) the case of the bed initially filled with solids and then subject to vibration and iii) the case of the continuous mode of operation with a continuous overbed feeding and vibration in time intervals. The experimental test section was presented with preliminary results for combustion conditions [11] The grate fired laboratory model consists of a chamber 0.15 m wide and 0,5 m long where an inclined grate (perforated plate) is installed with the possibility of changing the inclination and being vibrated using an eccentric of radius 5 mm with rotation speeds up to 20 rps.

Case of Continuous Feeding Over a Still Grate

For this case the bed was considered initially empty and a continuous feed with a flow of 0.0037 kg/s was considered. The time step for the calculation was 5 ms and particles were tracked until they are still in contact with the grate or bed. To compare the model results with the experiment, colored pellets were fed in batches for different time periods. Figure 3 presents the comparison of the bed free surface after the accumulated time for each colored pellets. It can be appreciated that there is a very good agreement between the model results and experiments, showing that the formation of the bed in a still grate is rather uniform.

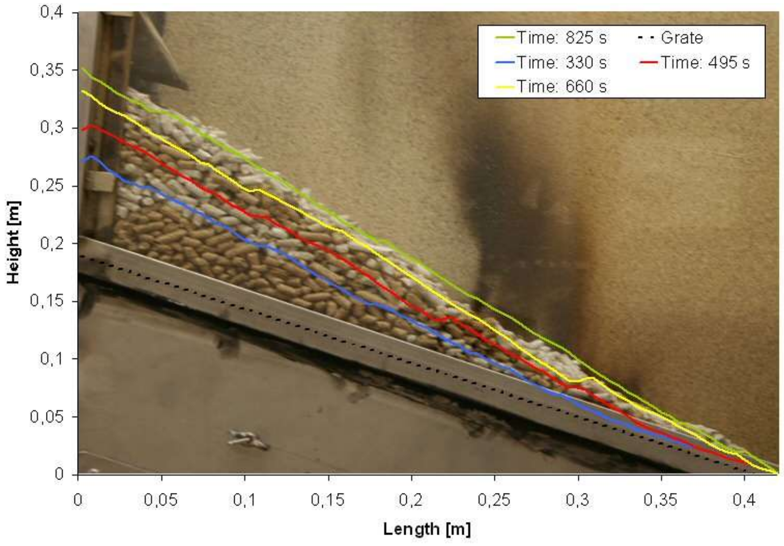

Figure 3. Comparison of bed surface.

Case of Continuous Vibration Without Feeding

For this test case the grate was set with an inclination of 18° and the initial bed was set with an angle of 26 °. Numerical simulations were performed with a vibration time of 3 s using 6 rps in 5 s periods with a total of two cycles, that is 10 s. For this simulation it was found that the bed evolved from the flat inclined bed to the pile as presented in figure 4. It can be seen that the larger variation occurred in the first vibration period.

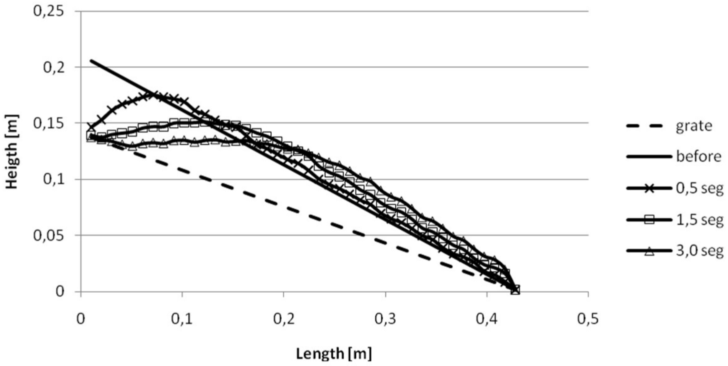

Figure 4. Comparison of the bed structure for a bed subject to vibration only.

Figure 5 presents the average velocity of the solids in the bed during the 2nd vibration time. The velocity close to the inlet has an upward component owing to the vibration of the grate that is larger in that part.

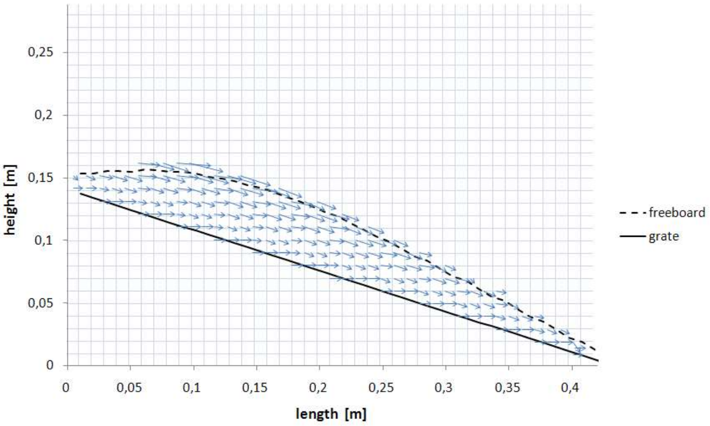

Figure 5. Velocity of the solids in the bed at the middle of the 2nd vibration.

Later the equivalent experiment was carried out but it was found that the bed did not moved significantly from the initial situation. Therefore another test was made vibrating the bed for 3 s at 16 rps. With this vibration the shape of the bed obtained was very similar to the initial numerical simulation as it can be observed from Figure 6. The use of more vibration to achieve the same effect as indicated in the model is a consequence of considering the acceleration due to the vibrating device acting in a solid, rather than a medium that will absorb part of the energy so it is essential to introduce damping and compression effects.

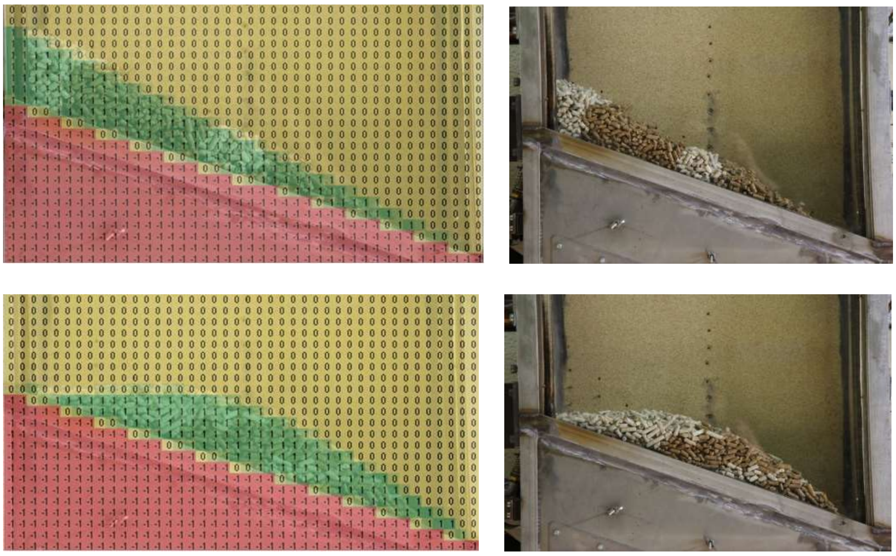

Figure 6. Comparison of the bed structure for a bed subject to vibration only.

Case of Continuous Vibration and Feeding

This test corresponds to the consideration of continuous operation of the grate and it is expected that following a transient period when the bed is built up, the behaviour of the bed should be repeatable along time, corresponding to the situation where the inlet flow is similar to the outlet flow. The numerical simulation was done for the grate at 20° using the continuous feeding rate of 0.0037 kg/s already considered that corresponds for the pellets considered to a thermal input of 60 kW. The operation of the vibrator was considered during 1 s at 5 rps in periods of 60 s. The initial conditions in the bed correspond to a bed inclination of 30°. For this case only numerical simulations were performed and the shape of the bed was observed along time with the results presented in Figure 7.

From the initial situation considered it can be observed that comparable situations are obtained after a period of 300 s (5 cycles). This can be confirmed from the evolution of the difference between the inlet and outlet flow rates that are represented in Figure 7 as a function of the number of vibration periods. After 6 cycles the values oscilate around the balanced value (zero) but it can be observed that the total ammount of solids in the bed will change along time so several periods are required to define an average bed shape.

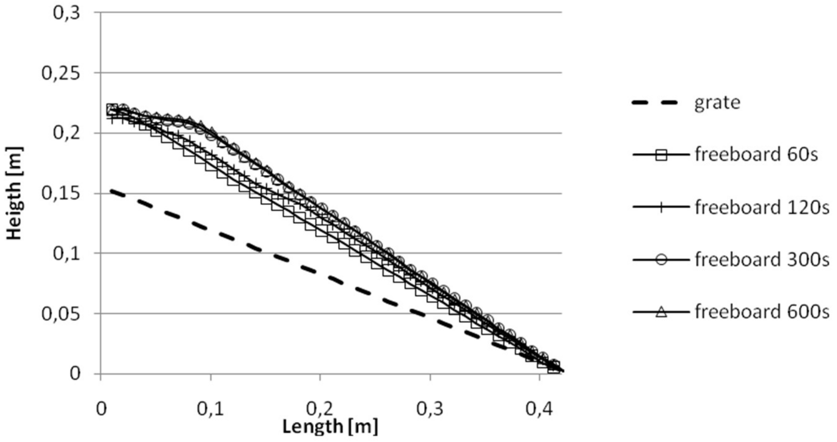

Figure 7. Variation of the free surface of the bed for the initial vibration periods.

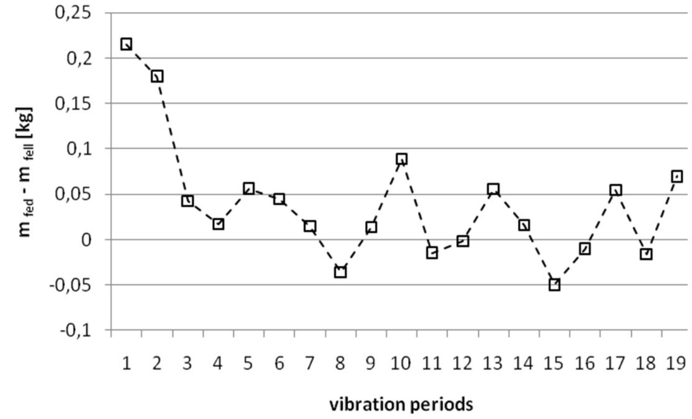

Figure 8. Variation of the difference between inlet and outlet mass in the bed.

The surface of the bed remains almost constant between the vibrations and the solids velocities. During the short vibration period the bed moves decreasing the bed height close to the inlet and increasing the inclination of the surface as shown in Figure 9. The solids velocities are represented in Figure 10, showing that the solids velocities are mainly in the grate direction with downward flow close to the feeding point due to the displacement of the bed layers. The definition of an average velocity in the bed along the whole period is not representative of the bed behaviour. Further during the vibration period the variations will affect the gas distribution, not analysed in the present paper so the development of a combustion model should include the transient variations.

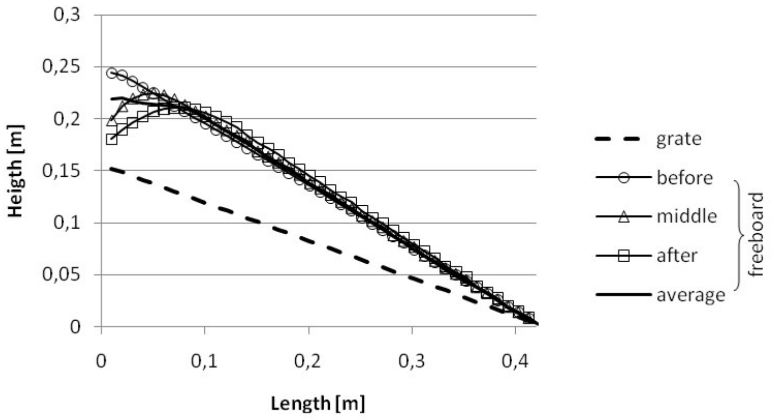

Figure 9. Calculated surface of the bed during the vibration period.

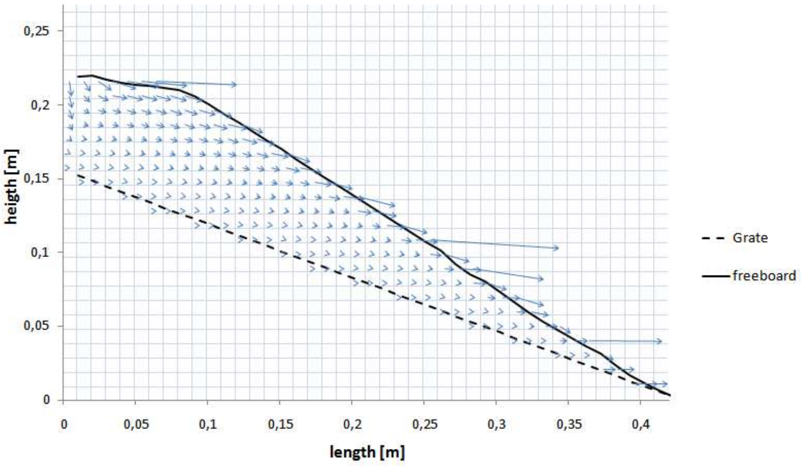

Figure 10. Average solids velocity in the bed during the vibration time.

CONCLUSIONS

A model has been developed to represent the motion of the solids in a bed created over a grate. The model development introduced several simplifications to allow for a simple calculation.

The calculation of the overbed feeding provides a good representation of the bed height along time achieving the equilibrium angle of the granular material.

The model over-predicts the effect of vibration as it does not consider damping and compression effects, but provides qualitatively a good representation of the observations.

The simulation of continuous operation showed that an initial set of five periods is required to achieve representative continuous operation and the variations in cycles occur mainly during the vibration time.

The present model is a innovative contribution to the description of solids motion over a grate. This will be further extended to consider the conversion of fuel in the bed, coupled with mass and energy balances to form a combustion model of grate combustion.

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NOMENCLATURE

C_D	Drag coefficient
D	particle diameter
F	Force
g	acceleration of gravity
i,j,k	Indices
m	mass of particle
N	Force normal to surface
P	Pressure
u	Velocity of solid (in horizontal or grate direction)
U	Absolute velocity
v	Velocity of solid (in vertical direction)
V	Volume of bed element
x	Coordinate along the grate
t	Time

Greek Symbols	
α	Grate angle with horizontal
μ_d	Dynamic friction coefficient
ρ	Density
τ	Stress
Subscript	
a	Friction (force)
g	Gas

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