Mathematical Modeling of Heat and Mass Transfer in a Rotary Kiln

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MATHEMATICAL MODELING OF HEAT AND MASS TRANSFER IN A ROTARY KILN

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Abstract

The main objective of this research was to compare the results of the proposed 1D transport model with numerical simulations of mass transport in a direct-heat rotary kiln at laboratory scale. Another objective was to investigate the effect of the number of flights on the formation of an active particle surface in the airborne phase, which enables efficient heat transport.
The studied rotary kiln is a low-angle cylinder with a length of 0.5 meter and a diameter of 0.108 meter with regularly arranged flights on the inside. The heat is transported into the rotary kiln by hot air at the inlet. The load in the rotary kiln consists of spherical particles with 1 millimeter diameter. The rotary kiln rotation speed is 21.5 rpm. For each simulation, 20 rotations were performed. The Discrete Element Method implemented in an open-source code LIGGGHTS was used for simulations.
Efficient heat transfer is made possible primarily by the large number of particles in the airborne phase, which are heated by the warm air blowing in. To begin with, the number of flights and their geometry were found to be a key parameter controlling the amount of particles in the gaseous regime. It was also found that an area in the right part of the base of the cylinder is formed which is not reached by particles from the flights. This phenomenon is due to the dynamics of particle transport, as the particles are not maintained in the active phase and move rapidly towards the load due to gravity. In conclusion, the effect of this zone is negative, as hot air flows through it without resistance, preventing the system from heating effectively.

Introduction

The climatic context highlights the needs to carefully manage the energetic resources. Thus, the industrial activity must be sized with respect to the new energy strategy. The energy-intensive process steps used in the industrial plant are particularly targeted. For one of them, they appeal to the rotary kiln. This device is widely used in the field of civil, metallurgical and chemical industries as a unit operation in chemical engineering especially for drying, reacting, mixing, granulating and heating of granular materials.
Figure 1 shows the dependence of the amount of extracted materials (left) and stock traded materials (right) as a function of time. Here we can observe an exponential increase in the extraction and stock trading of materials over the past hundred years. Note that cement and asphalt are mainly processed in rotary kilns. It is obvious that the current management of materials is unsustainable. In the near future we will have to move towards a circular economy in order to increase the efficiency of processing these materials. Therefore, examining the heat transfer phenomena in order to improve modelling tools and understand the dynamics of mass transport in rotary kilns is of fundamental importance.
A simplified scheme of a direct heated rotary kiln is shown in Figure 2. A rotary kiln is usually a longer steel tube with a drive gear that provides the rotation. There are flights on the inside of the tube that lift the material out of the bed. For the preparation of the asphalt, direct heating with a hot flame is mainly used, as shown in the figure. In the case of direct heating, all mechanisms contribute to heat transport. It is essential to lift particles from the bed to the so-called active phase.

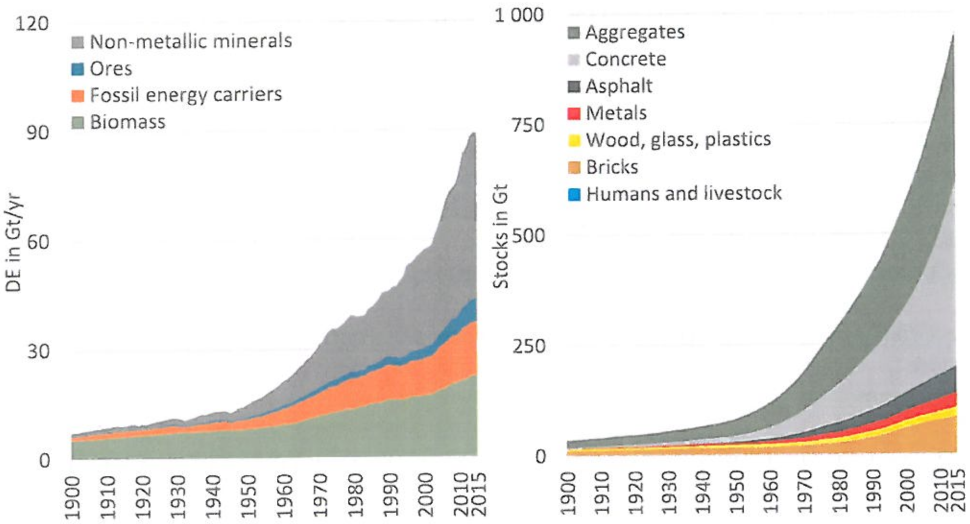

Figure 1. Extraction of different materials and traded stocks of materials in the past 100 years [1].

A 1D heat and mass transport model was introduced by Sunkara et al. [3]. Piton et al. [4] extended this model with additional flight's geometry and used it to investigate a particle's discharge in an industrial device. Nascimento et al. [5] studied solids holdup in flighted rotating drums by using the euler-euler approach. Karali et al. [6] found an optimal loading volume ratio of about 12.5 % in an operated flighted rotary drum. Zhang et al. [7] studied the influence of the number of flights on the phase ratio in rotary kilns by using the Discrete Element Method (DEM). They found out that eight flights in a kiln are optimal for their geometry. The design and arrangement of flights in a rotary drum by using DEM were recently studied by Silveira [8]. In their research, they determined the ideal kiln arrangement leading to the highest active phase.

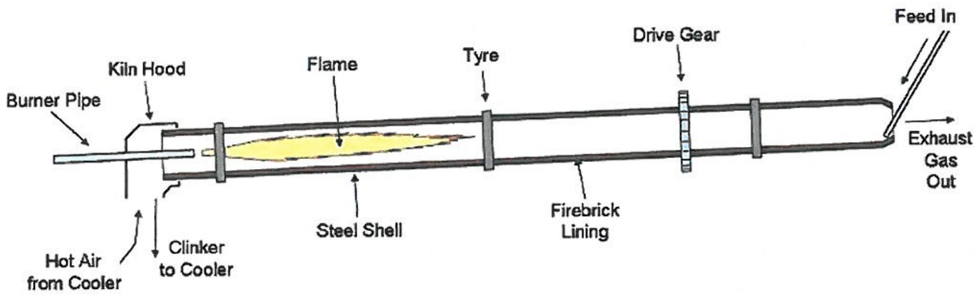

Figure 2. The scheme of a direct-heated rotary kiln [2].

The main objective of this research is to compare the results of the 1D transport model with Discrete Element Method (DEM) numerical simulations of mass transport in a direct-heat rotary kiln at a laboratory scale. Another objective is to investigate the effect of the number of flights on the formation of particles in the active phase, which enables efficient heat transport.

Method

In this work, the effect of the number of flights on the active phase formation in a rotary kiln was studied by using a 1D axial model and DEM. The scheme of the studied rotary kiln including the flight geometry is shown in Figure 3. The geometrical parameters of the rotary kiln are given in Table I. The rotary kiln rotation speed was 21.3 rpm corresponding to a Froude number of 0.0274. DEM parameters i.e. Young's modulus Y, coefficient of restitution e, timestep Δt, coefficient of friction μ, rolling friction μ_r and Poission's ratio v were set according to Silveira [8], see Table I, Parameters section.

The 1D model derived by Sunkara consists of integral equations that can be solved by simple implementation of advanced integration methods and obtain results quickly. The 1D model generally works only for over-loaded systems. A sufficient condition is that the height of the bed exceeds the length of the flight. The chosen volume ratio V_f = 15 % satisfies this condition. DEM is basically a molecular dynamics method for repulsive force interaction. The system of second-order ordinary differential equations is solved by using Verlet's algorithm. The DEM used in this paper is implemented in the open-source code LIGGGHTS. The obtained results are detailed information on particle positions, velocities, forces and rotational velocities. DEM, on the other hand, is a more time consuming method. In this case, according to Silveira, only 10% of the rotary kiln length, i.e. 5 cm, is modelled with the application of periodic boundary conditions. The number of particles at the same volume ratio corresponds to N = 63.837. This method significantly reduces the computation time. Data post-processing was performed in Matlab.

Table I

Geometrical parameters and DEM simulation conditions of the rotary kiln

Geometry				Parameters			
L [m]	0.5	L_{oart} [m]	0.05	N [-]	63,837	μ_r [-]	0.04
D [m]	0.108	V_f [-]	0.15	Fr [-]	0.0274	e_{pp} [-]	0.8
l_1 [m]	0.01	d_p [m]	0.00109	Y [Pa]	5.10^6	e_{ww} [-]	0.9
l_2 [m]	0.005	ρ [kg.m^{-3}]	2445	μ_{pp} [-]	0.7	Δt [s]	2.10^{-5}
l_3 [m]	0.005	ω [s^{-1}]	21.3	μ_{ww} [-]	0.4	ν [-]	0.3

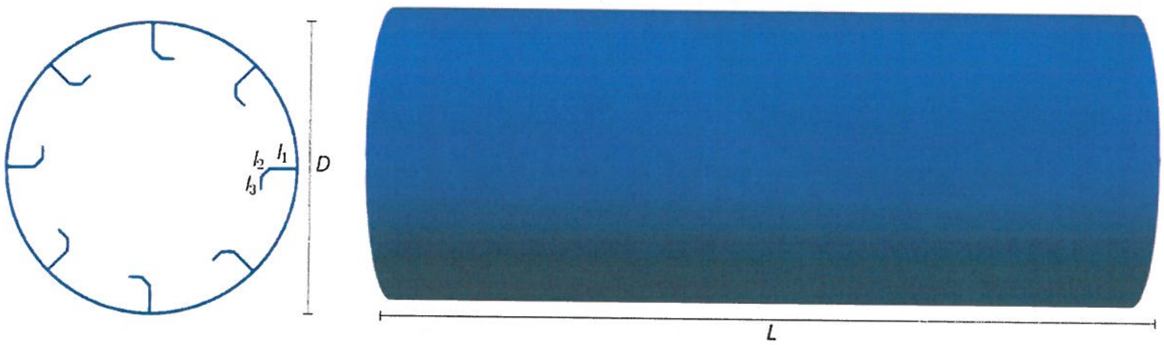

Figure 3. Geometry of the rotary kiln according to Silveira.

Results

Figure 4 on the left shows a visualisation of the DEM results for 20 flights in the 80th revolution. Particles in the kiln are coloured by the magnitude of the velocity. Based on this simple visualisation, we can distinguish between particles in the active phase and in the bed. Particles in the active phase (gaseous regime) have a higher magnitude of velocity. It can be observed that the active zone of the particles forms mainly in the centre of the cylinder with a diameter of about 7 cm. In this active zone, however, there are two main areas, or bands, where particles cannot reach. These bands are located in the left and right sections of the cylinder base. In the left particle section of the cylinder base the particles don't fall out of the flight because of lower inclination. In the right section of the cylinder base, the particles fall back into the bed very quickly due to free fall. It can also be seen that particles from the bed are evenly distributed in all flights. It is obvious that for this case the height of the bed is less than the length of the flight.

For an objective evaluation of the active phase, it is necessary to proceed to more detailed characteristics. It is useful to evaluate the volume ratio of particles in a single flight as a function of its angular position. The first flight located at the highest point of the cylindrical base is displaced 90 degrees counterclockwise at each full revolution. The shifted position is equal to δ = 0 degree. The scheme is shown in the upper right part in figure 4. This characteristic is usually manifested by a steeply declining curve.

In the figure 4 on the right there can be seen the volume ratio of the particles in the flight relativized to the mass of the bed depending on its angular position for different number of flights. The graph shows that about 12 % of the total particle mass is in the flight. This volume ratio of the flight is almost the same for the number of flights from one to fifteen on the other hand it decreases for higher numbers of flights. This decrease in the volume ratio can be explained by the spreading of the particles in a larger number of flights, which in total have a larger volume than the particles in the bed.

The graph in the figure 4 on the right also shows that within about fifteen flights the particles fall out of the flight at a smaller angle of inclination. For a higher number of flights than fifteen, however, the particles tend to stick in the flight even for larger inclination of the kiln. The particles then discharge the flight more steeply at kiln's inclination about 50°. In the case of twenty-five flights particles falling out of the kiln are an exception. In this case the flights are already very close and there is not enough space for the particles to fall out of the flight. However, a higher number than twenty five flights leads to an undesirable steric effect. The particles neither enter the flight nor fall out of it. In this way a higher number of flights don't support the formation of the active phase.

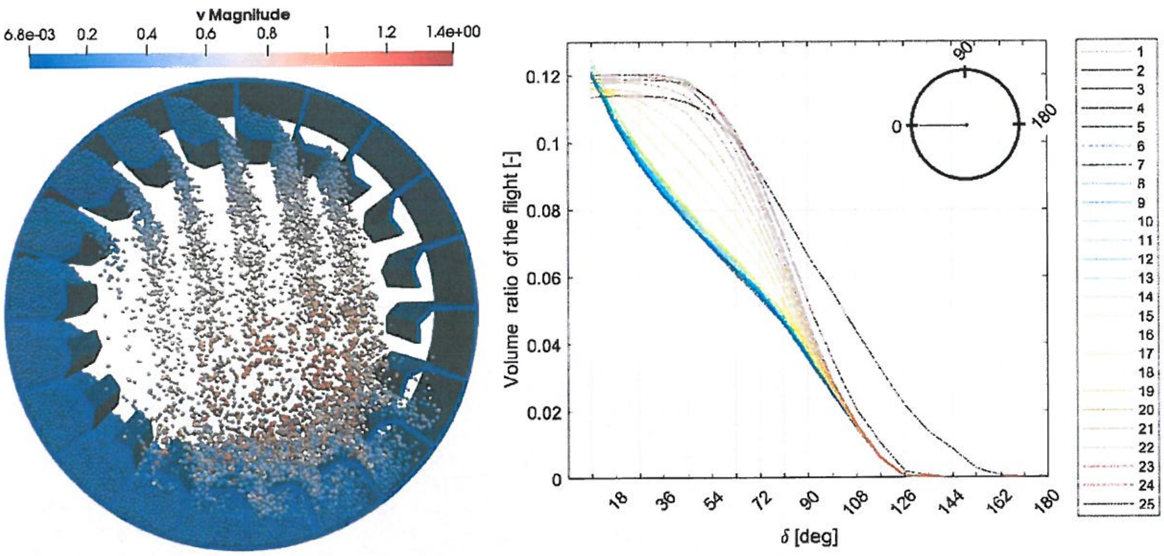

Figure 4. Visualisation of particles in the rotary kiln for 20 flights in the 80th revolution (left), the volume ratio of particles within the flight depending on its angular position for different numbers of flights (right).

To analyse the results, it is most important to track the formation of the particles' in the active phase. In the 1D model, the volume ratio of particles' in the active phase is determined by the calculation in the model. In the case of DEM, it is necessary to trace these particles by using physical quantities. The magnitude of the velocity was chosen as a suitable quantity. In this case, the particle in the active phase was set to have a magnitude of the velocity superior to 0.4 m/s.

Figure 5 on the left shows the dependence of the volume ratio of the particles' active phase relative to the total volume of the bed on the angular position of the flight. We can observe three zones on the graph. For a smaller number of flights, a zone with periodic dependence of the active phase on the position of the flight is evident. In this case the active phase occurs only in peaks and then completely disappears during the rotation. From about five flights onwards, the value of the volume ratio of the active phase stabilises at an average. The active phase does not cease in this second zone. For about fifteen flights, it can be seen that the volume ratio of the active phase reaches its highest value. In the case of this third zone we can talk about reaching a certain optimal value of the active phase volume ratio. After reaching this zone a higher number of lifters no longer contributes to an increase in the active phase.

In order to easily detect the value of the active phase, the mean value of the function given by the curve in Figure 5 on the left was calculated. The resulting mean values of the volume ratio of the active phase as a function of the number of flights in the kiln are shown in Figure 5 on the right for both 1D model and DEM.

The graph in Figure 5 on the right corresponds to the three zones presented in the left graph. For the first zone up to 5 flights a small active phase can be observed. In the second zone we can see that the active phase increases linearly. An optimal number of flights at which the value of the active phase reaches its highest point and does not grow further corresponds to the third zone. Furthermore, the 1D model seems to give bad results for a higher number of flights than the reached optimum by the DEM results. This phenomenon corresponds to the visualisation, see Figure 4 on the left, that the bed volume spreads out in the flights. In this case the total sum of the volume of particles in the flights appears to exceed the volume of the bed. Obviously, the over-loaded condition of the system is violated. As a result, the 1D model does not work correctly in this case.

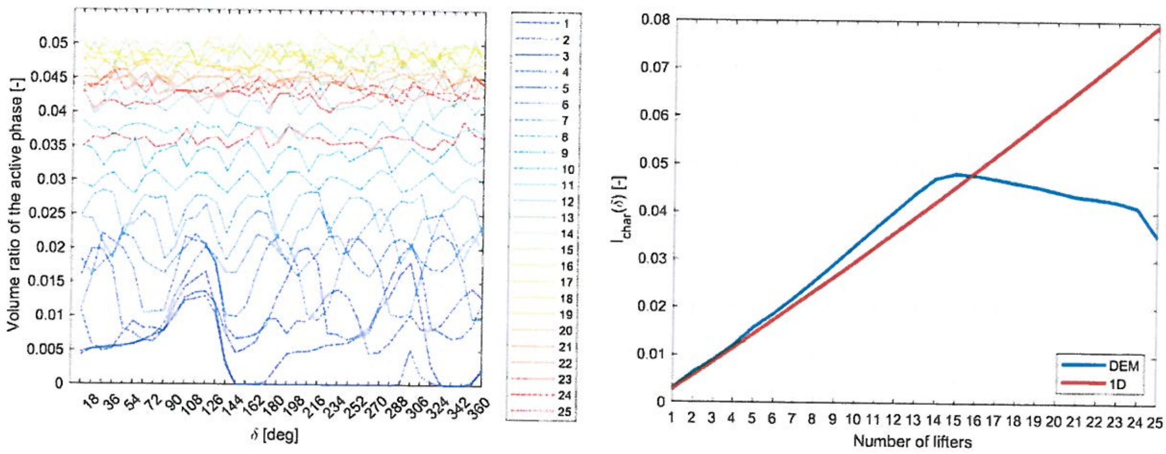

Figure 5. The volume ratio of the active phase depending on the angular position of the flight in the rotary kiln (left), the mean of a volume ratio of the active phase depending on the number of flights in the rotary kiln (right).

Conclusion

In this work, the effect of the number of flights on the active phase formation in a rotary kiln was studied by using a 1D axial model and DEM.

It was found out that the active zone of the particles forms mainly in the centre of the cylinder with a diameter of about 7 cm. In this active zone, however, there are two main areas, or bands, where particles cannot reach. It was also observed that particles from the bed are evenly distributed in all flights for a higher number of flights and as a consequence the height of the bed is less than the length of the flight in this case. Furthermore it was found out that a higher number than twenty five flights leads to an undesirable steric effect. The particles neither enter the flight nor fall out of it. In this way a higher number of flights don't support the formation of the active phase.

Moreover three zones of the active phase were observed. For a smaller number of flights, the active phase occurs only in peaks and then completely disappears during the rotation. From about five flights onwards, the value of the volume ratio of the active phase stabilised at an average. The active phase didn't cease in this second zone. For about fifteen flights the volume ratio of the active phase reached its highest value. After reaching this optimum a higher number of lifters no longer contributed to an increase in the active phase.

To conclude an optimal number of flights at which the value of the active phase reaches its highest point and does not grow further was found out. The 1D model seemed to give bad results for a higher number of flights. However, this phenomenon was explained by the violation of the over-loaded condition of the system. As a result it was found out, the 1D model does not work correctly for a higher number of lifters. The operating range of the 1D model can be approximately determined by the equality of the flights' volume summation and the bed volume.

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