# A direct numerical simulation of trickle flow in cokes bed

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**Abstract:** A new numerical model was successfully developed for analyzing packed bed structures containing non-spherical solids such as cokes and the high-temperature melt trickle flow characteristics of such beds. This enables the direct three-dimensional analysis of packed beds that are difficult to visualize in experimental tests. The sophisticated smoothed particle hydrodynamics (SPH) method can track the motion of liquids without discriminating between continuous and dispersed phases. Meanwhile, the advanced discrete element method (DEM) is employed as a highly-accurate method for solid-particle motion simulation. It is a method using a contact force model that is expanded to capture the motion of 3-dimensionaly freely shaped rigid bodies. We used the boundary for the packed bed configured with non-spherical solids to carry out a trickle flow simulation. Based on this model, we carried out the large-scale simulations, and perform case studies and other studies of statistical processing, and investigate the effects of both physical properties and packed bed formed from various types of non-spherical cokes.

## 1. Introduction

The liquid phase in a packed bed decreases the gas permeability and affects the stability and productivity of the blast furnace process. It also decreases the void fraction and the permeability of the media, and is held up easily by an upward force from the gas [1]. When a large amount of liquid accumulates in a coke bed, flooding occurs, and the gas permeability decreases significantly. It has been found that the structure and the moving behavior of the granular media and the physical properties of the liquid affect the hold-up of liquid in a packed bed. However, the melt flow form remains poorly understood because of the diversity of possible packing structures in the coke bed.

In this research, we evaluated the individual packing behavior for non-spherical cokes, based on DEM with expanded functions. We then simulated the liquid trickle flow behavior in the packing structures containing non-spherical cokes using SPH. We investigated the effect of actual coke shapes on the holdup characteristics by introducing a highly accurate 3D scanning technique.

## 2. Methodology

### 2.1. SPH scheme

The basic idea of the SPH method is to introduce a kernel function for flow quantities such that fluid dynamics is represented by a set of particle evolution equations [2]. The schematic diagram of this scheme is shown in Fig. 1(a). The density of the particles was expressed in terms of the sum of the kernel functions of number of particles present within the radius of influence [3]. The governing equations for an incompressible viscous flow are based on the relationship between the velocity of sound and the flow density under adiabatic conditions as well as the Navier–Stokes equations. Tait's equation of state can be used for estimation of pressure [2]. The MLS method improves the mass-area-density consistency and filters out small-scale pressure oscillations [4].

### 2.2. Multi-sphere DEM scheme

Solid motion depends on Newton's second law, and the interparticle contact force was calculated by the "soft sphere" assumption based on Hertzian contact theory [5]. This is depicted as shown in Fig. 1(b). Here, we call each element or calculation point constituting a solid as a "particle." Particles existing inside solids conform to the equations governing the respective translational and rotational motion. Since the non-spherical solid takes an arbitrary shape and position, the solid's inertia tensor at each step was determined by using rotational tensor [6]. In consideration of the coke size distribution immediately

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above the blast furnace raceway, sieving was performed using mesh sizes of 15 mm and 25 mm to obtain representative coke samples [7]. By using the 3D laser scanner, about 300,000 surface points of each coke sample were obtained. The obtained coordinates were converted to standard triangulated language (STL), and the surface shape was polygonated with a triangular mesh. It was replaced with arranged particles at suitable resolutions by using the level set function [8].

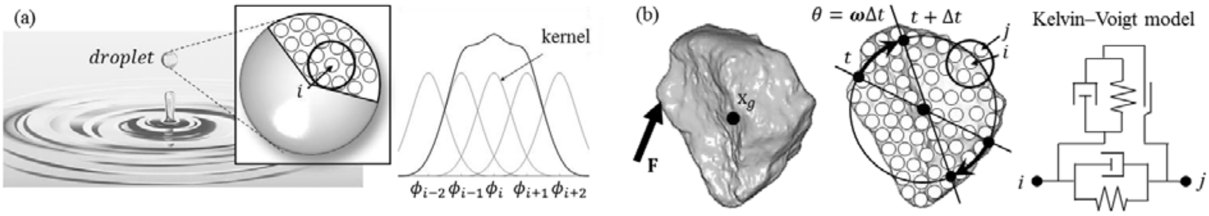


Fig. 1. Full-Lagrangian model for interfacial flow of liquid and solids. (a): Description of the distribution of a physical quantity using the SPH kernel function. (b): DEM with expanded functions for freely shaped cokes.

## 3. Result and discussion

The calculation results obtained by this method is shown in Fig. 2. In the partial region of the packed bed is obtained with high resolution, the voids are shown in red. And the region corresponding to the trickle flow is shown in the centre of Fig. 2. The colour shows the fluid velocity. Liquid drops form an icicle shape. The liquid passing region is limited and preferentially passes through a certain volume [9]. The low-velocity parts shown in blue colour correspond to static hold up. The hold up sites are dispersed randomly in the coke packed bed. In other words, there are many points in space that can be a “neck”, but the upstream information strongly affects the determination of the hold up sites. As shown in the right of Fig. 2, the picked up coke in contact with a hold up droplet was observed. The largest droplets was picked up. When viewed from directly above, it is understood that all the droplets are exposed, and there is a relatively large free space in the upper part. Further, from the bottom, it turns out that there are only gaps at the scale below the “capillary length” [10].

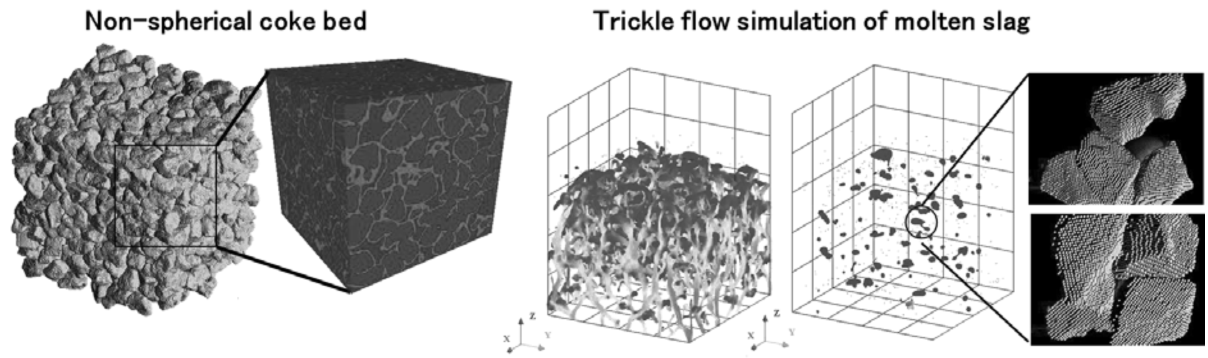


Fig. 2. Example of simulation results with over 14 million particles. In this figure, (left) packed structure of non-spherical coke packed bed (solid: blue, void: red), (centre) molten slag dripping velocity distributions with free surface, and (right) the close up views of representative holdup sites (liquid slag is shown as red viewed from the top and from the bottom).

## 4. Conclusion

A direct numerical simulation was performed for the analysis of non-spherical packed bed structure of metallurgical coke, and molten slag permeability and trickle flow characteristics were also evaluated. In a complicated coke bed, the hold-up characteristics can be determined depending on the individual postures from the view point of the local structure. Since the size of the hold up site is also influenced by the shape of the void at the top of the neck, the flow hysteresis on the upstream side of the packed bed can also have a large influence.

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