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Heat Transport in Drying of Iron Ore Pellets in a Two-Dimensional Bed

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Abstract

Drying of iron ore pellets is considered with use of hot steam going through the system. Two-dimensional system of round pellets is considered. The system is divided by modified Voronoi diagrams. Then using the data for particular configuration of three nearest pellets the relationship between average vorticity and the change of the stream function is obtained. Using the principle of minimisation of dissipation rate of energy the overall stream function distribution is obtained. This enables to consider the convective heat transfer of hot stream through the system including dispersion because of random configuration of the pellets. The evaporation is further added in order to describe the drying of iron ore pellets.

Introduction

The use of iron ore pellets offers many advantages such as good transportability, mechanical strength and quality control. Nevertheless, the production of pellets requires considerable amount of energy in drying of iron ore pellets. Throughout the drying zone in pelletizing plant, balled pellets made from a mixture of iron ore, binders and water are transported as a continuous bed on rosters while warm air is convected through the bed from either above or below. For the drying zone to be optimized, it is of highest importance that this process is known in detail. Following the work [1], heat and mass transport past a single cylindrical pellet is modelled with Computational Fluid Dynamics (CFD). A two-dimensional model of randomly packed pellets is then constructed to describe the drying in whole system since the drying conditions vary significantly from the inlet to the outlet of warm air. The model is based on Voronoi discretisation of the system and calculation of the stream function by minimisation of the dissipation rate of energy [2]. Heat transport to and from pellets is further added to the leading convective transport of air through the pellets for a particular local configuration basing on the CFD results for a single pellet [1].

1. Discrete Model of Pellets

The size of the system contains particles with average diameter 10 mm in a box with length 500 mm. Thus, it is better to consider the system of pellets as a discrete system. This will enable to study the statistical variation in macroscopic heat and mass transfer parameters caused by microscopic stochasticity both in size of pellets and their position. Moreover, it enables to include the dispersion of temperature distribution in a natural way.

2.1. Voronoi Discretisation of the System

In order to divide the system in cells each containing one pellet, Voronoi diagrams are used. Because the pellets can have different size a modified version of the Voronoi discretisation is used so that Voronoi lines do not cross the surface of particles [2]. The closest Voronoi lines with respect to the surface of particles are placed in the middle of the two nearest surfaces of particles and are perpendicular to the line connecting the centres of the particles.

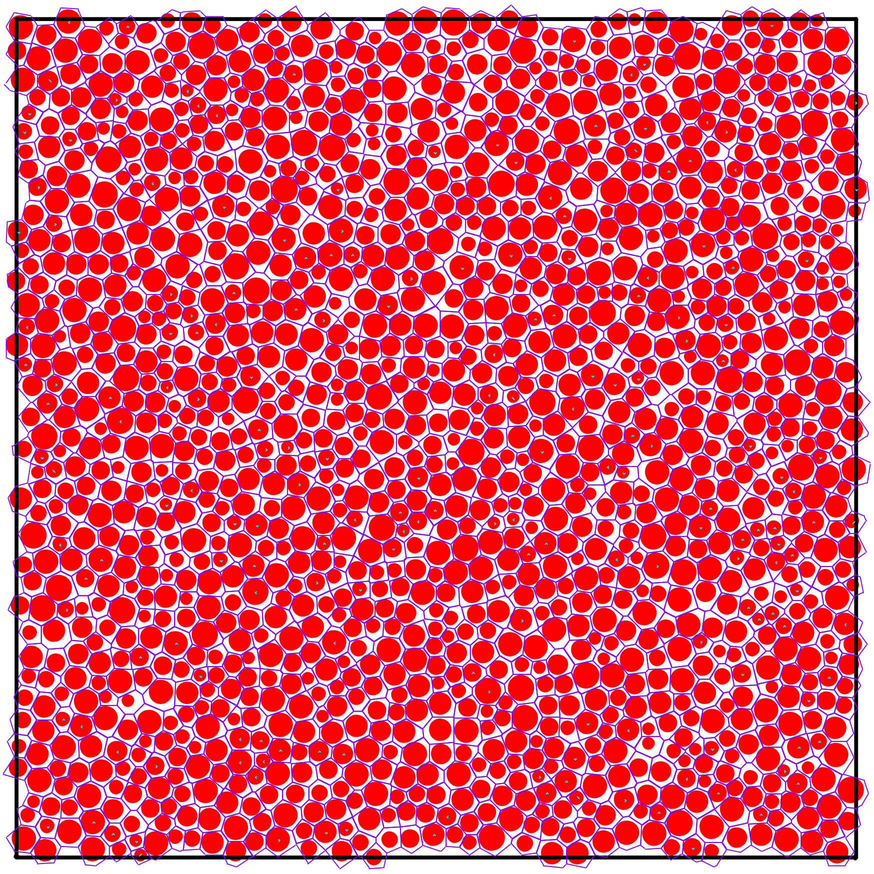

Fig. 1. Voronoi mesh of the system with periodic boundary conditions

2.2. Obtaining the Stream Function

The pellets are not permeable to the stream. Therefore, the stream function is constant along the surface of a single pellet. Furthermore, non-slip boundary condition further limits possible variation of the stream function. The vorticity distribution results from the distribution of the stream function. For that reason we use CFD results for a series of nearest three particle configurations [2]. Then we get non-dimensional coefficients relating average vorticity and difference in the stream function in a local area. Such an approach is justified by the fact that highest vorticity occurs only in the close proximity of the closest spacing between two neighbouring pellets as estimated by analytical formulas in [3] and CFD calculations in [2] for well packed systems. For low Reynolds number, we can apply then the minimisation of the dissipation rate of energy to obtain the distribution of the stream function [2, 4]. Because the dissipation rate of energy has quadratic dependence on vorticity, we get a linear system of equations with respect to the stream function values for the pellets. Despite the system can have slight pressure gradient incompressible fluid mechanics is used.

2.3. Heat and Mass Transfer between Pellets and Steam

Heat of steam is gradually transferred to the pellets starting from the inlet of pellets. It is assumed that the convective heat transfer is dominating in the space between pellets because of the high stream rate. Heat transfer by conduction can be added later if required.

The flow pattern between pellets required for convective heat transfer is calculated basing on the model described in previous sub-section. Heat and mass transfer between the steam and interior of pellets is a complicated process dependent on the flow pattern at the exterior of pellet, heat conduction through the solid part and porous part of the pellet and diffusion through pores of pellet. Systematic studies of heat and mass transfer to single pellet are made in [1]. We apply, now, the specific data for Nusselt number on given size of pellet and flow rate between the pellets to obtain the local heat transfer. Because the pellets are made from iron ore, there is only slight change of temperature within the pellet, see Fig. 2.

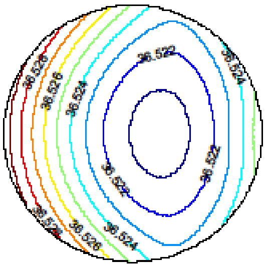

Fig. 2. Temperature distribution in °C within a single pellet as calculated by CFD. The hot steam goes from the left to right

2.4. Evaporation

The drying of iron ore pellets causes evaporation of water from the inner part of the pellets. This requires additional amount of heat and further increase of temperature is slow or even cooling is possible if dry input air is used. The heat of evaporation ΔH is nearly constant for water in the range of temperatures 20-150 °C and is set to 40.657 kJ/mol. The partial pressure of water above flat phase interface corresponds to Clausius-Clapeyron relation:

$$\ln \frac{P}{P_1} = -\frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{T_1}\right), \tag{2.1}$$

where P_1=1.03·10^5 Pa is partial pressure of water at absolute temperature T_1=373.15 K; R is universal gas constant. As the water wets iron ore, the partial pressure of water is a bit lower than over flat surface. This difference can be estimated by known pore diameter but the change of partial pressure on temperature is more important than capillary pressure for micron sized pores. The evaporation of water from the inside of pellets can start at lower temperatures than boiling temperature at given pressure if dry input air is used. This, however, leads to decrease of the temperature of pellet and further evaporation slows down until temperature rises again. Heat capacity of wet air is calculated from the ratio of partial pressures between dry air and water:

$$C_p = \frac{P_{air}}{P_{air} + P_{H20}} \frac{7}{2} R + \frac{P_{H20}}{P_{air} + P_{H20}} \frac{8}{2} R \ . \tag{2.2}$$

Heat capacity of solid iron ore is kept constant 3.03·10^6 J/K/m^3 and of water 4.19·10^6 J/K/m^3. Depending on the process parameters, recondensation of water is possible in the colder part of the system, i.e., high amount of water vapour leaves the hottest pellets and recondensates as it reaches the colder part of the system. Then the water content in the pellets can slightly increase in the corresponding part of the system. Because the temperature of the pellets is lower or equal with the temperature of surrounding steam, the condensation can occur predominantly on the pellet or inside it. Therefore, recondensation of water in the gaps between the pellets is neglected.

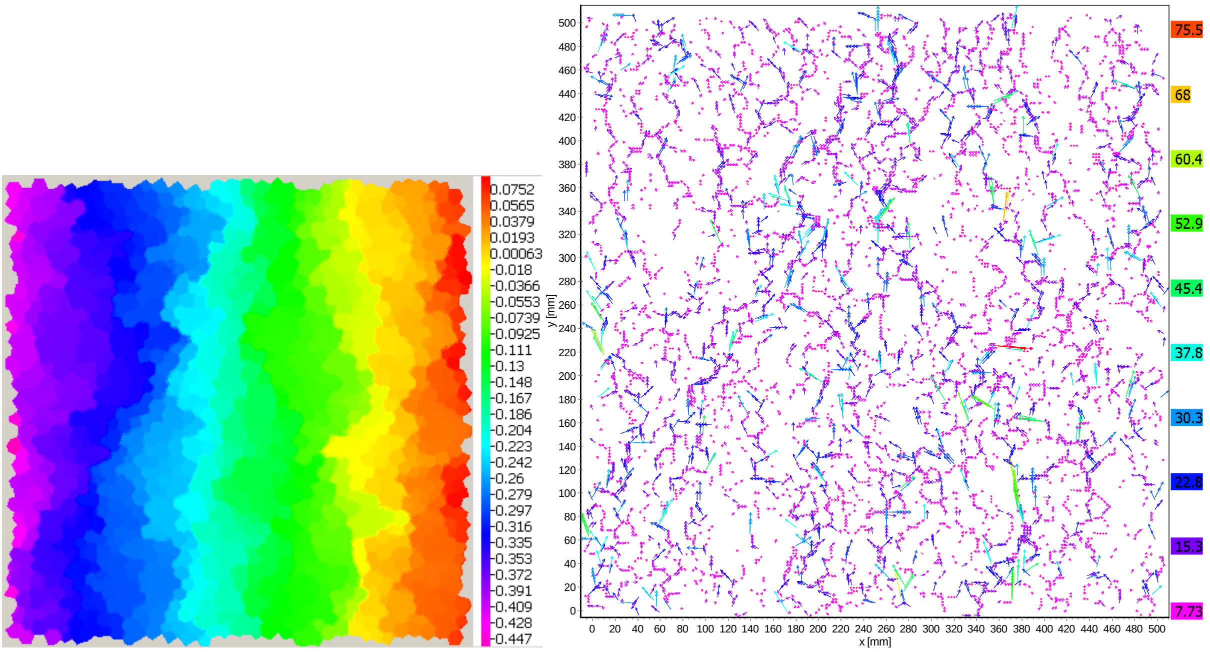

Fig. 3. Distribution of velocity for the system in Fig. 1. Left: the stream function, right: distribution of velocity

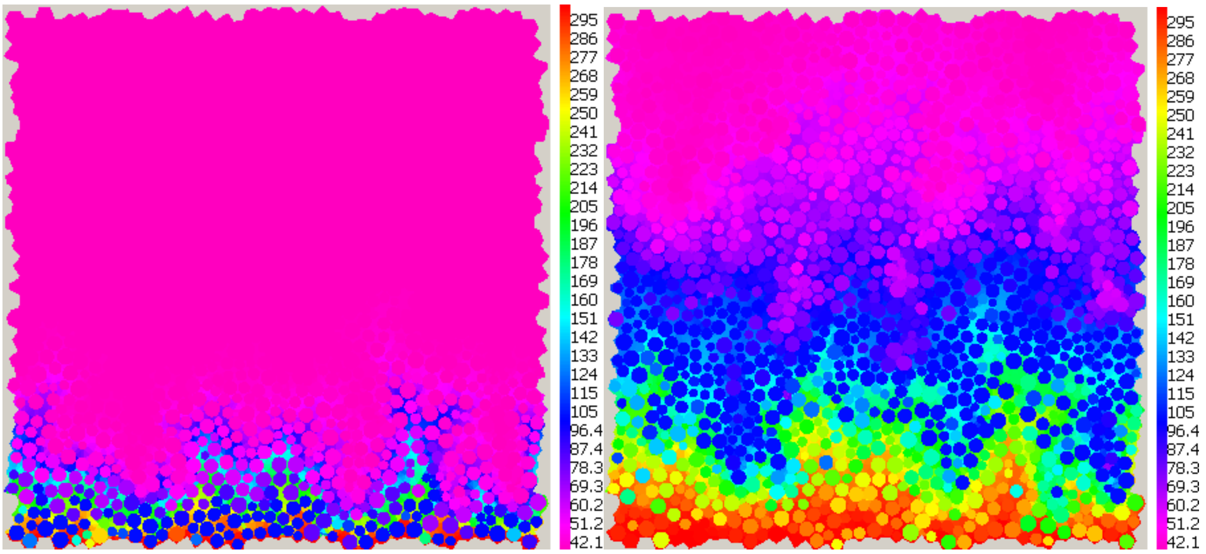

Fig. 4. Distribution of temperature with no boiling at two successive time moments

2. Results

2.1. Setup of the System

We use a quadratic box 50 cm×50 cm with around 1000 pellets. The periodic boundary conditions are applied to side walls. The initial positions of the pellets is randomised by Monte Carlo procedure described in [5] avoiding overlapping of the pellets. The input of the steam occurs through the bottom surface and the input temperature of the steam is 300 °C. The outlet occurs through the top surface. The initial temperature of the pellets is 35 °C. Porosity of pellets is 0.315 and initially the pores inside pellets are filled 50% by volume with water.

2.2. Heat Transfer without Evaporation

First, let us consider the case when there is no water in pellets and we just look on the increase of temperature of pellet. The temperature front advances much faster in the gaps between pellets than in interior of pellets. The advancement is especially fast along wide gaps where the convective transport is much larger, see Fig. 3.-4. This is related with the natural dispersion occurring in the random system of pellets. The pellets at the outlet do not feel yet the heat from the inlet in Fig. 4. As we see all the heat energy of the steam goes in heating of pellets at the high temperature front. Thus, the heating process will certainly not be faster if we switch the inlet side from bottom to top as then the hot air can leave the system from already heated pellets.

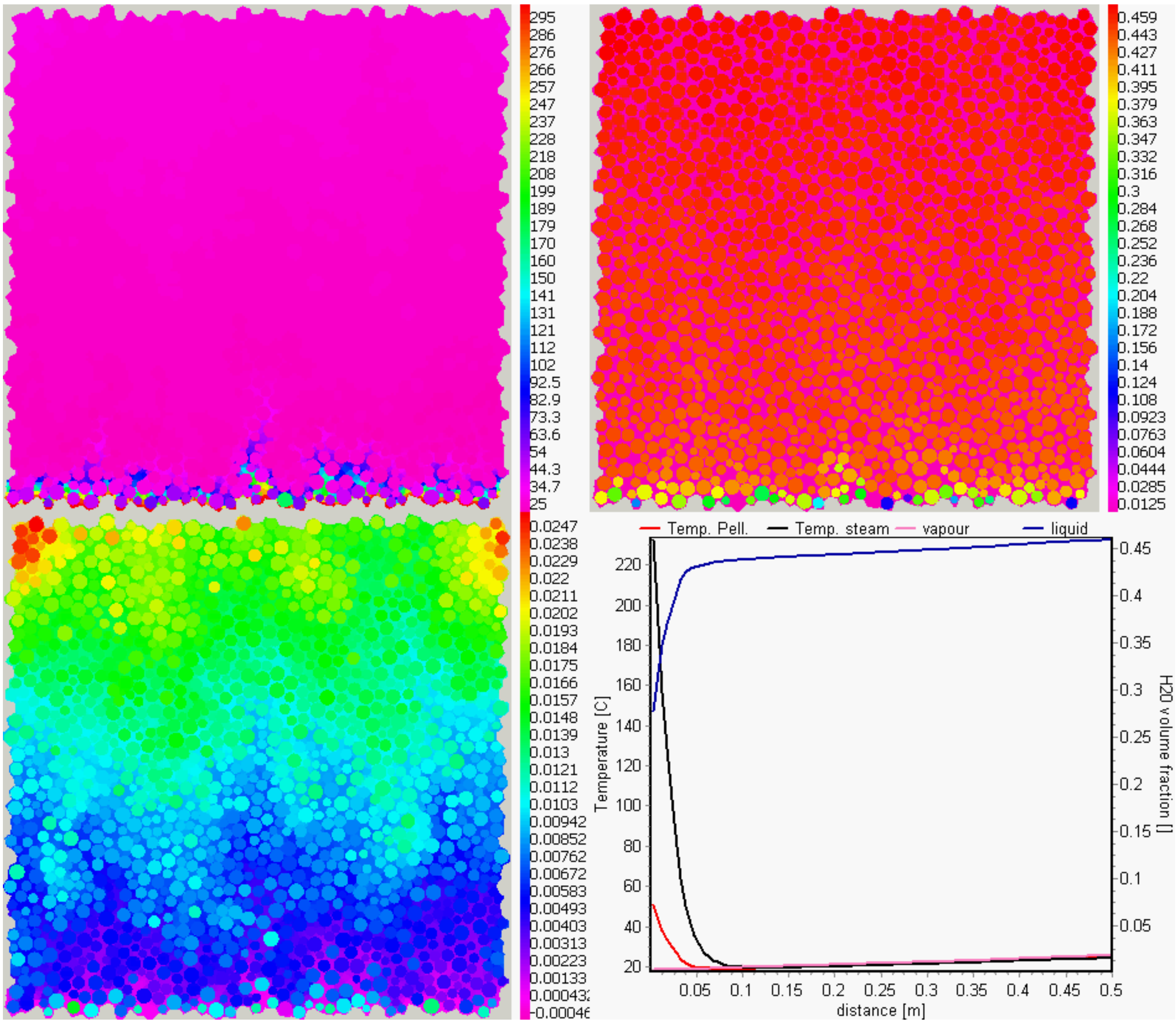

Fig. 5. Case with boiling when input air has absent moisture. The system is shown at the first stage of the drying process. Top-left: temperature distribution in Celsius. Top-right: remained water volume-fraction inside pellets. Bottom-left: moisture volume-fraction in steam both inside and outside the pellets. Bottom-right: profiles of averaged temperature and water volume fractions along vertical line

2.2. Heat and Mass Transfer with Evaporation

Now, let us include the evaporation of water present in the pellets. Consider, now, that input air is completely dry and vapour from the interior of pellets has to leave them all the time depending on the temperature. Then the increase of temperature is limited until all the water is evaporated. Moreover, decrease of temperature is possible, see top-left and bottom-right parts of Fig. 5, where the initial temperature of pellets has decreased from 35 °C to 20 °C because the water content in these pellets has decreased, see blue line in bottom-right in Fig. 5. However, temperature cannot fall lower than dew point temperature of input steam. The vapour content in the steam increases continuously from the inlet to the outlet as it is collected from low temperature evaporation of the pellets. The temperature profile is not monotonous because low temperature evaporation is lower in wet air close to the outlet, see black and red curves in Fig. 5 bottom-right. Much higher amount of heat is required to heat up the pellets than without the evaporation of water as in previous sub-section. The increase of temperature of already dry pellets is much faster.

Conclusions

The drying of iron ore pellets in two-dimensional bed is considered using Voronoi discretisation and flow pattern obtained by minimisation of the dissipation rate of energy. The dispersion of temperature and humidity is introduced in natural way through randomness of the arrangement of pellets. Using dry input stream the drying of pellets occurs even before the boiling temperature of the pellet is reached. In the other case of wet air the temperature cannot decrease below the dew point temperature of input steam. Slight recondensation occurs of the wet steam reaching the colder pellets.

Acknowledgements

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References

[1] Ljung, A. L., Lundström, T. S., Tano, K.: *Fluid flow and heat transfer within and around a porous iron ore pellet placed in infinite space.* Proceedings of the 19th International Symposium on Transport Phenomena, Reykjavik, 2008.

[2] Hellström, J. G. I., Frishfelds, V., Lundström, T. S.: *Mechanisms of flow-induced deformation of porous media.* Journal of Fluid Mechanics (in print).

[3] Lundström, T. S., Gebart, B. R.: *Effect of perturbation of fibre architecture on permeability inside fibre tows*. Journal of Composite Materials. Vol. 29, 1995, pp. 424-443.

[4] Berlyand, L., Panchenko, A.: *Strong and weak blow-up of the viscous dissipation rates for concentrated suspensions*. Journal of Fluid Mechanics, Vol. 578, 2007, pp. 1-34.

[5] Chen, X., Papathanasiou, D.: *The transverse permeability of disordered fiber arrays: a statistical correlation in terms of the mean nearest interfiber spacing*. Transport in Porous Media, Vol. 71, 2008, No. 2, pp. 233-251.

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