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CFD-DEM MODELLING OF SHAFT FURNACES, USING THE VOLUME FRACTION SMOOTHER APPROACH

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ABSTRACT

Shaft furnaces are widely used in high processing granular materials at high temperatures due to their high energy efficiency. The modelling of those furnaces is challenging. Small geometric details like the burner nozzles demand a fine Computational Fluid Dynamic (CFD) grid that requires a resolved Discrete Element Method (DEM) approach. The long process time of the granular material and the huge amount of particles make a resolved DEM approach not manageable in terms of computing resources. Therefore, two techniques were developed, the Volume Fraction Smoother (VFS) where the particle size can be independent of the cell size and the Timescale Splitting Method (TSSM) which allows to separate the fluid and DEM time scales to speed up the simulation.

Keywords: CDF, DEM, Shaft furnace, Timescale Splitting Method, Volume Fraction Smoother

NOMENCLATURE

C_p	[-]	static pressure coefficient
$\underline{U}$	$[m/s]$	relative velocity
S_{comb}	$[J/m^3s]$	enthalpy combustion source term
$S_{comb,Yi}$	$[kg/m^3s]$	combustion species source term
S_p	$[J/m^3s]$	enthalpy particle source term
$S_{p,Yi}$	$[kg/m^3s]$	particle species source term
S_μ	$[kg/m^2s^2]$	viscosity term
Y_i	$[kg/m^2s]$	mass fraction of the species i
c	[-]	force coefficient
d	$[m]$	diameter
g	$[m/s^2]$	gravity
h	$[J/kg]$	relative enthalpy
p	$[Pa]$	absolute pressure
t	[s]	time
$\underline{u}$	$[m/s]$	gas phase velocity
α	$[W/mK]$	thermal conductivity
δ	[-]	Kronecker delta
ε	[-]	gas volume fraction
μ	$[Pas]$	gas phase viscosity
ρ	$[kg/m^3]$	gas phase density

Subscripts and Superscripts

comb	combustion
p	particle
eff	effective, from the turbulence model
i, j,m	direction index

1. INTRODUCTION

Shaft furnaces use off-gas to preheat the granular product in the top part of the furnace and use the hot product after the burning zone to preheat the combustion air. This direct heat exchange leads to energy efficiency and wide use in high-temperature processes handling granular materials. Due to the constantly moving granular material, measurements inside shaft furnaces are difficult and often the temperature profile, one of the key parameters for energy efficiency of those furnaces is unknown in industrial processes.

To model the temperature profile of shaft furnaces, the movement of the granular phase in combination with combustion, flow, and heat transfer by convection and radiation must be considered. The combustion and geometry of the burner nozzles need an according mesh resolution, often smaller than the particles. To avoid the computing-intensive resolved Discrete Element Method (DEM) approaches, the Volume Fraction Smoother (VFS) was created by Pollhammer [1]. This approach shifts the volume fraction in the grid to neighbour cells to create the structure of the particle bed. To further reduce the transient calculation time of the furnace, Timescale Splitting Method (TSSM) was introduced. This method corrects fluxes to different time scales for the heat up of the particles.

2. MODEL DESCRIPTION

2.1. Granular phase

2.1.1 Particle flow

For the particle movement and collisions, the in OpenFOAM 2.4.0 [2] implemented "basicKinematicCollidingCloud" was used. This model calculates the particle contact forces with the Pair–Spring–Slider–Dashpot Model by Cundall and Strack [3]. To increase the collision time step, the Young's modulus of the particles was decreased from $2.00 \cdot 10^{11}$ Pa to $3.77 \cdot 10^{8}$ Pa so that the particles at the bottom of the furnace overlap by max. 2 %. Höhner [4] showed that an overlap of 2 % has no significant impact on the granular flow. The fluid-particle interaction forces on the particles were modelled by the Ergun–Wen–Yu–Drag model implemented in OpenFOAM [2].

2.1.2 Particle-particle heat transfer

For modelling the conductive heat transfer between individual particles, the thermal resistance between overlapping particles was modelled based on the approach of Zhang et al. [5]. Because the particles were softened, the contact areas were calculated by the forces, using the unsoftened Young's modulus. To evaluate the sub-model, the heat flux between two steel particles, with a diameter of 19.8 mm and fixed contact forces, was compared to the measurements by Kuwagi et al. [6] (Figure 1). The given implementation in the model underestimates the rate of heat flow between paricles slightly for high contact forces.

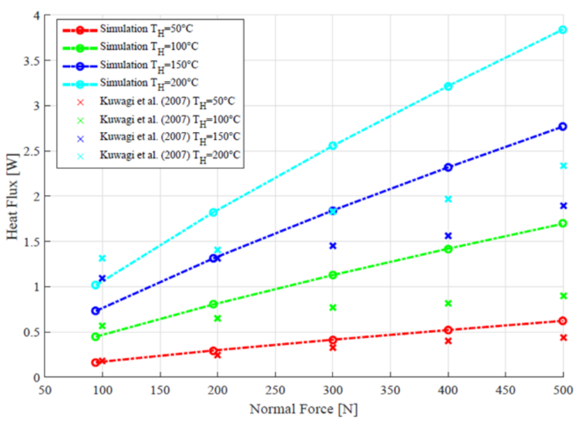


Figure 1. Comparison of the rate of heat flow for different normal forces between the presented model and the measurements of Kuwagi et al. [6]

The dominating mechanism for particle-particle heat transfer in a shaft furnace is radiation. To model the radiation between particles in a packed bed, shadowing must be considered. Feng and Han [7] calculated the view factors between individual particles in a monodispersed packed bed, considering shadowing effects. These results are implemented by a fitted function in the model. The assumption of a monodisperse bed is valid for a refractory shaft furnace due to its narrow size distribution. Yagi and Kunii et al. [8] measured the effective heat conductivity of 11 mm iron spheres in a packed bed. This setup was used to evaluate the particle-particle heat transfer by radiation and conduction. The comparison in Figure 2 shows that the model can predict the effective heat conductivity inside the uncertainty of different measurements from 400 K to 1100 K.

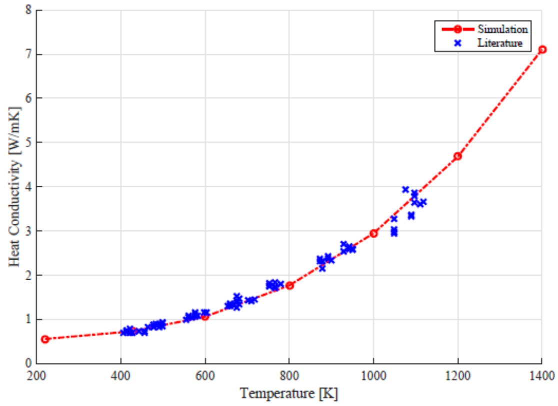
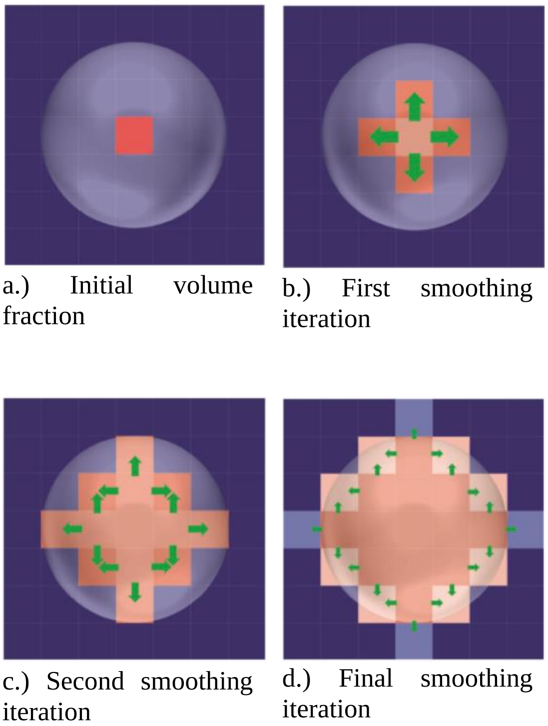


Figure 2. Comparison of the model to the measurements of Yagi and Kunii [8].

2.2. Gas phase

2.2.1 VFS

In the presented model, the particles are none resolved in the CFD grid and lager than the cells. This could lead to a particle volume fraction larger than 1 in certain cells. The rest of the cells have a volume fraction of 0 (Figure 3 a.)). To obtain a physical correct volume fraction, Pollhammer [1] developed the VFS. The basic idea is to displace the volume fraction in neighbour cells, over a pre-defined volume fraction threshold of 0.9. (Figure 3 b.)). The neighbour cells reach in this step a volume fraction over the threshold and the smoothing and the process is continued, till all cells have a volume fraction smaller than the defined threshold. The smoothing algorithm is used at the beginning of each time step.



a.) Initial volume fraction

b.) First smoothing iteration

c.) Second smoothing iteration

d.) Final smoothing iteration

Figure 3. Schematic explanation of the Volume Fraction Smoother algorithm [1]

2.2.2 Flow

Shaft furnaces are only partially filled with particles. So, the gas phase momentum balance equation must differentiate between the packed bed and free fluid flow. If the particle volume fraction in a cell is higher than 0.1 the approach for the packed bed is used. The momentum equation (equation 1) uses different viscosity terms S_μ based on the regime.

$$\frac{(\partial \rho \varepsilon u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j u_i) + S_\mu = -\frac{\partial p}{\partial x_i}\varepsilon + \rho g_i \varepsilon \tag{1}$$

For the free flow regime, a turbulence-based viscosity pressure drop equation (equation 2) is used. To model the effective viscosity μ_{eff}, sum of laminar viscosity and turbulent viscosity, the standard k-ε model [9] is used.

$$S_\mu = -\mu_{eff}\left(\frac{\partial u_i}{\partial x_j}\varepsilon + \frac{\partial u_j}{\partial x_i}\varepsilon\right) + \frac{2}{3}\mu_{eff}\frac{\partial u_m}{\partial x_m}\varepsilon\delta_{ij} \tag{2}$$

In the packed bed regime, the Ergun equation (equation 3) is used to model the pressure drop.

$$S_\mu = \left[150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\eta_f U_{sf,i}}{d_P^2} + 1.75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho_f U_{sf,i}|\vec{U_{sf}}|}{d_P}\right]\frac{1}{\varepsilon(1-\varepsilon)} \tag{3}$$

To evaluate the implemented model, an experiment was set up, using a 145 mm high packed bed of 14 mm glass speres and a 155 mm free flow region. The pressure drop for different superficial velocities was measured. This bed was modelled using the VFS and a resolved DEM approach. As shown in Figure 4 both models show a good comparison to the experimental data. The Ergun equation deviates at higher superficial velocities, due to wall effects on the volume fraction.

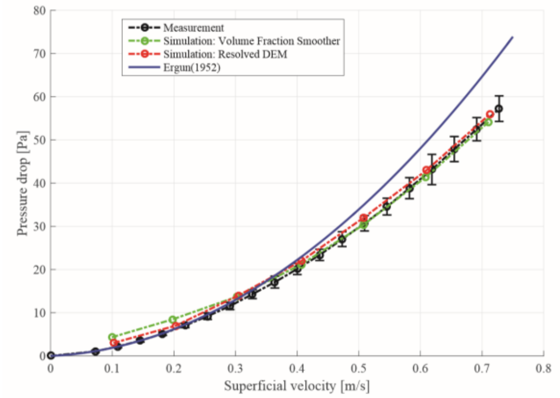


Figure 4. Comparison of the pressure drop as function of superficial velocity between measurements, the Volume Fraction Smoother, resolved DEM and the Ergun equation in a packed bed of 14 mm glass spheres.

2.2.3 Enthalpy

The equation for the enthalpy (equation 4) is adapted for the gas phase volume fraction ε and has a source term for the heat of combustion S_{comb} modelled from the combustion model, corrected by the gas phase volume fraction and the source for the practice-gas heat transfer S_p. This source term is modelled using a heat exchange model by Gunn et al. [10].

$$\frac{\partial}{\partial t}(\rho\varepsilon h) + \nabla\cdot(\rho\varepsilon u h) - \nabla\cdot(\alpha_{eff}\varepsilon\nabla h) = S_p + \varepsilon S_{comb} \tag{4}$$

2.2.4 Species

The species equations (equation 5) have a similar structure as the energy equation (equation 5). The particle source term $S_{p,Yi}$ describes the emitted or consumed gas from a particle due to drying or chemical reaction. The source term for the combustion $S_{comb,yi}$ calculated by the combustion model and must be corrected by the gas phase volume fraction ε.

$$\frac{\partial}{\partial t}(\rho\varepsilon Y_i) + \nabla\cdot(\rho\varepsilon u Y_i) - \nabla\cdot(\mu_{eff}\varepsilon\nabla Y_i) = S_{p,Y_i} + \varepsilon S_{comb,Y_i} \tag{5}$$

2.2.5 Combustion

To model the chemical reactions of the combustion process, the in OpenFOAM [2] implemented Partially Stirred Reactor model (PaSR) by Peng and Kärrholm [11] is used. To ensure reasonable computing effort the 4-step global mechanism by Jones and Lindstedt [12] is in use.

2.3 TSSM

The model of the shaft furnace is transient. In the industrial process, the particles have a residence time of approx. 6 hours in the furnace. To reach a quasi-steady state condition in the furnace, Pollhammer [1] developed the TSSM. The unaccelerated timestep is used for the gas phase equations and the collision substyles for the granular phase. For the particle fluxes, an accelerated timescale is introduced. The relation between the timescales is called the acceleration factor and all particle fluxes like heat, species, and the mass flow of particles into the furnace are multiplied by this pre-defined factor.

To evaluate the TSSM, the heat-up of a fixed bed, with a hight of 150 mm was simulated, with and without time scale splitting. The particles in his bed have a diameter of 10 mm, and a temperature of 300 K as the initial condition. Air with a superficial velocity of 0.5 m/s and a temperature of 400 K is injected from the bottom of the bed. Figure 5 compares the particle temperatures at 20 mm, 50 mm, and 100 mm bed height, between the unaccelerated case and by using the TSSM with an acceleration factor of 200. The maximum deviation between the cases is 8 % for the particles at 100 mm. The calculation time using the TSSM with a factor of 200 can be reduced to 2 % in this test case.

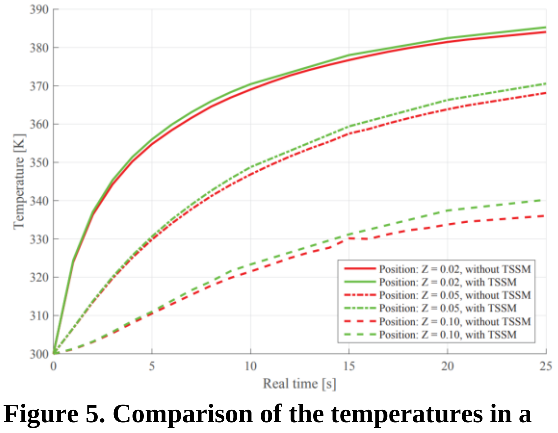


Figure 5. Comparison of the temperatures in a packed bed, with and without using the TSSM.

3. SHAFT FURNACE

The presented shaft furnace is used for spinel production, where the crystal structure is changed at 2130 K and no heterogeneous reactions occur. The furnace has a hight of 10 m and an inner diameter of 0.85 m. 3000 kg/h particles with a diameter range from 16 mm to 19.5 mm feed from the top by hopper (Figure 6). The off-gas is extracted with a side pipe under the hopper. At the height of 8 m, 12 premixed air-natural gas burners with a diameter of 15 mm are installed, flush fitting to the wall in a circular arrangement (Figure 6). The particles are extracted at the bottom of the shaft, and 2000 Nm³/h secondary air is fed into the furnace.

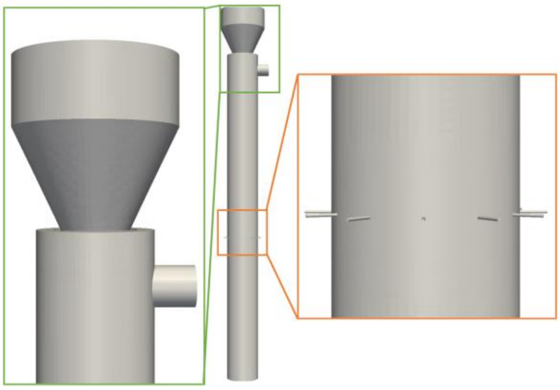


Figure 5. The geometry of the shaft furnace. At the top the feeding hopper and the exhaust pipe are shown (green). In the middle section 12 premixed burners are installed (orange).

The mesh of the furnace consists of 6.3 million hexahedral cells. The furnace is filled with approx. 1.8 million particles. For the simulation an acceleration factor of 678 for the TSSM was used.

4. RESULTS

The temperature profiles of the gas and particle phase (Figure 6) show a nearly identical profile due to the high heat transfer coefficients, ranging from 120 W/m²K to 300 W/m²K. The particles reach a maximum temperature of 2243 K at the reaction zone of the burners. In the centre of the furnace, at same height the temperature reaches 2209 K. These results agree with the operation window of the furnace. The minimum temperature for changing the crystal structure is 2130 K and the maximum temperature is limited by the solidus temperature of the particle at 2320 K. The dominant heat transfer mechanism in the hotter sections of the furnace is particle-particle radiation, leading to a low radial temperature gradient. The radial temperature profiles form in the top and bottom sections, where the temperatures are lower and particle-particle radiation is less dominant. The particle-particle conduction has no significant impact on the temperature profile due to the low heat fluxes in comparison to the radiation at the high temperatures in the furnace.

The pressure drop between the exhaust duct and the secondary air inlet, at the bottom of the furnace, is predicted with 67×10^3 Pa. The control system of the furnace measures an average pressure drop of 62×10^3 Pa.

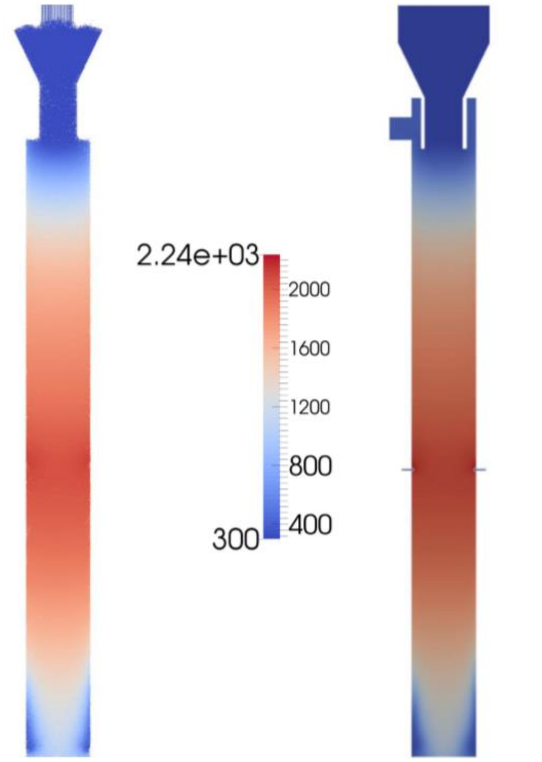


Figure 6. Left, modelled particle temperature in the furnace. Right, modelled gas phase temperature in the furnace.

5. SUMMARY

Modelling an industrial shaft furnace with a CFD-DEM approach is challenging due to the large number of particles and long process times. The granular phase in the presented spinel shaft furnaces is modelled by 1.8 million particles. To avoid using a resolved DEM approach, the VFS was developed. This approach is able to predict the pressure drop and fluid flow in the packed bed. This was shown by modelling lab-scale test and the industrial furnace. To avoid the transient modelling of long process times, the TSSM was developed. This method separates the timescales and corrects the fluxes accordingly. This allows to reduce the processing time that has to be modelled by a factor of up to 680. The method showed up to an 8 % temperature difference for the transient heat up of particles compared to DEM without TSSM. This difference should decrease when a quasi-steady-state condition is achieved, like in the shaft furnace. The model predicted maximal temperatures inside the operation window of the furnace from 2130 K to 2320 K. A weak point of the model presented is the implementation of combustion. The combustion model considered is basically valid for turbulent combustion in an unconfined space. However, in the void spaces among the particles the heat released by the combustion process is absorbed quickly by the neighbouring particles. This effect should be considered in the combustion model and is part of our future work. For the shaft furnace, this assumption is not a significant impact. The heat of combustion process is rapidly distributed due to the particle-particle radiation. In the future, an improvement of the combustion model is intended.

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