



Advanced Simulation Methods for Bulk Material Processing in Metallurgy and Metalworking

Pokročilé simulační metody pro zpracování sypkých materiálů v metalurgii a kovo zpracujícím průmyslu

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Abstract

This article explores the use of advanced digital modelling techniques – Discrete Element Method (DEM), Finite Element Method (FEM), and Computational Fluid Dynamics (CFD) – in optimizing metallurgical processes and equipment design. These methods enable detailed simulation of bulk material behaviour, structural responses, and thermal dynamics, replacing traditional empirical approaches. Their integration allows for multiphysics analyses that improve efficiency, reduce energy consumption, and minimize prototyping costs. Practical applications, such as those at VSB – Technical University of Ostrava, demonstrate the value of these tools in industrial settings. The integration of simulation tools with real-time data and digital twins is driving a shift toward smarter, more adaptive, and environmentally sustainable metallurgical processes.

Keywords: Discrete Element Method (DEM); Finite Element Method (FEM); Fluid Dynamics (CFD); bulk material simulation; process optimization

Abstrakt

Tento článek se zabývá využitím pokročilých technik digitálního modelování – metody diskrétních prvků (DEM), metody konečných prvků (FEM) a výpočetní dynamiky tekutin (CFD) – při optimalizaci metalurgických procesů a konstrukce zařízení. Tyto metody umožňují podrobnou simulaci chování sypkých materiálů, strukturálních reakcí a tepelné dynamiky a nahrazují tradiční empirické přístupy. Jejich integrace umožňuje multifyzikální analýzy, které zvyšují účinnost, snižují spotřebu energie a minimalizují náklady na prototypování. Praktické aplikace, například na Vysoké škole báňské – Technické univerzitě v Ostravě (VŠB-TUO), demonstrují přínos těchto nástrojů v průmyslovém prostředí. Integrace simulačních nástrojů s daty v reálném čase a digitálními dvojčaty podporuje posun směrem k inteligentnějším, adaptivnějším a environmentálně udržitelným metalurgickým procesům.

Klíčová slova: metoda diskrétních prvků (DEM); metoda konečných prvků (FEM); dynamika tekutin (CFD); simulace sypkých materiálů; optimalizace procesů

1. Introduction

Digitization and Industry 4.0 principles are becoming an integral part of all industrial sectors, including metallurgy and metalworking. In these areas, efficient processing and handling of bulk materials such as ores, powders, slags, and additives are key to ensuring product quality and economic viability. Traditionally, the design of process and transport equipment has relied on empirical equations and the experience of engineers. However, modern tools such as 3D CAD/CAM systems and numerical simulations have brought fundamental changes to the design process.

2. Simulation of Bulk Material Behaviour Using DEM

One of the most progressive numerical approaches is the Discrete Element Method (DEM). This method is based on the modelling of individual particles and their mutual interactions, allowing for accurate simulations of the dynamic flow of particulate matter in transportation, mixing, storage, and processing systems. DEM has gradually become a common tool in industrial design and research, enabling the prediction of behaviour and optimization of equipment before costly prototypes are manufactured. In metallurgy and materials engineering, DEM is used for designing mixers, feeders, and furnaces for particulate and granular substances. With properly defined input material parameters – such as particle size, shape, moisture, internal and external friction angle, cohesion, and flowability – DEM allows virtual testing of system functionality and optimization of machine geometry and processes [1, 4].

In addition to DEM, the Finite Element Method (FEM) is also widely used, particularly for analysing structural elements of processing machines. FEM enables the calculation of stresses, deformations, natural frequencies, and thermal expansion in critical parts. Combined with DEM, it allows for complex multi-physical simulations – e.g., applying forces from virtual particles in DEM to structural elements modelled in FEM, thus identifying critical stress locations or optimizing wall thickness. In **Fig. 1** DEM simulation of material flow from hopper is depicted. Colours represent different particle velocities. By combining DEM with FEM, the researchers can simulate not only the motion of particles but also the thermal and mechanical effects acting on them. This hybrid approach provides a comprehensive view of the process, enabling optimization of design and operation parameters in real industrial applications.

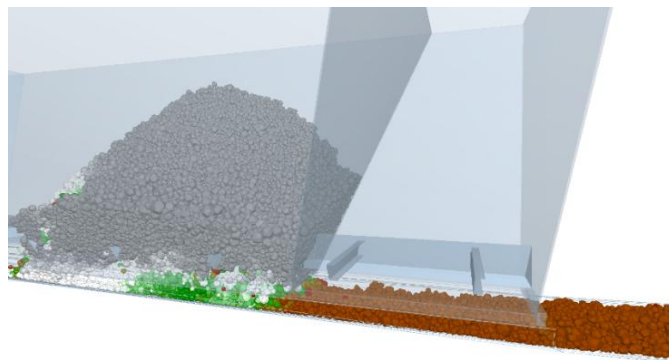


Fig. 1 Hopper simulation

Obr. 1 Simulace násypky

3. Thermal Process Simulation

Understanding the thermal behaviour of materials is crucial for metallurgical processes. Bulk materials such as ores, agglomerates, and slags are routinely processed under high temperatures. Their thermal properties, including thermal conductivity, heat capacity, and moisture content, influence heat transfer and the efficiency of sintering, casting, or slag cooling operations.

Thermal process simulation in granular and particulate systems increasingly relies on the integration of Discrete Element Method (DEM), Finite Element Method (FEM), and Computational Fluid Dynamics (CFD).

This multiscale, multiphysics approach enables a detailed investigation of heat transfer mechanisms, including particle-to-particle conduction, convective exchange with the surrounding gas, and thermal radiation, especially under high-temperature conditions. Such coupled models are essential for simulating industrial processes like sintering, calcination, pyrolysis, and thermal reduction, where the behaviour of individual particles interacts dynamically with gas flows and thermal gradients. DEM is used to capture the kinematics and contact mechanics of the particles, FEM provides insight into internal temperature distributions and structural responses, while CFD resolves the fluid flow, turbulence, and thermal fields in the gas phase.

Such models are particularly useful for optimizing furnace designs, reducing energy consumption, and improving thermal stability [3]. Studies have demonstrated how CFD-DEM coupling can accurately predict temperature evolution, residence times, and particle trajectories in rotary kilns, fluidized beds, or packed reactors [2]. These simulations also help identify hot spots, assess energy efficiency, and optimize reactor designs. In **Fig. 2** screw cooler DEM simulation can be seen, where colours represent different temperatures of particles.

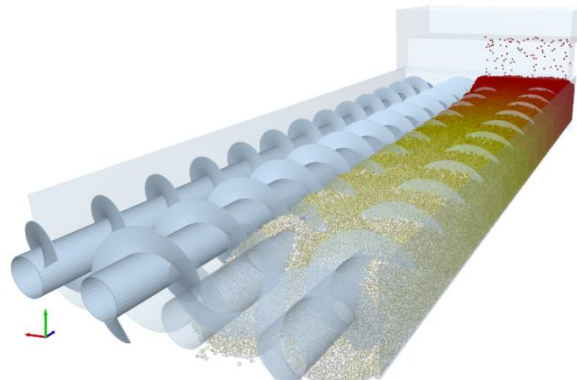


Fig. 2 Screw cooler simulation

Obr. 2 Simulace šnekového chladiče

In the future, integration of real-time data and adaptive digital twins could enable dynamic control of thermal processes. By linking live sensor inputs with simulation models, these systems can respond to changing conditions, detect anomalies early, and optimize operations in real time improving energy efficiency, product quality, and overall process stability.

4. Applications in Metallurgy and Process Engineering

In metalworking and steel production, bulk materials are used in processes such as sintering, smelting, and casting. These processes are demanding in terms of mechanical and thermal load on the materials and devices. DEM can be used to evaluate mechanical stress on linings, screens, and feeding systems, while also identifying potential operational issues such as clogging, uneven mixing, or excessive wear. Such modelling supports the design of systems with longer service life and reduced operational costs.

The Centre of Bulk Solids at VSB – Technical University of Ostrava plays a leading role in this area in the Czech Republic. It focuses on the study of bulk material behaviour and transport systems, conducts measurements of mechanical-physical properties of bulk materials and supplies input parameters for DEM and other simulation tools.



It collaborates closely with industrial partners to improve process efficiency, reduce energy consumption, and enhance product quality. The centre uses high-performance computing to simulate granular flow, contact forces, thermal behaviour, and wear mechanisms in equipment such as rotary kilns, screw conveyors, and ball mills. It also develops patented innovations in handling technologies and provides comprehensive consulting and design services for industrial partners.

5. Conclusion

The combination of DEM and FEM methods represents a powerful tool for the design, optimization, and diagnostics of equipment and processes in metallurgy and metalworking. When coupled with thermal simulations and CFD analysis, these digital methods provide a detailed understanding of heat transfer, fluid flow, and material behaviour under complex conditions – especially in high-temperature environments. This holistic modelling approach enables engineers to predict critical parameters such as temperature gradients, stress distributions, and flow instabilities, leading to more accurate and efficient process control.

Thanks to numerical modelling, it is possible to minimize prototyping costs, shorten development cycles, and enhance the competitiveness of industrial products. Moreover, the integration of real-time data and adaptive digital twins brings new opportunities for dynamic optimization, predictive maintenance, and sustainability improvements. The convergence of DEM, FEM, CFD, and thermal analysis is thus transforming traditional process design into a data-driven, intelligent system. The adoption of these digital methods into engineering practice is not just a trend but a key pillar for innovation, efficiency, and environmental responsibility in modern metallurgy and manufacturing.

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